

Reliability Analysis
and
Artificial Intelligence

By Zach Cramer

Road Map For Today's Discussion

1. Reliability Analysis

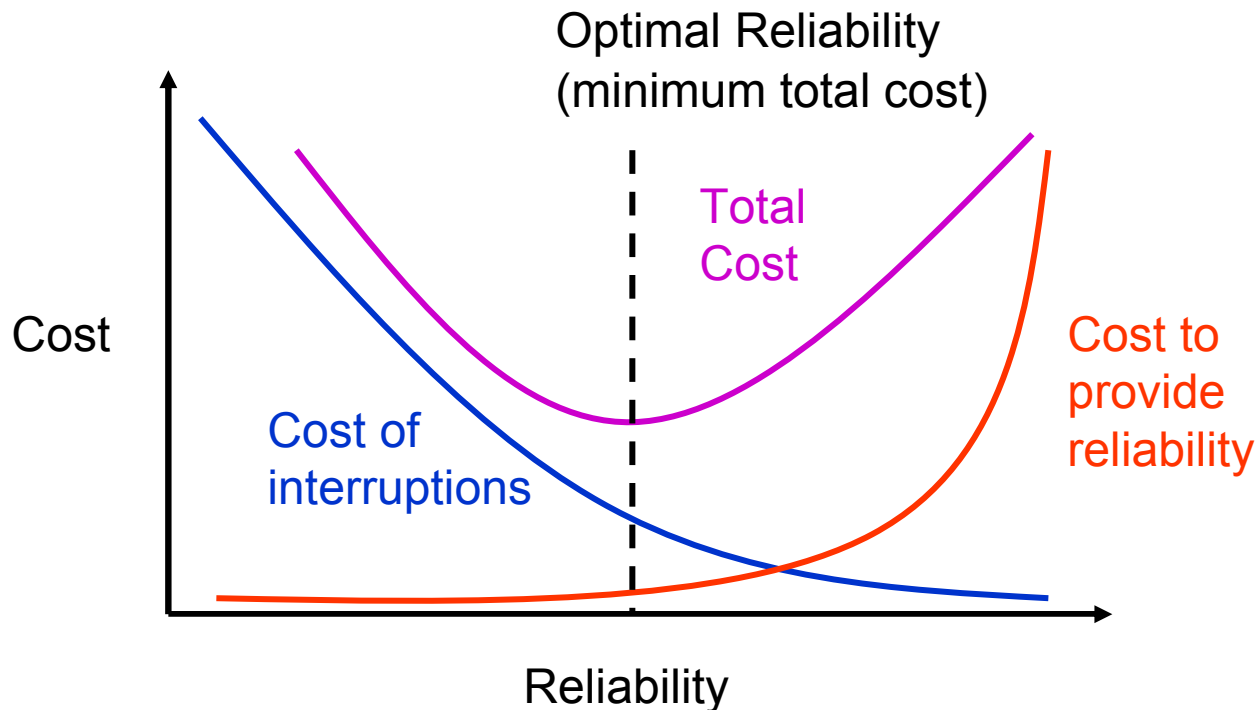
- a. Cost of Customer Reliability
- b. Component Reliability Models
- c. Standard Analysis – Transmission Line Example, SCADA Switches vs. Line Sectionalizing
- d. Advanced Analysis - How to quantify N-2, N-1-1, weather, load, maintenance and other events
- e. Substation Reliability Analysis - Green and brown field decision matrices for Main/Aux, Double Bus Single Breaker and Breaker and a Half bus configurations

2. Artificial Intelligence

- a. Genetic Algorithm - transmission network expansion planning example
- b. Artificial Neural Networks – pattern recognition, time series forecasting and clustering examples

Reliability Analysis

The traditional goal of most reliability programs is to design the minimum cost system. Costs include customer outage costs as well as the utility's costs of building, operating and maintaining the system.



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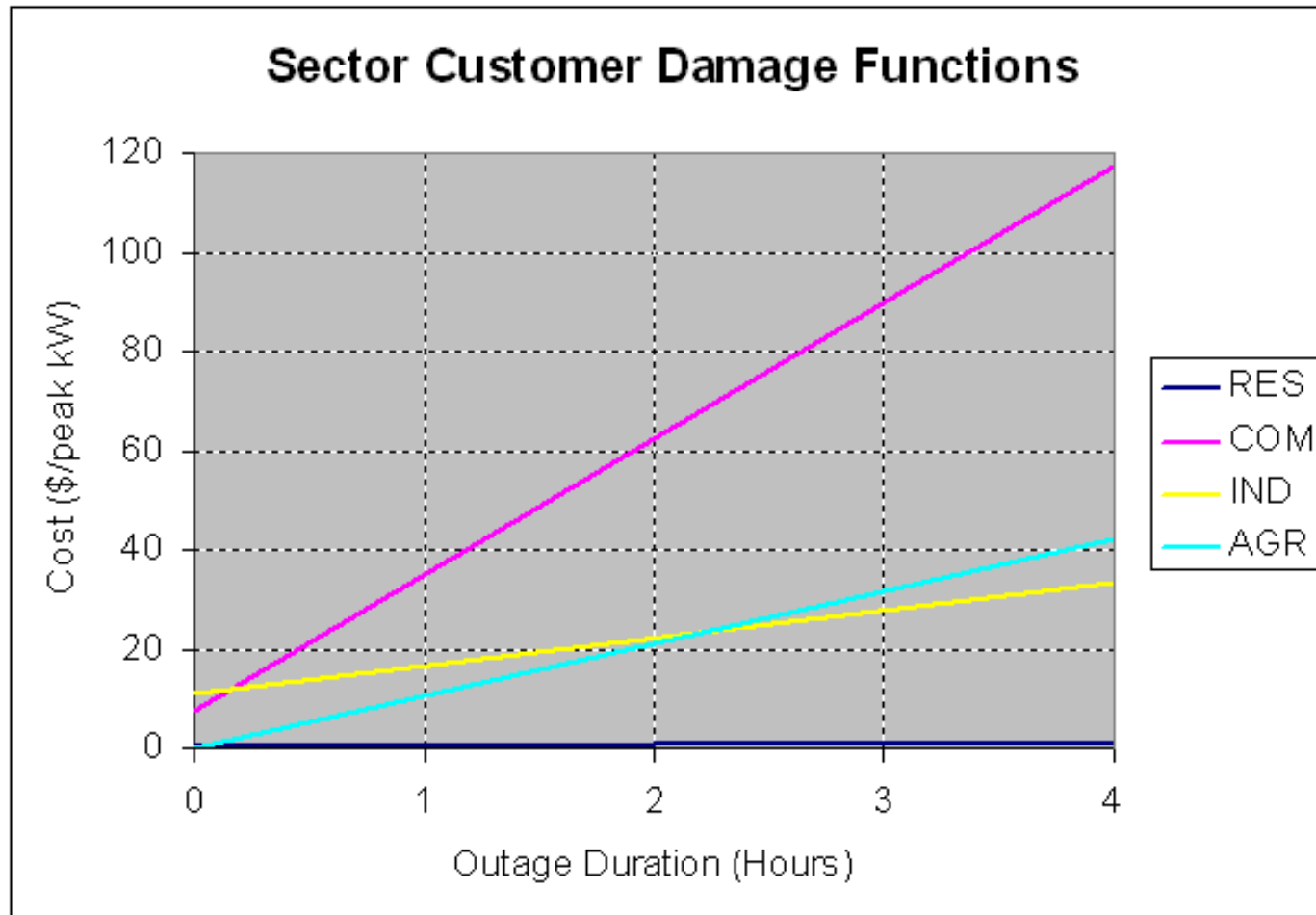
Reliability Analysis

Cost of Customer Reliability

- The cost of interruptions to customers is determined through surveys that ask customers how much they would be willing to pay for reliability and how much money they would lose for outages of various durations.
- The results of these surveys are used to create sector customer damage functions (SCDF), which are used to calculate the expected customer outage cost (ECOST). ECOST is then used to perform an economic evaluation of the various project alternatives.

Reliability Analysis

Cost of Customer Reliability



SCDF	RES	COM	IND	AGR
variable cost (\$/kWh)	0.15	27.56	5.64	10.56
fixed cost (\$/kW interrupted)	0.53	7.47	11	0

Reliability Analysis

Cost of Customer Reliability

Composite Customer Damage Functions and ECOST

- The composite customer damage function, CCDF, is the aggregation of SCDF at specified load points, i.e.

$$CCDF_k = \sum L_{peak\ i} * SCDF_i, \quad \text{for all customer sectors } i \text{ at load point } k$$

- Like the SCDF, the CCDF is a function of outage duration. The cost of a single interruption to load point k of duration r is computed from the CCDF, i.e.

$$COST_k = CCDF_k(r) \quad \$$$

- The expected customer outage cost (ECOST) due to a single outage of component i that interrupts load point k is

$$ECOST_{ki} = \sum \lambda_{ij} * CCDF_k(r_{kij}), \quad \text{for all failure modes } j \quad \$/\text{yr}$$

where,

λ_{ij} is the failure rate of component i in failure mode j , and

r_{kij} is the mean time to restore load k following a failure of component i in mode j

Reliability Analysis

Cost of Customer Reliability

Example 1 – Computing the CCDF for distribution bank “X”

Peak kW	RES	COM	IND	AGR
Dist Bk "X"	4000	10000	5000	0

SCDF	RES	COM	IND	AGR
variable cost (\$/kWh)	0.15	27.56	5.64	10.56
fixed cost (\$/kW interrupted)	0.53	7.47	11	0

Use the equation

$$CCDF_k = \sum L_{\text{peak } i} * SCDF_i, \text{ for all customer sectors } i \text{ at load point } k$$

$$\begin{aligned} \text{Variable cost} &= 4,000 * 0.15 + 10,000 * 27.56 + 5,000 * 5.64 + 0 * 10.56 \\ &= 304,362 \text{ \$/hr} \end{aligned}$$

$$\begin{aligned} \text{Fixed cost} &= 4,000 * 0.53 + 10,000 * 7.47 + 5,000 * 11 + 0 * 0 \\ &= 131,820 \text{ \$/interruption} \end{aligned}$$

Reliability Analysis

Cost of Customer Reliability

Example 2 – Computing ECOST

Suppose distribution bank “X” is served from a radial transmission line. Compute the expected outage cost for bank “X” due to the outage of the transmission line.

Based on a 10 year outage history this line’s reliability performance can be characterized by the following parameters:

λ_M = momentary failure rate = 1.4 momentary failures/yr

λ_S = sustained failure rate = 0.9 sustained failures/yr

r = mean time to repair = 4.5 hours

Dist Bk "X"	CCDF
variable cost (\$/hr)	304,362
fixed cost (\$/interruption)	131,820

$$\begin{aligned} \text{ECOST} &= \lambda_S * (\text{fixed cost} + r * \text{variable cost}) + \lambda_M * (\text{fixed cost} + 0 * \text{variable cost}) \\ &= 0.9 * (131,820 + 4.5 * 304,362) + 1.4 * (131,820 + 0 * 304,362) \\ &= 1,535,852 \text{ \$/yr} \end{aligned}$$

Reliability Analysis

Cost of Customer Reliability – Final Remarks on Cost Functions

- Most customer surveys show a nearly linear relationship between outage cost and duration. If strongly nonlinear relationships between cost and duration exist a piecewise linear model is often used.
- SCDFs can be created based on peak kW or average kW. However, using average kW will implicitly capture seasonal load effects and reduce computational burdens.
- One of the strongest criticisms is that this methodology isn't fair to residential customers because they end up paying for upgrades that mainly benefit other customer classes. If this is a major concern SCDF's can be normalized to revenues.
- An alternative to SCDFs are end-use models. In these models costs vary as a function of time of day, week and/or year. While this may produce slightly more accurate results, it is much more computationally intensive and usually reserved for studies aimed at improving reliability for a single critical customer. In these types of studies it is also common to include the cost of poor power quality in the analysis.
- For some of the larger and/or more diverse utilities regional variation in SCDFs may exist. If this variation is significant it is good practice to account for it.

Reliability Analysis

Cost of Customer Reliability – “Making it Fair”

SCDF	RES	COM	IND	AGR	Load Weighted Average
variable cost (\$/kWh)	0.15	27.56	5.64	10.56	7.22
fixed cost (\$/kW interrupted)	0.53	7.47	11.00	0.00	5.18
Contributions to Total Load	RES	COM	IND	AGR	
Load Composition	40%	15%	35%	10%	
Contributions to Total Revenue	RES	COM	IND	AGR	
Revenue Composition	40%	30%	20%	10%	
Revenue Normalized SCDF	RES	COM	IND	AGR	Load Weighted Average
variable cost (\$/kWh)	0.15	20.67	2.82	2.64	4.41
fixed cost (\$/kW interrupted)	0.53	5.60	5.50	0.00	2.98
normalized to residential class based on contribution to revenue					
Final SCDF	RES	COM	IND	AGR	Load Weighted Average
variable cost (\$/kWh)	0.25	33.84	4.62	4.32	7.22
fixed cost (\$/kW interrupted)	0.92	9.75	9.57	0.00	5.18
adjusted to preserve average costs found through survey					

Example for commercial customer class

Normalize for revenue relative to residential

Variable Cost = $27.56 * 0.3/0.4 = 20.67$ \$/kWh

Fixed Cost = $7.47 * 0.3/0.4 = 5.6$ \$/kW interrupted

Adjust to preserve load weighted average cost

Variable Cost = $20.67 * 7.22/4.41 = 33.84$ \$/kWh

Fixed Cost = $5.6 * 5.18/2.98 = 9.75$ \$/kW interrupted

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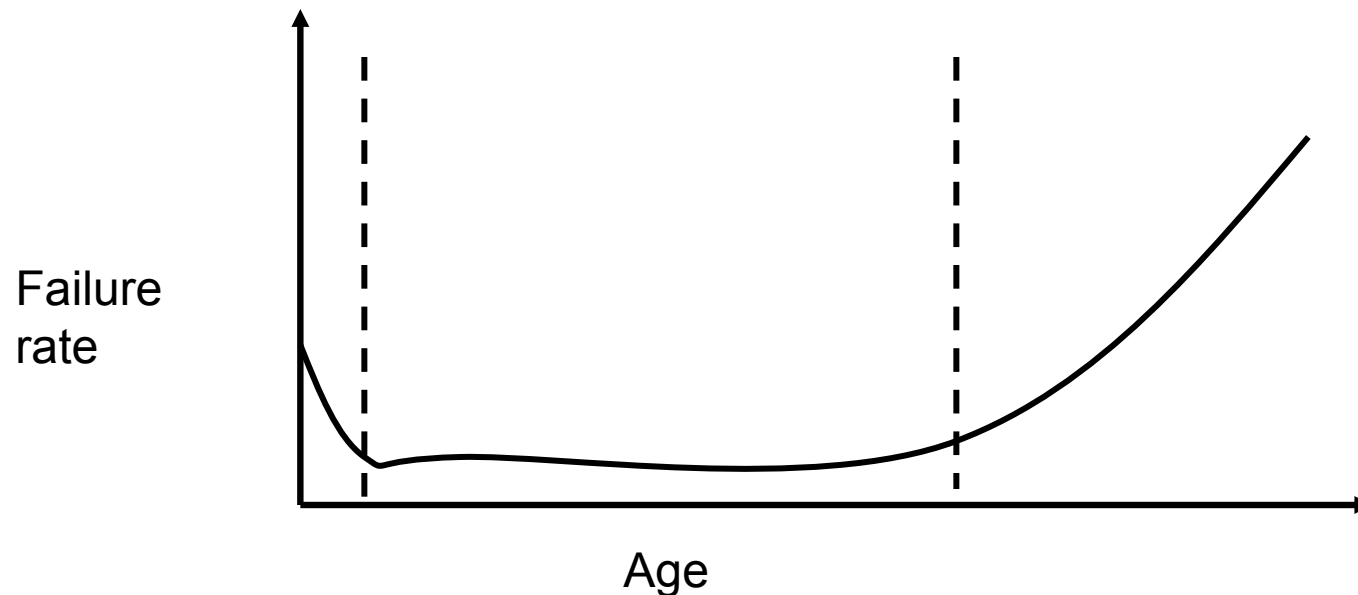
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Reliability Analysis

Component Reliability Models

Components with relatively high failure rates such as transmission and distribution lines can be modeled reasonably well using outage history data over 5 to 10 years. However, components with low failure rates such as substation components can not be modeled in this way. To predict failure rates for these components we analyze the entire population and try to define relationships between factors we can measure and the probability of failure. The most obvious indicator is component age. For many components the relationship between age and failure rate looks like the following figure:



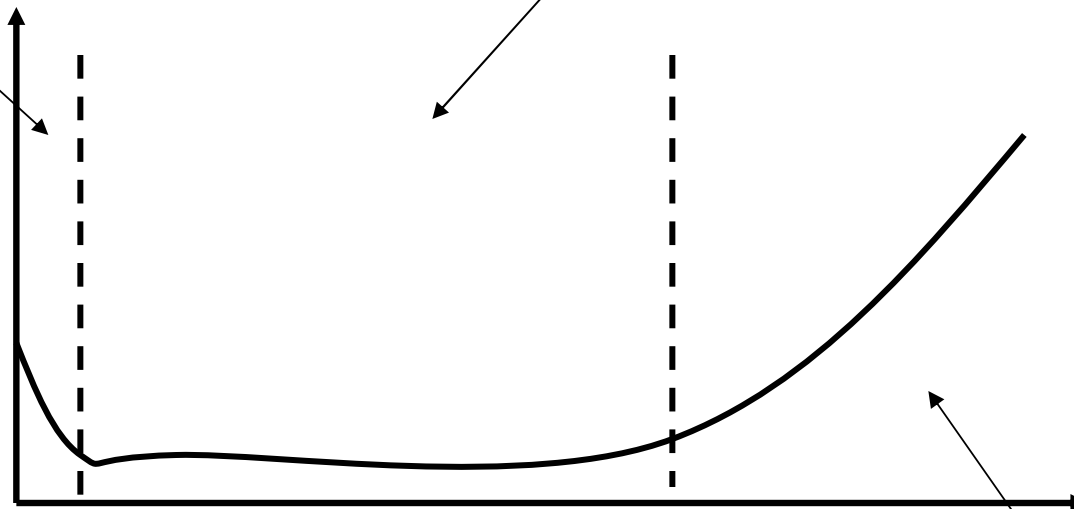
Reliability Analysis

Component Reliability Models – Hazard Rate Function

Burn in – components fail due to manufacturing defects or installation errors, failure rate decreases

Useful life – components suffer random failures, failure rates increase slowly

Failure rate



Age

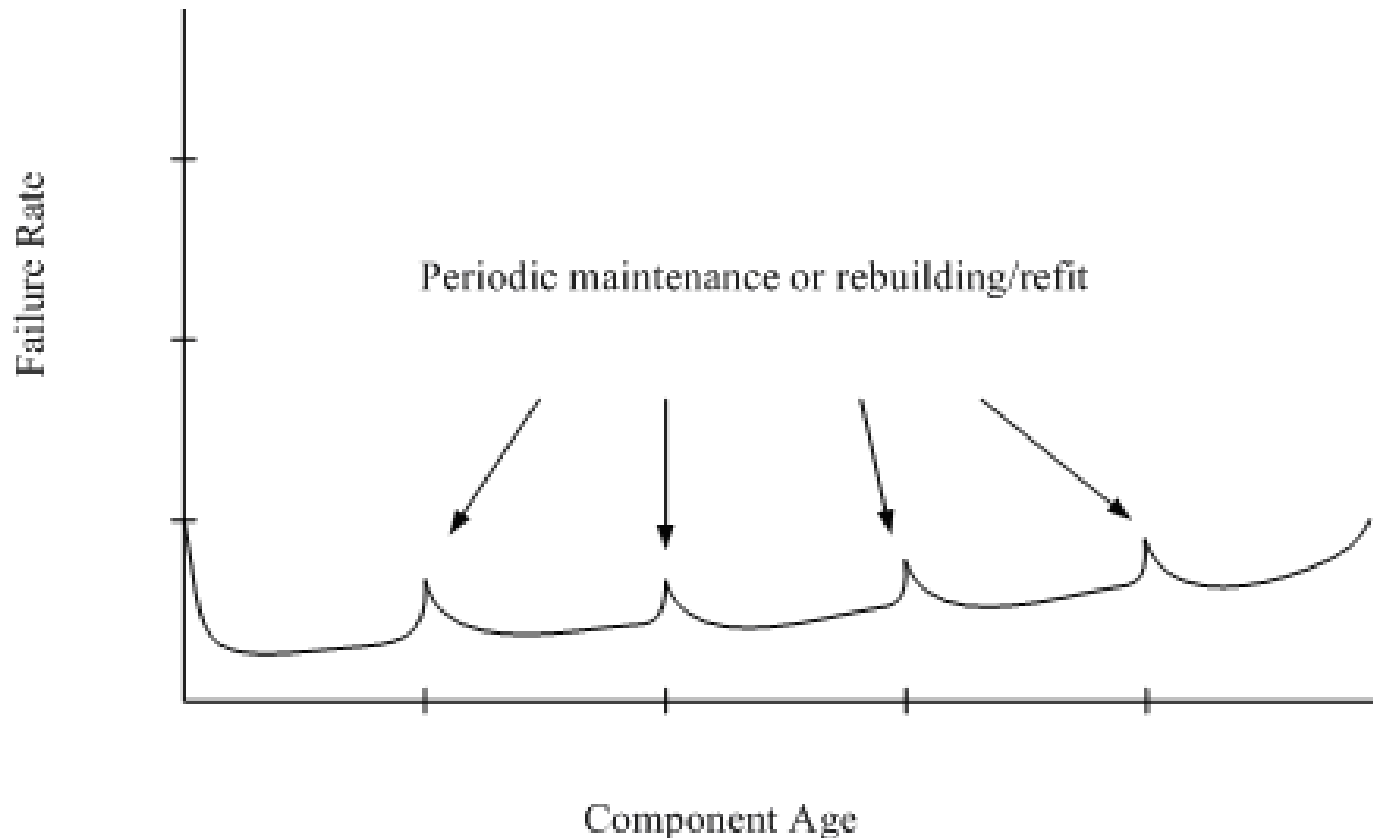
Wear out – components suffer deterioration due to the effects of cumulative service stress and aging, increase in failure rate accelerates

For certain components there are better indicators than age. For example, transformer failure rate prediction can be improved by considering DGA results, loading, risk of lightning strike, frequency and severity of through faults, vintage, maintenance, etc.

Reliability Analysis

Component Reliability Models - Maintenance

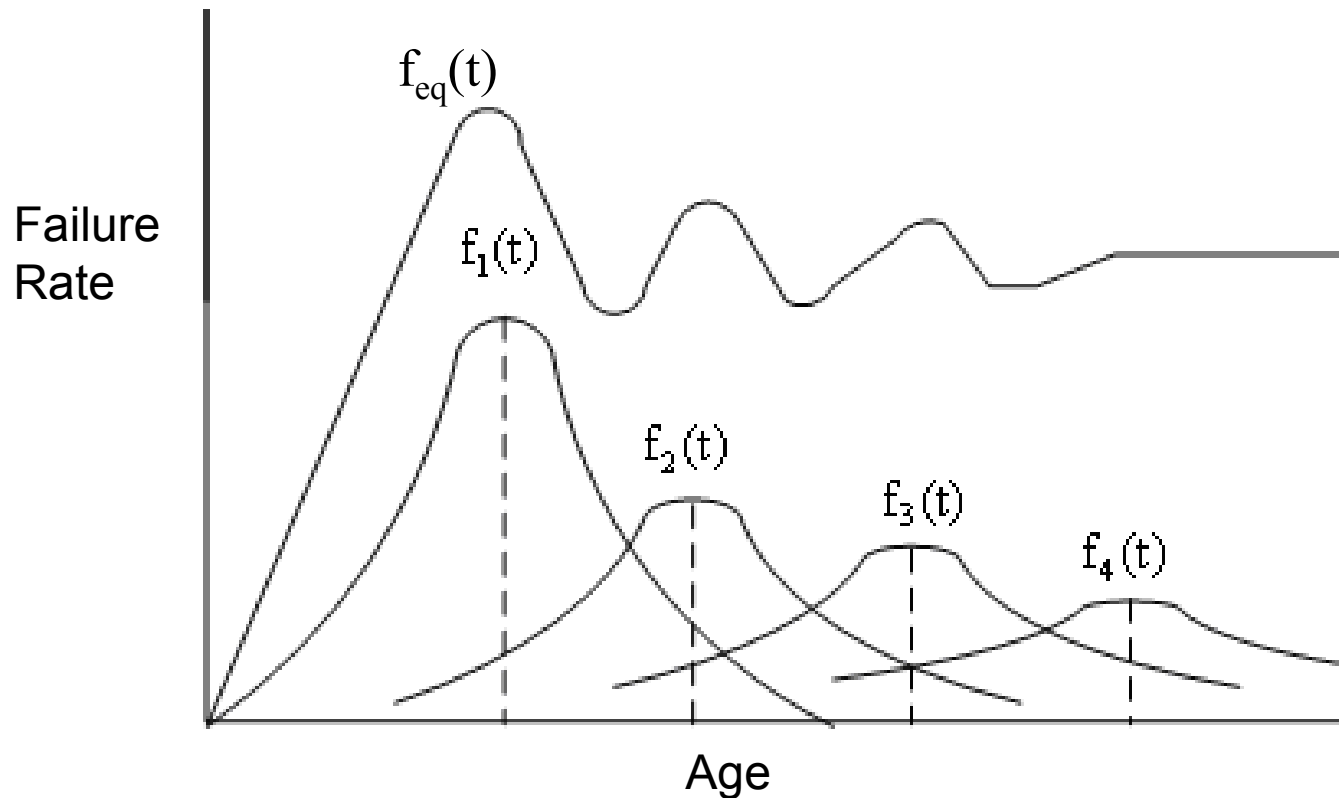
Maintenance is done during the time when failure rates are increasing. Maintenance can be done at regular intervals and/or triggered by equipment conditions. The effect is to reset the failure rate to a “newer” condition, although the rate of increase in failure rate usually continues to accelerate. Overall the effect is to extend the useful life of the equipment.



Reliability Analysis

Component Reliability Models - Repair

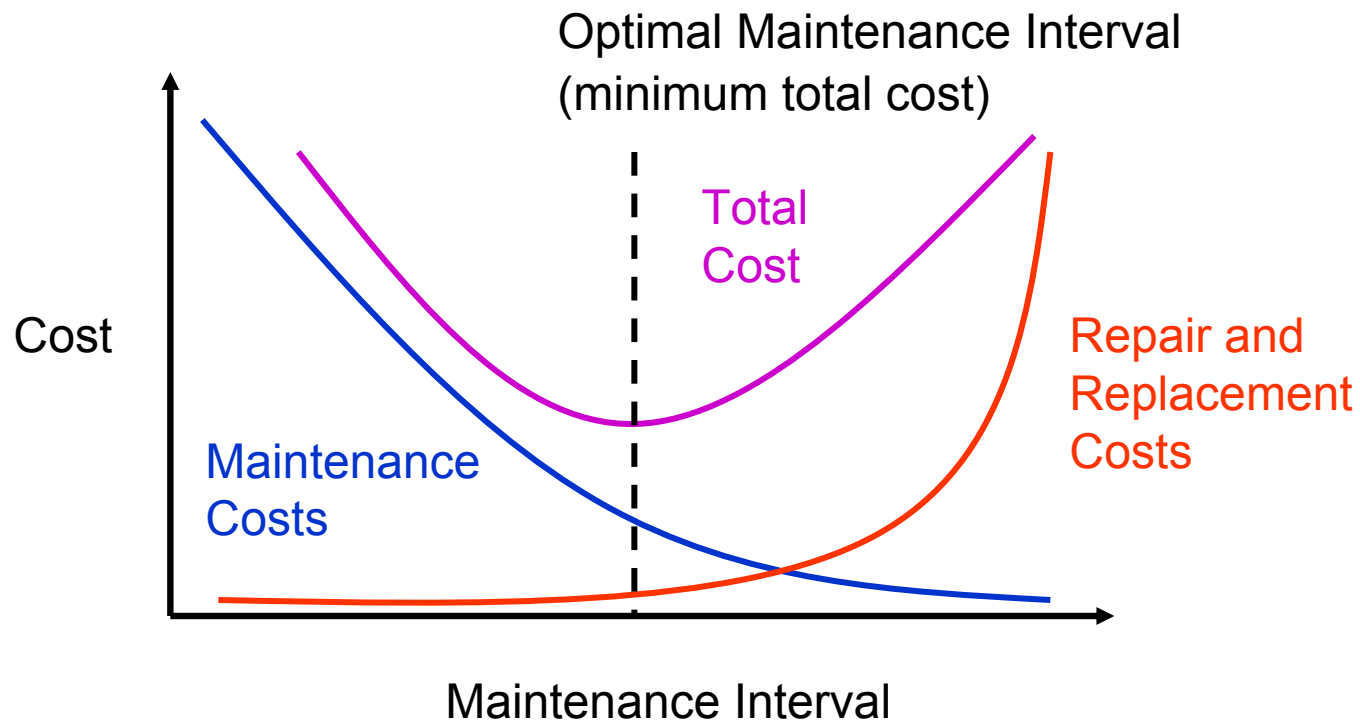
When a component failure is not catastrophic it is often repaired and placed back in service. For components that are repaired it is often useful to look at time to the first failure, time to second failure, etc. However, the overall effect is to create the illusion of a nearly constant failure rate.



Reliability Analysis

Component Reliability Models – Asset Management

In addition to maintenance and repairs, replacements must also be planned for. Asset management groups try to minimize the costs of all three actions. The relationship between maintenance, repair and replacement are shown below.



Reliability Analysis

Component Reliability Models – Failure Modes

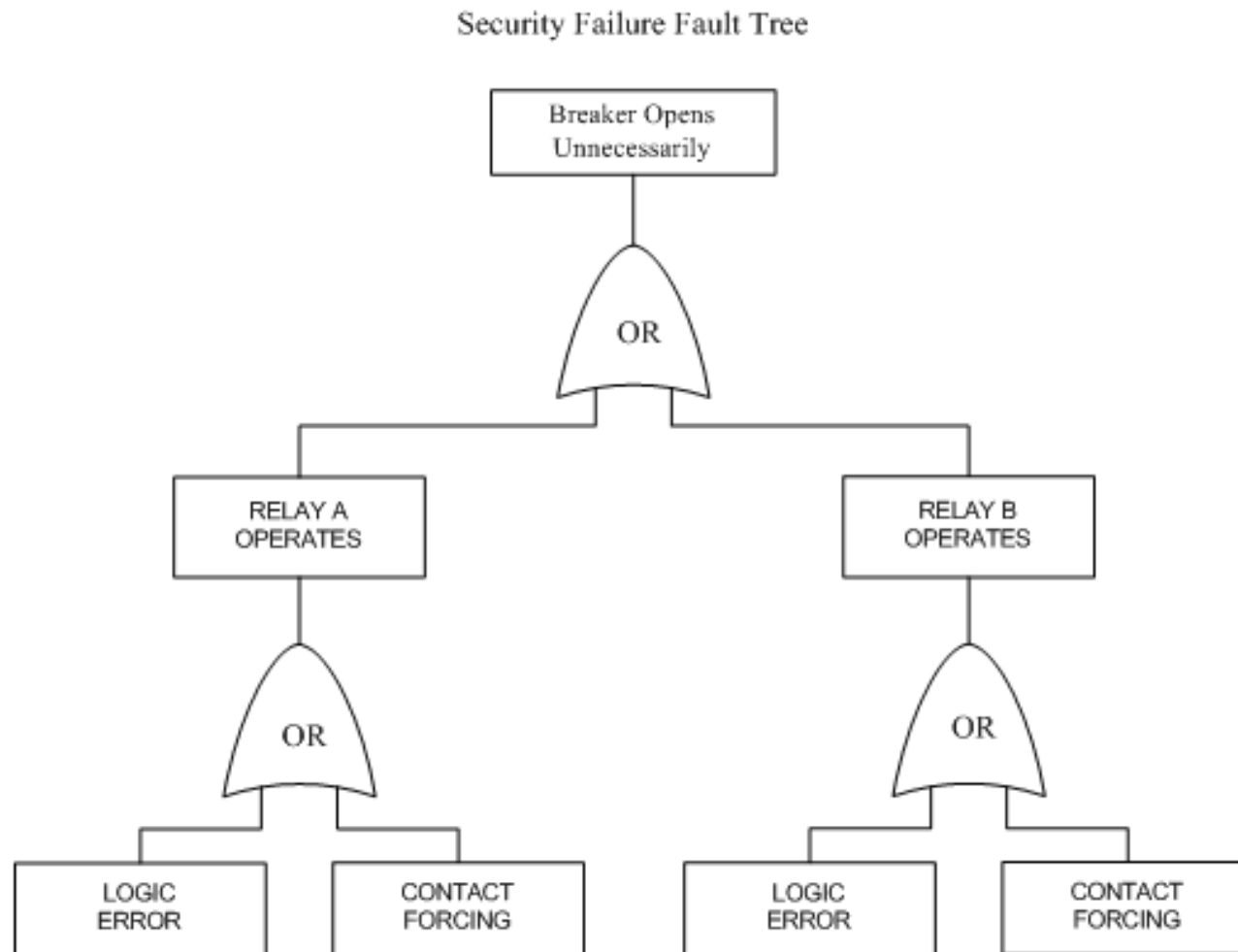
Some components have more than one failure mode. When these failure modes have different impacts on the system it is desirable to keep track of these events.

For example, a circuit breaker usually fails in one of three ways:

1. Active Failure (fault)
2. Operational Failure (stuck breaker)
3. Security Failure (false operation)

Reliability Analysis

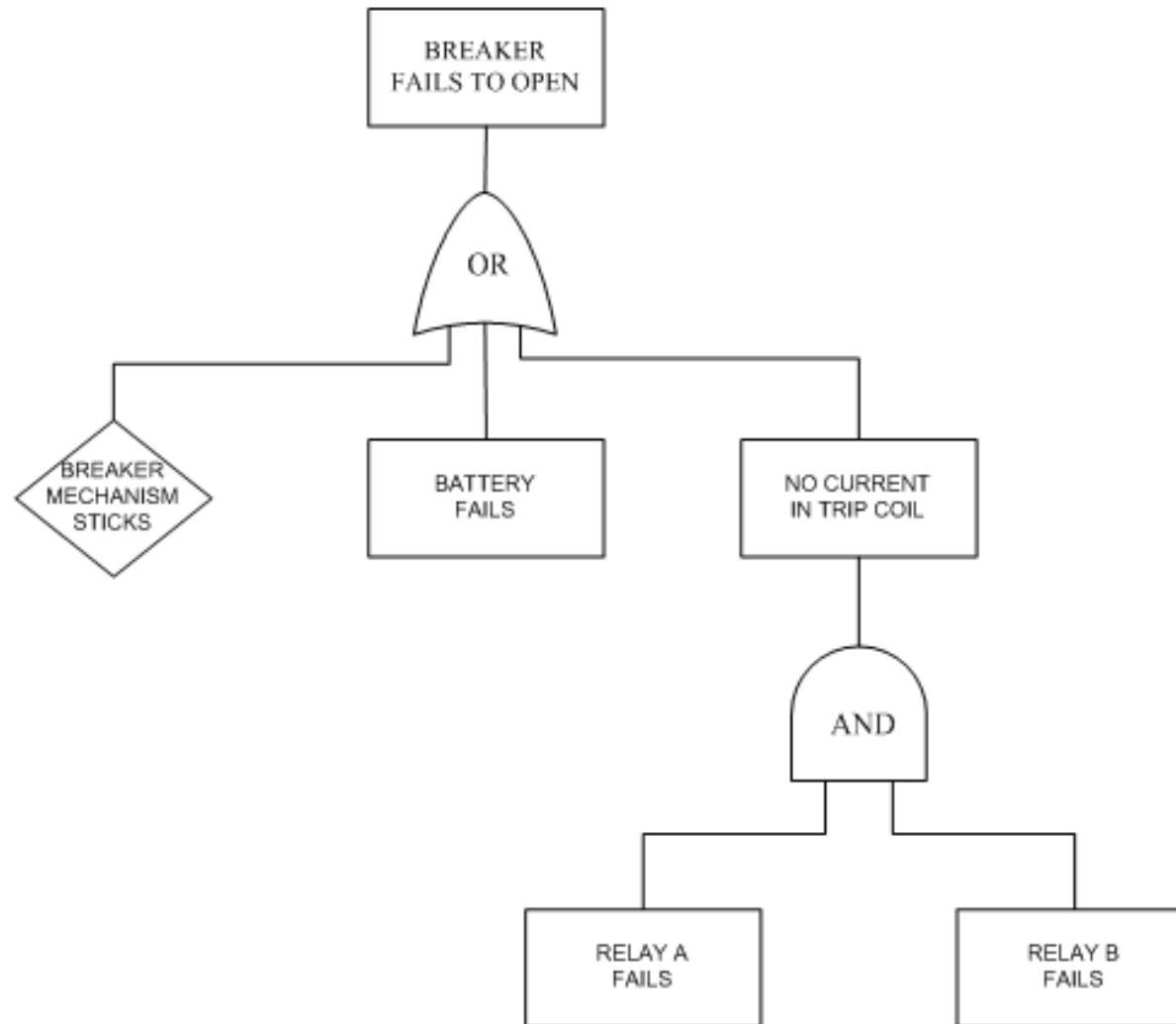
Component Reliability Models – CB Failure Modes part 1



Reliability Analysis

Component Reliability Models – CB Failure Modes part 2

Breaker Fault Tree
- Operational Failure



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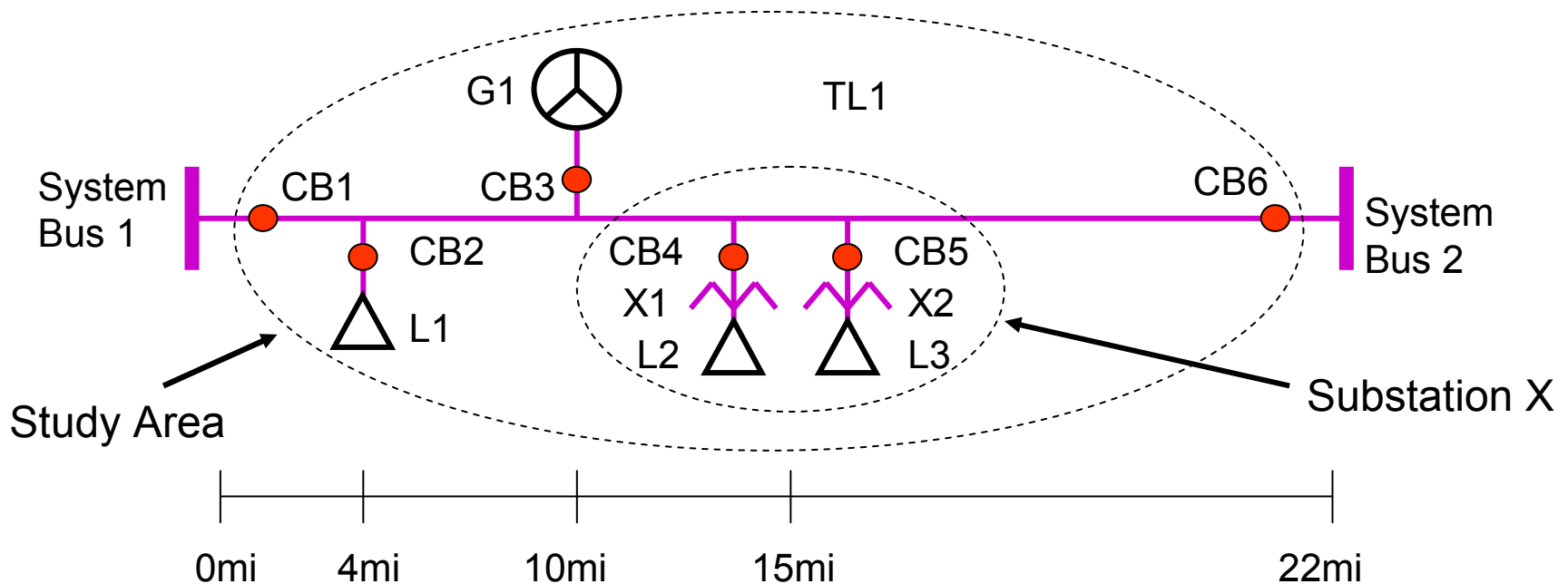
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Reliability Analysis

System Modeling – Transmission Line Example

An example transmission system is shown below. Loads L2 and L3 are near enough to each other that they could be brought into a single substation. Perform an economic analysis to determine the reliability upgrade to with the highest net present value considering the following alternatives:

1. Status quo
2. Install SCADA switches
3. Upgrade to a looped station
4. Upgrade to a ring station

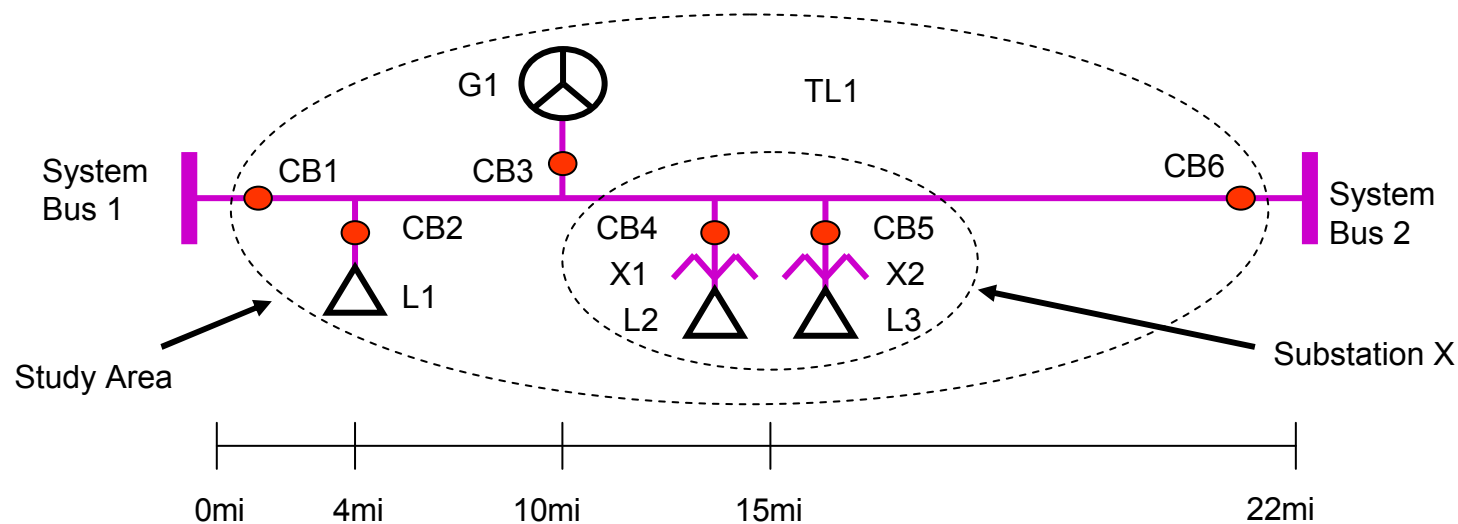


Reliability Analysis

System Modeling – Transmission Line Example

Considering N-1 transmission line, circuit breaker, bus and transformer outages, compute ECOST for the system. Assume all load and generation on the line can be carried from system bus 1 or system bus 2 and islanding is not allowed. Neglect restoration through the distribution system. Breakers 1 and 6 have SCADA. All components have disconnect switches. There are also manual switches on either side of Station X. The mean time to operate manual switches is $MTTS = 2$ hr. With SCADA, $MTTS = 0.25$ hr.

Start by gathering the necessary component and customer data.



Reliability Analysis

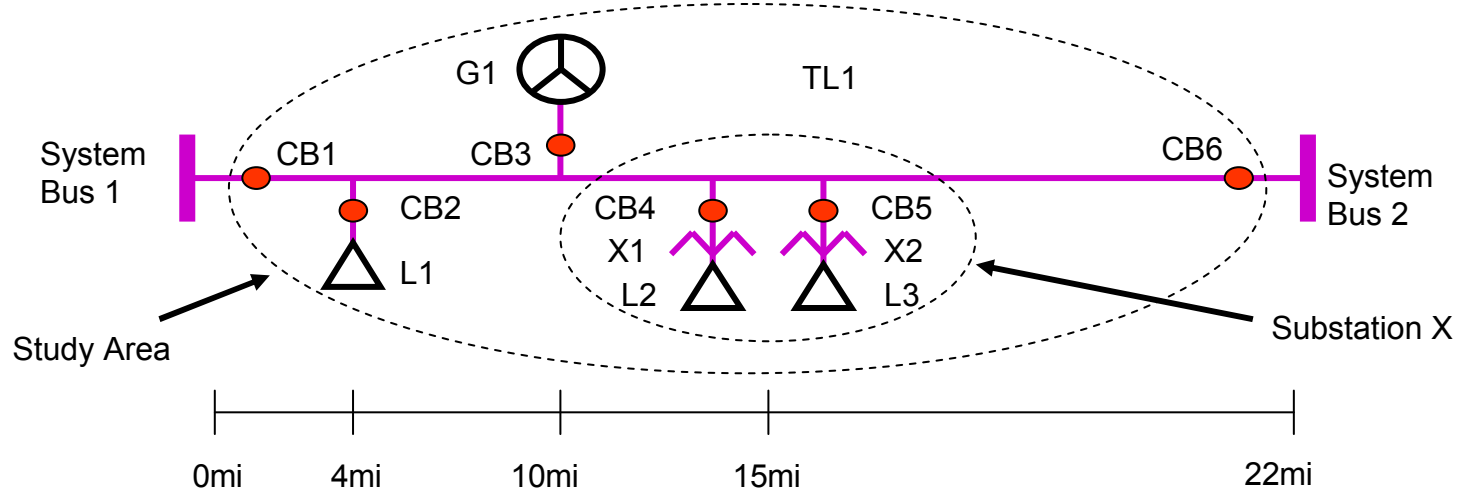
System Modeling – Transmission Line Example

Reliability Cost Data

SCDF	RES	COM	IND	AGR
variable cost (\$/kWh)	0.15	27.56	5.64	10.56
fixed cost (\$/kW interrupted)	0.53	7.47	11.00	0.00

Peak kW	RES	COM	IND	AGR	\$/int	\$/hr
L1	2,000	5,000	20,000	4,000	258,410	293,092
L2	10,000	16,000	10,000	0	234,820	498,801
L3	18,000	16,000	1,000	0	140,060	449,270

Generator	Average MW	Average Cost of Energy (\$/MWh)	\$/hr	Minimum Down Time (hours)
G1	40	80	3200	2



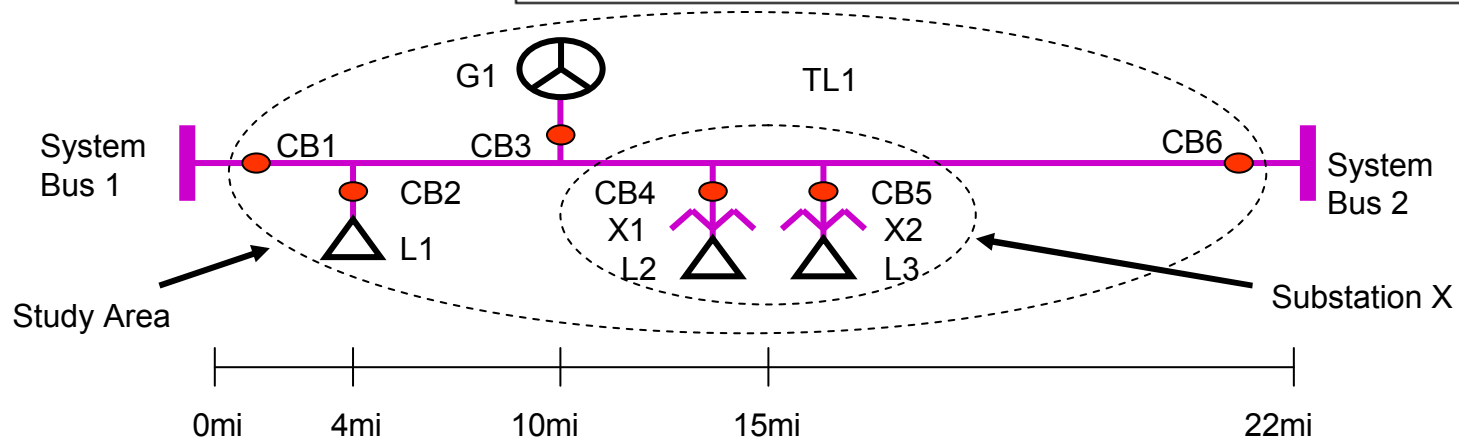
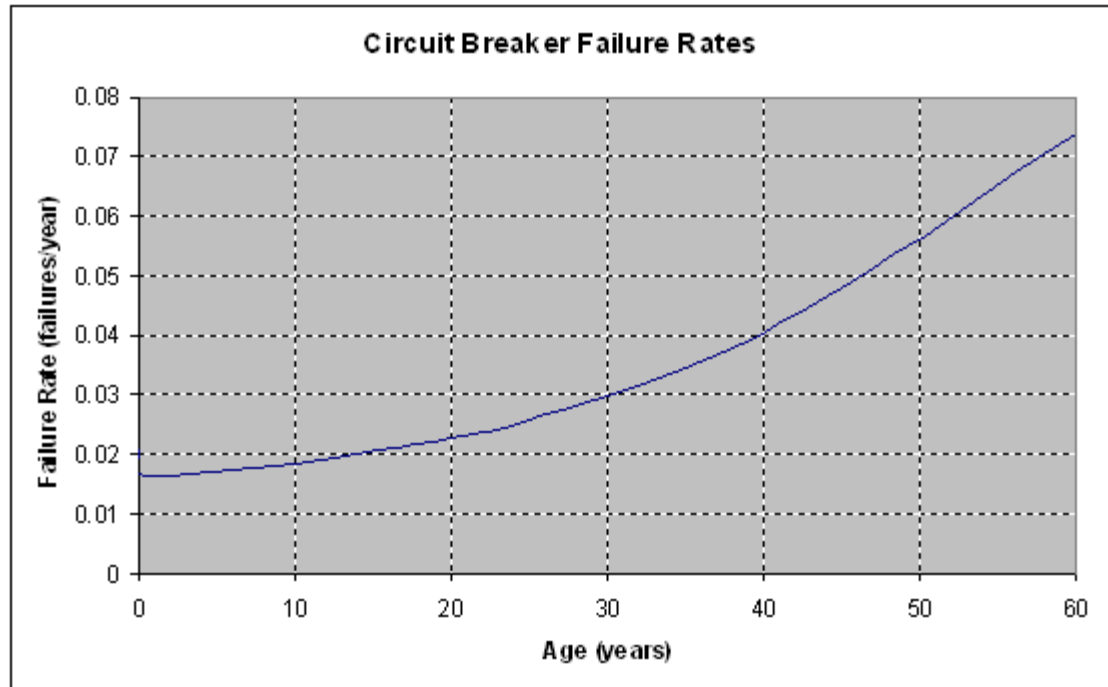
Reliability Analysis

System Modeling – Transmission Line Example Component Reliability Data – Circuit Breakers

Breaker	Age	Failure Rate
CB1	15	0.02
CB2	48	0.055
CB3	37	0.038
CB4	54	0.065
CB5	44	0.048
CB6	30	0.03

MTTR = 4 hr
(Mean Time To Repair)

Note: failure rate data is for illustration purposes only



Reliability Analysis

System Modeling – Transmission Line Example Component Reliability Data – Transformers

Transformer	Age	Failure Rate
X1	41	0.025
X2	30	0.02

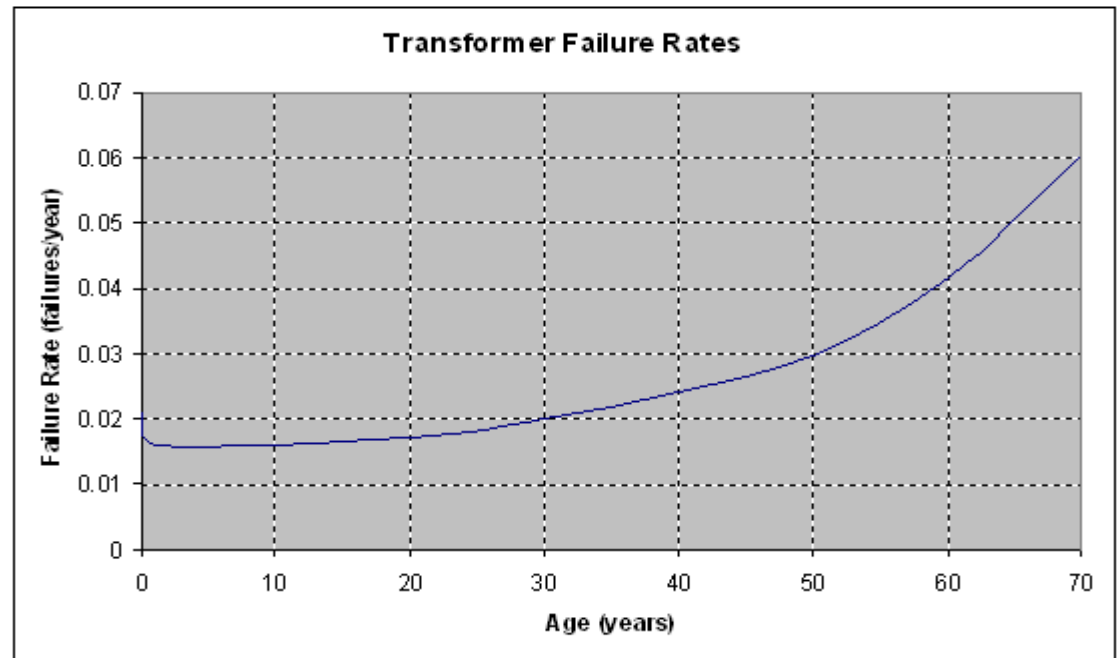
Transformer	Wndg	MTTS (hr)	MTTR (hr)
X1	4-1ph	8	72
X2	1-3ph	24	72

8 hours to switch in a spare

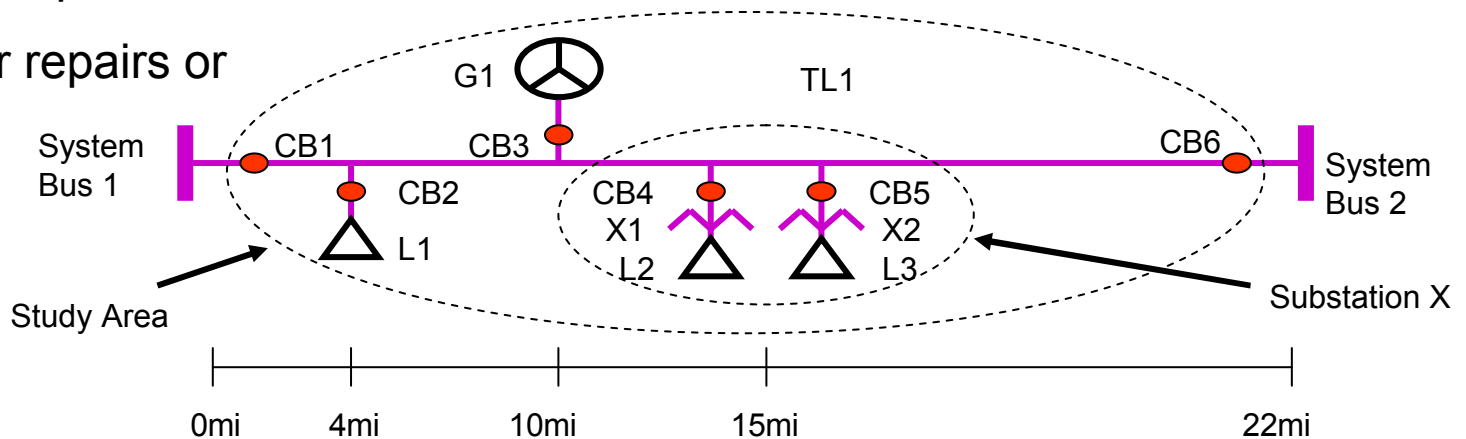
24 hours to role a mobile

72 hours for minor repairs

3 months for major repairs or replacement



Note: failure rate data is for illustration purposes only



Reliability Analysis

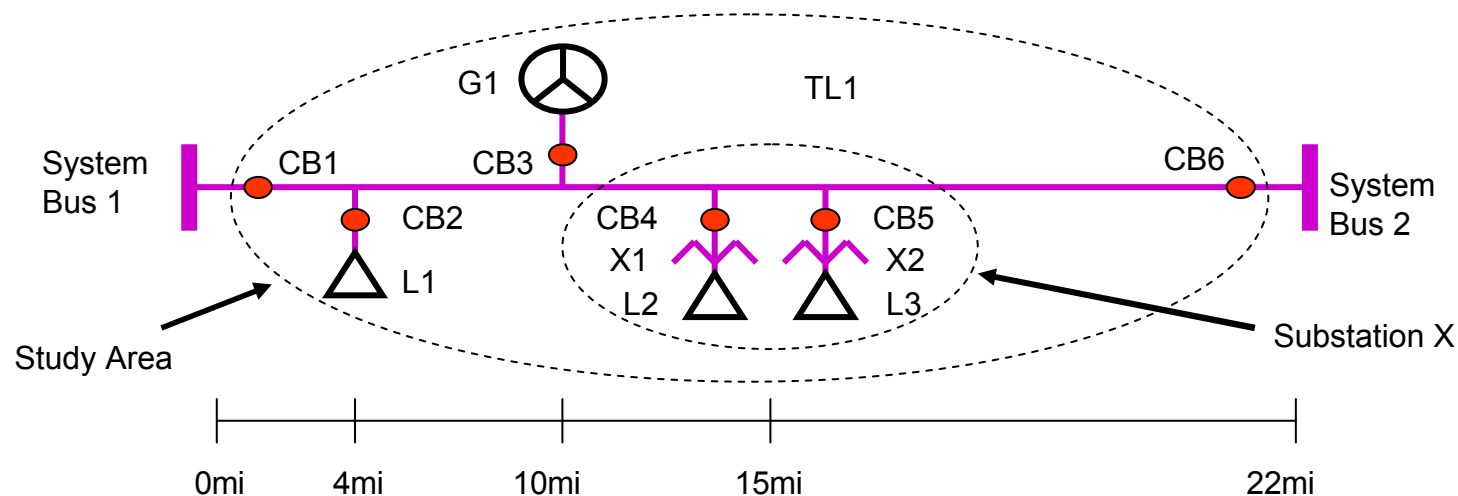
System Modeling – Transmission Line Example

Component Reliability Data – Transmission Lines

Outage History 2005-2010	
Year	Time to Repair
2005	5.84
2006	3.71
2007	0
2007	0
2008	5.62
2008	0
2010	0

Momentary Failures Per Year	0.8
Sustained Failures Per Yaer	0.6
Mean Time To Repair (hr)	5.06

Section	miles	λ_M	λ_S
Bus 1 to L1	4	0.15	0.11
L1 to G1	6	0.22	0.16
G1 to L2	5	0.18	0.14
L3 to Bus 2	7	0.25	0.19
Total	22	0.8	0.6

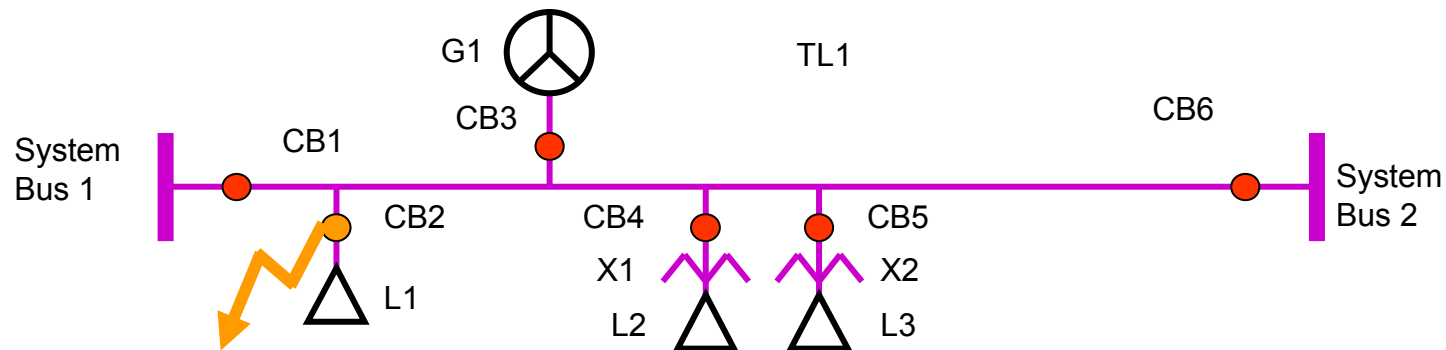


Reliability Analysis

System Modeling – Transmission Line Example

Status Quo Alternative - Failure Effect Analysis for a fault on CB2

1) CB2 faults

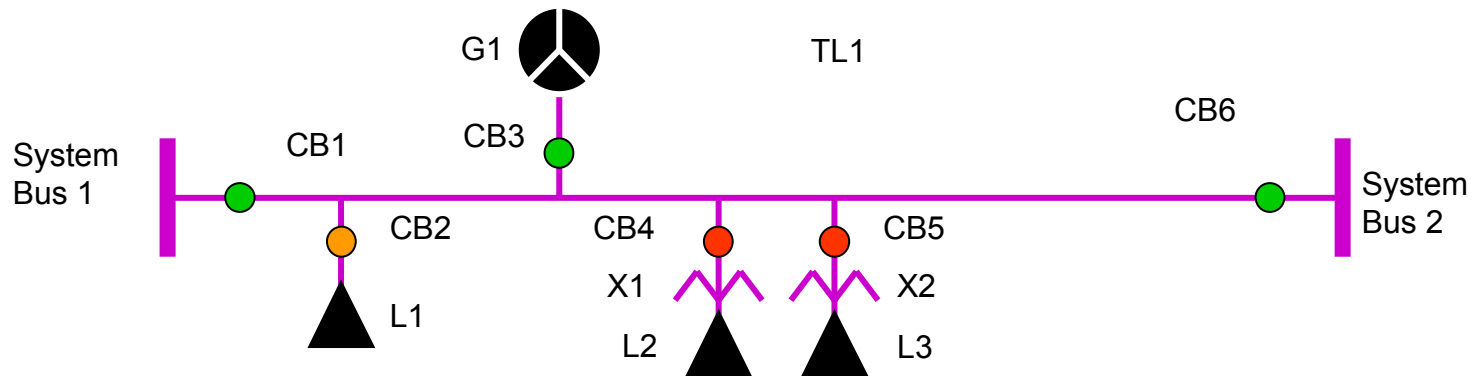


Reliability Analysis

System Modeling – Transmission Line Example

Status Quo Alternative - Failure Effect Analysis for a fault on CB2

2) CB1, CB3 and CB6 open to clear the fault, L1, L2, L3 and G1 are interrupted

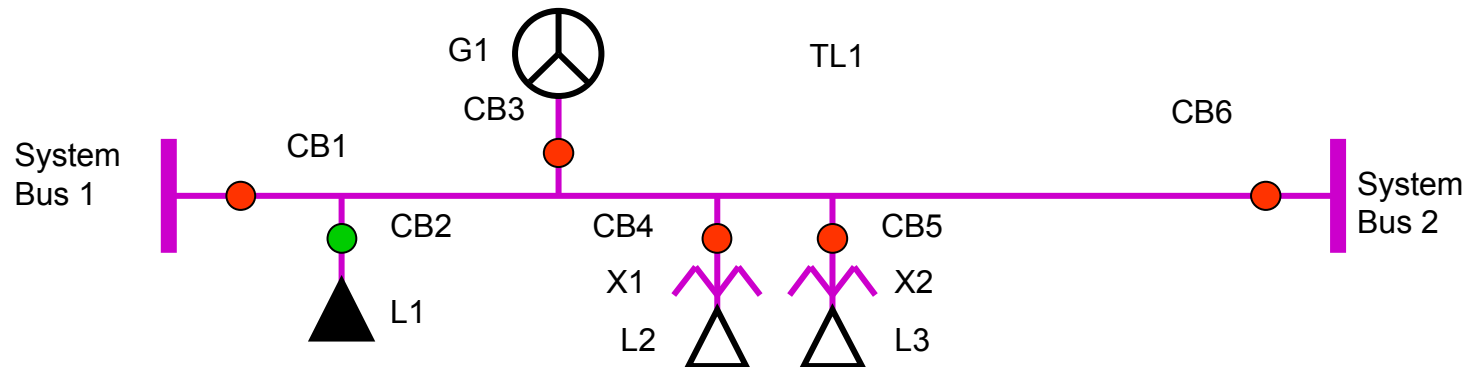


Reliability Analysis

System Modeling – Transmission Line Example

Status Quo Alternative - Failure Effect Analysis for a fault on CB2

3) A crew switches to isolate CB2 and restores L2, L3 and G1 (MTTS=2hr)

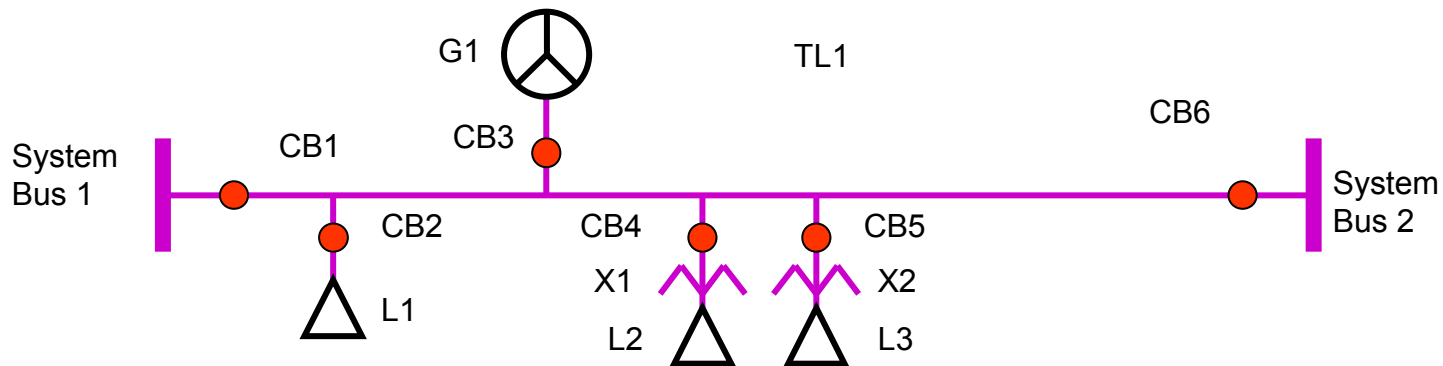


Reliability Analysis

System Modeling – Transmission Line Example

Status Quo Alternative - Failure Effect Analysis for a fault on CB2

4) The circuit breaker is repaired and L1 is restored (MTTR=4hr)

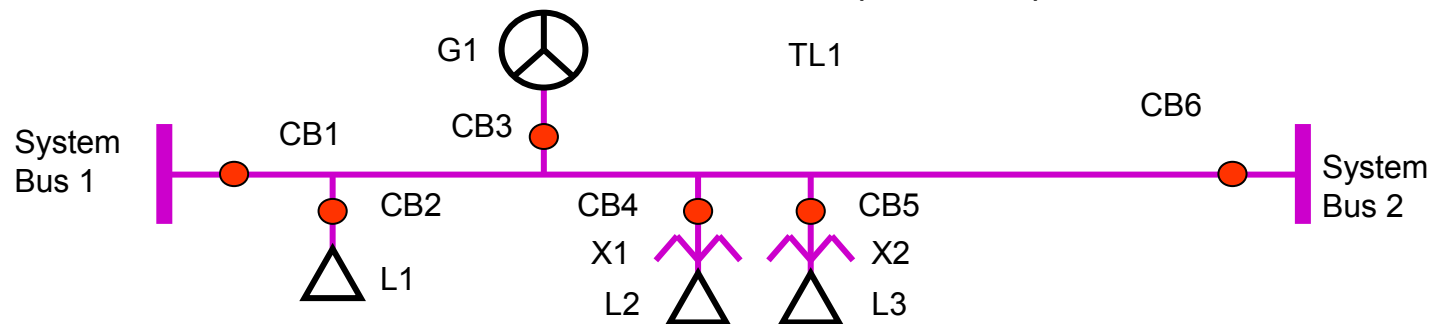


Reliability Analysis

System Modeling – Transmission Line Example

Status Quo Alternative

5) Repeat the failure effect analysis for all components. Assume there are manual switches on either side of Station X (L2 & L3).



Outage/Impact	L1	L2	L3	G1
TL1 _M	M	M	M	2 *
TL1 _S (Bus1-L2)	5.06	2	2	5.06
TL1 _S (L3-Bus2)	2	2	2	2
CB1	2	2	2	2
CB2	4	2	2	2
CB3	2	2	2	4
CB4	2	4	2	2
CB5	2	2	4	2
CB6	2	2	2	2
X1	0	8 **	0	0
X2	0	0	24 **	0

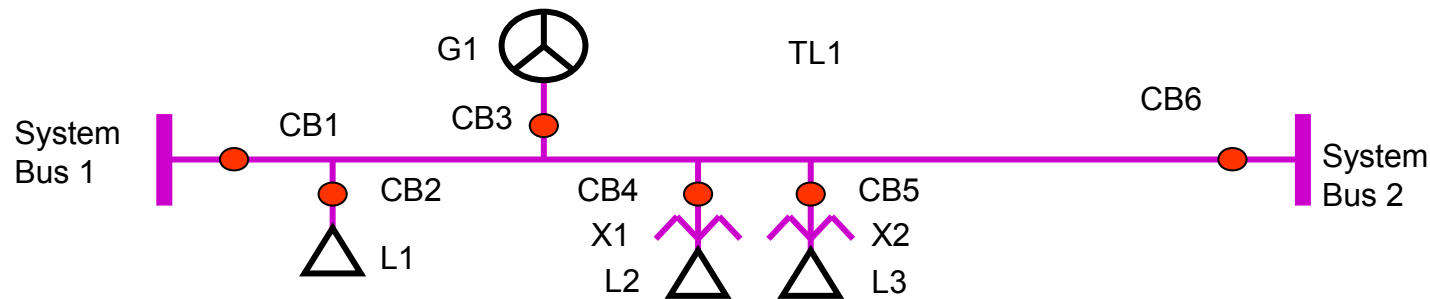
Only active failures (faults) are considered.
For Tlines momentary and sustained failures are considered
TL1 may be sectionalized manually at Station X
M - momentary failure (less than 5 minutes)
S - sustained failure
* G1 has minimum down time of 2 hours anytime it trips offline
** Neglect restoration through distribution.

Reliability Analysis

System Modeling – Transmission Line Example

Status Quo Alternative

6) Compute reliability indices (frequency and unavailability are the basis for most indices)



Outage/Impact	L1	L2	L3	G1
TL1 _M	0.800	0.800	0.800	0.800
TL1 _S (Bus1-L2)	0.409	0.409	0.409	0.409
TL1 _S (L3-Bus2)	0.191	0.191	0.191	0.191
CB1	0.020	0.020	0.020	0.020
CB2	0.055	0.055	0.055	0.055
CB3	0.038	0.038	0.038	0.038
CB4	0.065	0.065	0.065	0.065
CB5	0.048	0.048	0.048	0.048
CB6	0.030	0.030	0.030	0.030
X1	0	0.025	0	0
X2	0	0	0.020	0

Outage/Impact	L1	L2	L3	G1
TL1 _M	N/A	N/A	N/A	1.600
TL1 _S (Bus1-L2)	2.070	0.818	0.818	2.070
TL1 _S (L3-Bus2)	0.382	0.382	0.382	0.382
CB1	0.040	0.040	0.040	0.040
CB2	0.220	0.110	0.110	0.110
CB3	0.076	0.076	0.076	0.152
CB4	0.130	0.260	0.130	0.130
CB5	0.096	0.096	0.192	0.096
CB6	0.060	0.060	0.060	0.060
X1	0	0.200	0	0
X2	0	0	0.480	0

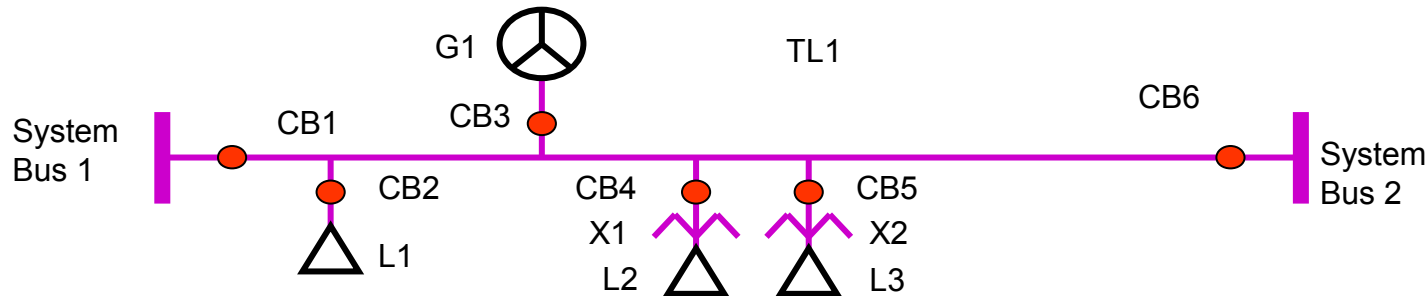
Unavailability, U , is the probability of failure. For N-1 events $U \approx \lambda r$

Reliability Analysis

System Modeling – Transmission Line Example

Status Quo Alternative

6) Compute reliability indices, continued - ECOST



ECOST Table (\$/year)				
Outage/Impact	L1	L2	L3	G1
TL1 _M	206,728	187,856	112,048	5,120
TL1 _S (Bus1-L2)	712,414	504,173	424,882	6,624
TL1 _S (L3-Bus2)	161,241	235,281	198,278	1,222
CB1	16,892	24,648	20,772	128
CB2	78,693	67,783	57,123	352
CB3	32,095	46,832	39,467	486
CB4	54,899	144,952	67,509	416
CB5	40,541	59,156	92,983	307
CB6	25,338	36,973	31,158	192
X1	0	105,631	0	0
X2	0	0	218,451	0

Reliability Analysis

System Modeling – Transmission Line Example

Status Quo Alternative

7) Rank components and delivery points by their contribution to system ECOST (sum the corresponding rows and columns of the ECOST table)

Component	ECOST (\$/year)
TL1	2,755,865
CB4	267,775
X2	218,451
CB2	203,951
CB5	192,987
CB3	118,880
X1	105,631
CB6	93,660
CB1	62,440
Total	4,019,640

ECOST Table (\$/year)				
Outage/Impact	L1	L2	L3	G1
TL1 _M	206,728	187,856	112,048	5,120
TL1 _S (Bus1-L2)	712,414	504,173	424,882	6,624
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CB6	25,338	36,973	31,158	192
X1	0	105,631	0	0
X2	0	0	218,451	0

System ECOST = 4,019,640 \$/year

The system total ECOST will be used for the economic evaluation of the project alternatives

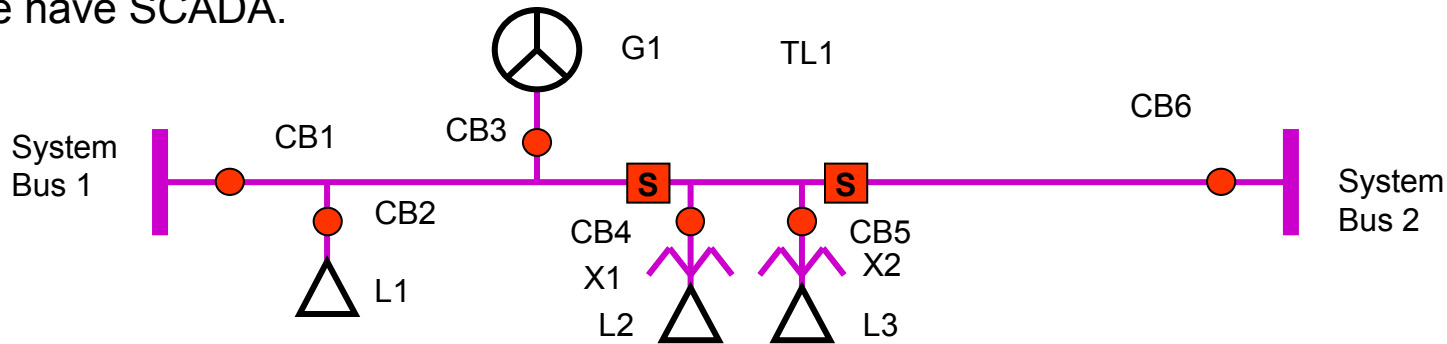
Delivery Point	ECOST (\$/year)
L2	1,413,284
L1	1,328,838
L3	1,262,670
G1	14,847
Total	4,019,640

Reliability Analysis

System Modeling – Transmission Line Example

Alternative 1 – SCADA Switches

Assume SCADA switches do not have automatics but can be operated in 15 minutes. Continue to neglect switch failures. Keep in mind that breakers 1 and 6 in this example have SCADA.



Outage/Impact	L1	L2	L3	G1
TL1 _M	M	M	M	2 *
TL1 _S (Bus1-L2)	5.06	0.25	0.25	5.06
TL1 _S (L3-Bus2)	0.25	0.25	0.25	0.25
CB1	2	0.25	0.25	2
CB2	4	0.25	0.25	2
CB3	2	0.25	0.25	4
CB4	2	4	2	2
CB5	2	2	4	2
CB6	0.25	0.25	0.25	0.25
X1	0	8 **	0	0
X2	0	0	24 **	0

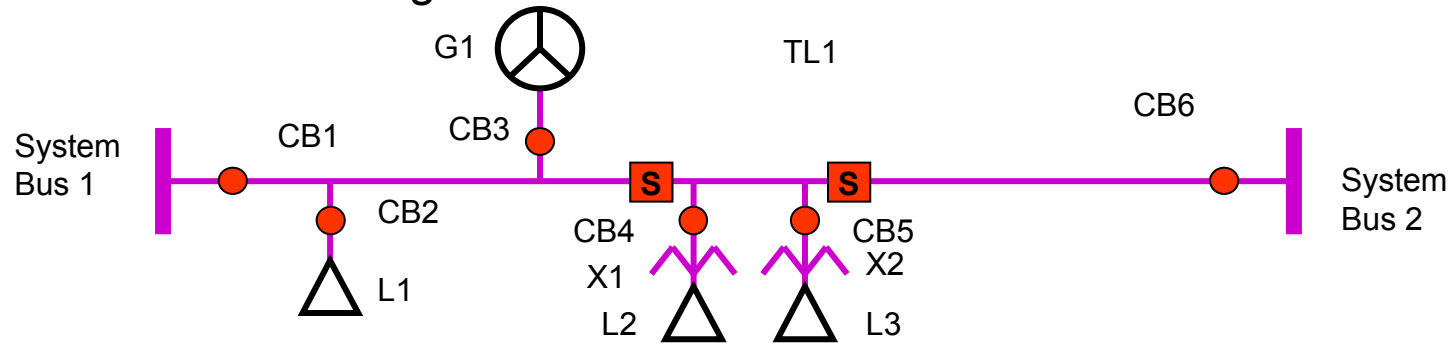
Notes:
Only active failures (faults) are considered.
For Tlines momentary and sustained failures are considered
TL1 may be sectionalized manually at Station X
M - momentary failure (less than 5 minutes)
S - sustained failure
* G1 has minimum down time of 2 hours anytime it trips offline
** Neglect restoration through distribution.

Reliability Analysis

System Modeling – Transmission Line Example

Alternative 1 – SCADA Switches, continued

Assume SCADA switches do not have automatics but can be operated in 15 minutes. Continue to neglect switch failures.



Outage/Impact	L1	L2	L3	G1
TL1 _M	0.800	0.800	0.800	0.800
TL1 _S (Bus1-L2)	0.409	0.409	0.409	0.409
TL1 _S (L3-Bus2)	0.191	0.191	0.191	0.191
CB1	0.020	0.020	0.020	0.020
CB2	0.055	0.055	0.055	0.055
CB3	0.038	0.038	0.038	0.038
CB4	0.065	0.065	0.065	0.065
CB5	0.048	0.048	0.048	0.048
CB6	0.030	0.030	0.030	0.030
X1	0	0.025	0	0
X2	0	0	0.020	0

Outage/Impact	L1	L2	L3	G1
TL1 _M	206,728	187,856	112,048	5,120
TL1 _S (Bus1-L2)	712,414	147,076	103,245	6,624
TL1 _S (L3-Bus2)	63,321	68,636	48,181	153
CB1	16,892	7,190	5,048	128
CB2	78,693	19,774	13,881	352
CB3	32,095	13,662	9,590	486
CB4	54,899	144,952	67,509	416
CB5	40,541	59,156	92,983	307
CB6	9,950	10,786	7,571	24
X1	0	105,631	0	0
X2	0	0	218,451	0

System ECOST = 2,672,367 \$/year

Reliability Analysis

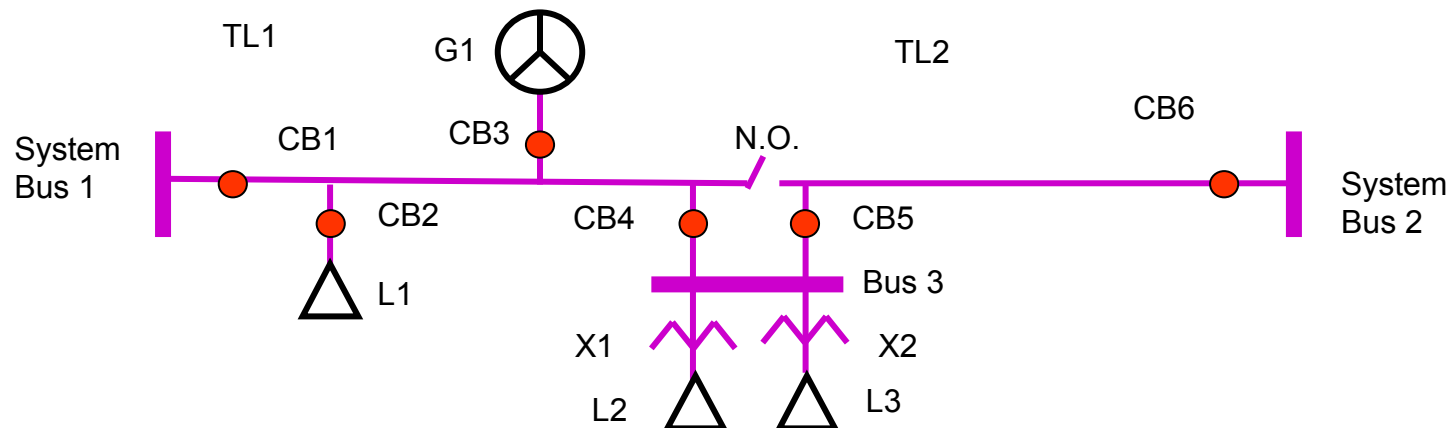
System Modeling – Transmission Line Example

Alternative 2 – Loop

Assume the loop station makes use of existing breakers and transformers.

$$\begin{aligned}\text{Failure rate for Bus 3} &= 0.01 + 0.005 * \# \text{ of elements connected to bus} \\ &= 0.01 + 0.005 * 4 = 0.03 \text{ failure/yr}\end{aligned}$$

$$\begin{aligned}\text{MTTR} &= 2 \text{ hours} + 1 \text{ hour} * \# \text{ of elements} \\ &= 2 + 1 * 4 = 6 \text{ hours}\end{aligned}$$

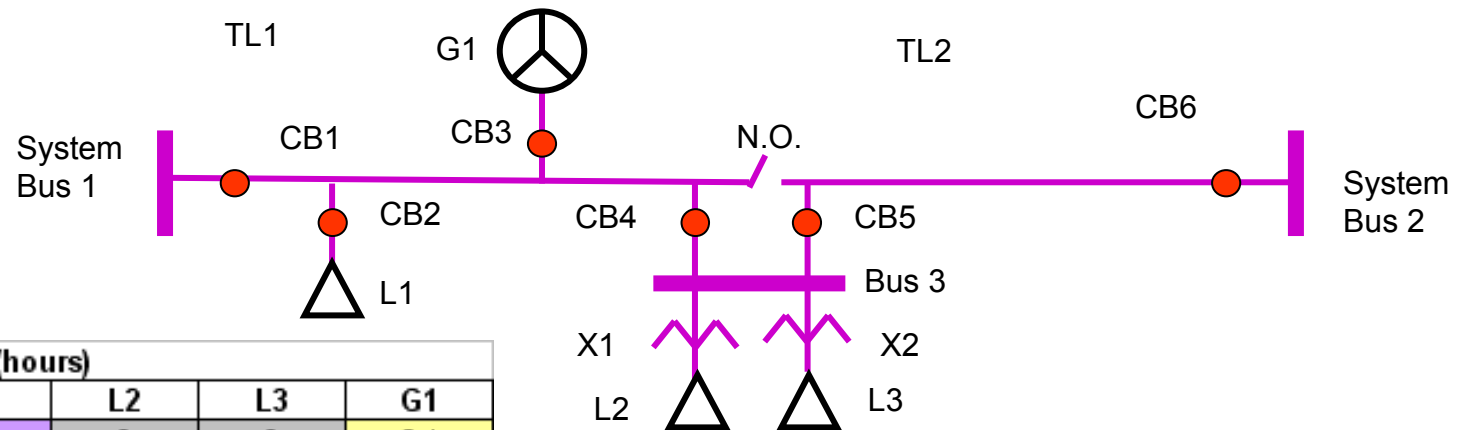


Reliability Analysis

System Modeling – Transmission Line Example

Alternative 2 – Loop

Assume the loop station makes use of existing breakers and transformers.



Outage/Impact	L1	L2	L3	G1
TL1 _M	M	0	0	2 *
TL2 _M	0	0	0	0
TL1 _S	5.06	0	0	5.06
TL2 _S	0	0	0	0
CB1	2	0	0	2
CB2	4	0	0	2
CB3	2	0	0	4
CB4	2	2	2	2
CB5	0	2	2	0
CB6	0	0	0	0
X1	0	8 **	6	0
X2	0	6	24 **	0
Bus 3	0	6	6	0

Notes:

Only active failures (faults) are considered.

For Tlines momentary and sustained failures are considered

TL1 may be sectionalized manually at Station X

M - momentary failure (less than 5 minutes)

S - sustained failure

* G1 has minimum down time of 2 hours anytime it trips offline

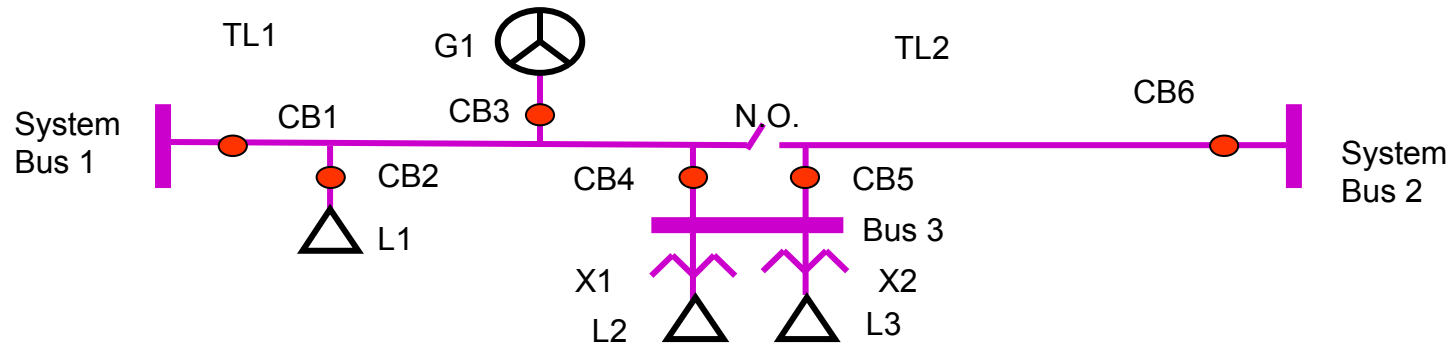
** Neglect restoration through distribution.

Reliability Analysis

System Modeling – Transmission Line Example

Alternative 2 – Loop

Assume the loop station makes use of existing breakers and transformers.



Outage/Impact	L1	L2	L3	G1
TL1 _M	0.545	0	0	0.545
TL2 _M	0	0	0	0
TL1 _S	0.409	0	0	0.409
TL2 _S	0	0	0	0
CB1	0.020	0	0	0.020
CB2	0.055	0	0	0.055
CB3	0.038	0	0	0.038
CB4	0.065	0.065	0.065	0.065
CB5	0	0.048	0.048	0
CB6	0	0	0	0
X1	0	0.025	0.025	0
X2	0	0.020	0.020	0
Bus 3	0	0.030	0.030	0

Outage/Impact	L1	L2	L3	G1
TL1 _M	140,951	0	0	3,491
TL2 _M	0	0	0	0
TL1 _S	712,414	0	0	6,624
TL2 _S	0	0	0	0
CB1	16,892	0	0	128
CB2	78,693	0	0	352
CB3	32,095	0	0	486
CB4	54,899	80,107	67,509	416
CB5	0	59,156	49,853	0
CB6	0	0	0	0
X1	0	105,631	70,892	0
X2	0	64,553	218,451	0
Bus 3	0	96,829	85,070	0

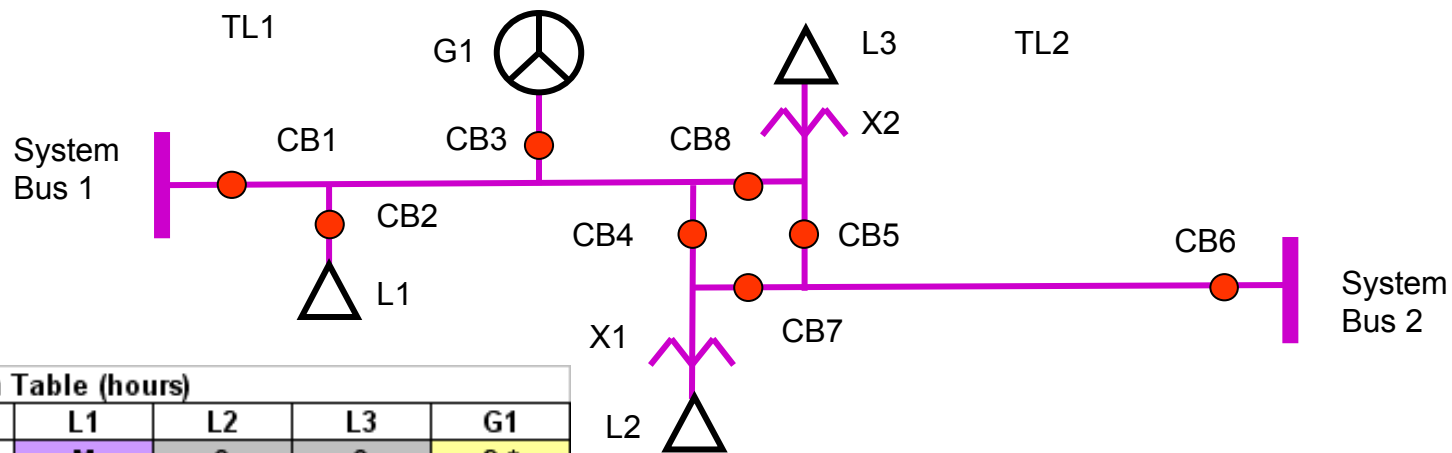
System ECOST = 2,147,522 \$/year

Reliability Analysis

System Modeling – Transmission Line Example

Alternative 3 – Ring Bus

Assume Station X is rebuilt as a ring bus and every component is new except for X1 and X2.



Outage/Impact	L1	L2	L3	G1
TL1 _M	M	0	0	2 *
TL2 _M	0	0	0	0
TL1 _S	5.06	0	0	5.06
TL2 _S	0	0	0	0
CB1	2	0	0	2
CB2	4	0	0	2
CB3	2	0	0	4
CB4	2	2	0	2
CB5	0	0	2	0
CB6	0	0	0	0
X1	0	8 **	0	0
X2	0	0	24 **	0
CB7	0	2	0	0
CB8	2	0	2	2

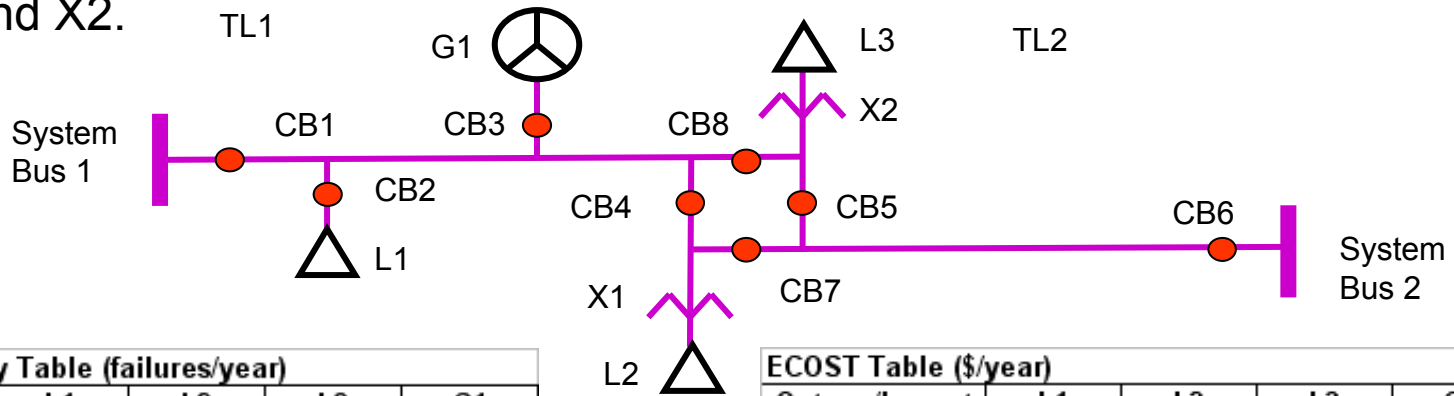
Only active failures (faults) are considered.
For Tlines momentary and sustained failures are considered
TL1 may be sectionalized manually at Station X
M - momentary failure (less than 5 minutes)
S - sustained failure
* G1 has minimum down time of 2 hours anytime it trips offline
** Neglect restoration through distribution.

Reliability Analysis

System Modeling – Transmission Line Example

Alternative 3 – Ring Bus

Assume Station X is rebuilt as a ring bus and every component is new except for X1 and X2.



Outage/Impact	L1	L2	L3	G1
TL1 _M	0.545	0	0	0.545
TL2 _M	0	0	0	0
TL1 _S	0.409	0	0	0.409
TL2 _S	0	0	0	0
CB1	0.020	0	0	0.020
CB2	0.055	0	0	0.055
CB3	0.038	0	0	0.038
CB4	0.020	0.020	0	0.020
CB5	0	0	0.020	0
CB6	0	0	0	0
X1	0	0.025	0	0
X2	0	0	0.020	0
CB7	0	0.020	0	0
CB8	0.020	0	0.020	0.020

Outage/Impact	L1	L2	L3	G1
TL1 _M	140,951	0	0	3,491
TL2 _M	0	0	0	0
TL1 _S	712,414	0	0	6,624
TL2 _S	0	0	0	0
CB1	16,892	0	0	128
CB2	78,693	0	0	352
CB3	32,095	0	0	486
CB4	16,892	24,648	0	128
CB5	0	0	20,772	0
CB6	0	0	0	0
X1	0	105,631	0	0
X2	0	0	218,451	0
CB7	0	24,648	0	0
CB8	16,892	0	218,451	128

System ECOST = 1,638,766 \$/year

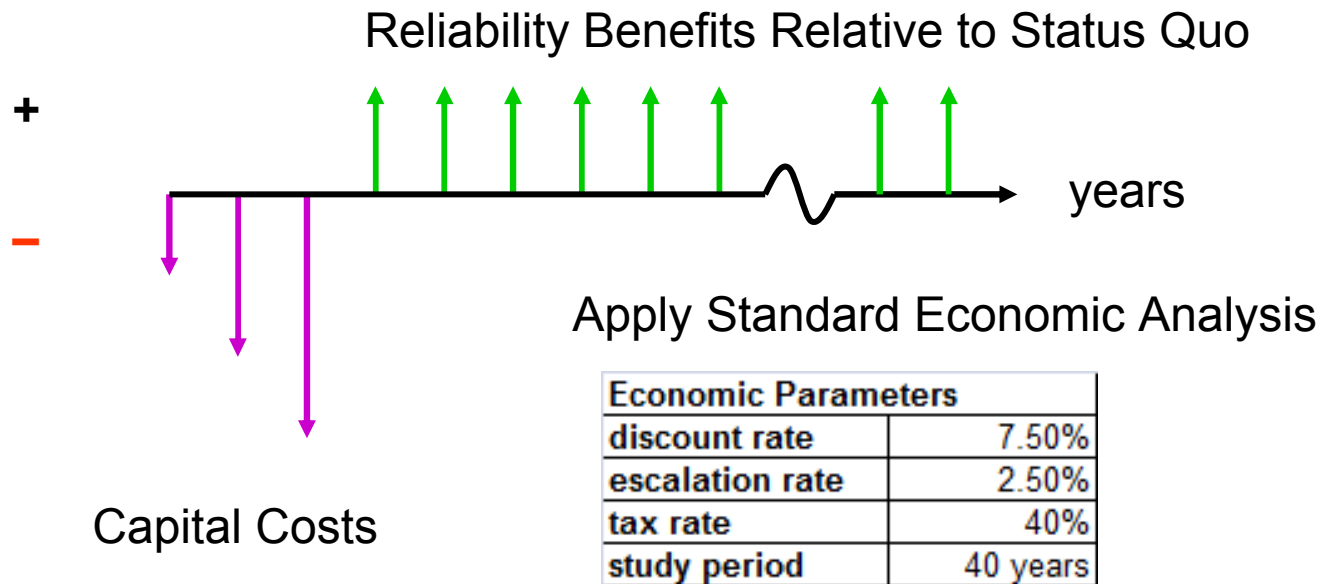
Reliability Analysis

System Modeling – Transmission Line Example

Economic Comparison

Alternative	ECOST (\$/year)	Benefit Relative to SQ (\$/year)	System Reliability Improvement	Capital Cost (\$)	NPV (\$)
Status Quo	4,019,640	N/A	0%	0	0
SCADA Switches	2,672,367	1,347,273	34%	800,000	11,854,646
Loop	1,945,490	2,074,150	52%	3,000,000	16,603,123
Ring	1,638,766	2,380,874	59%	5,000,000	17,608,587

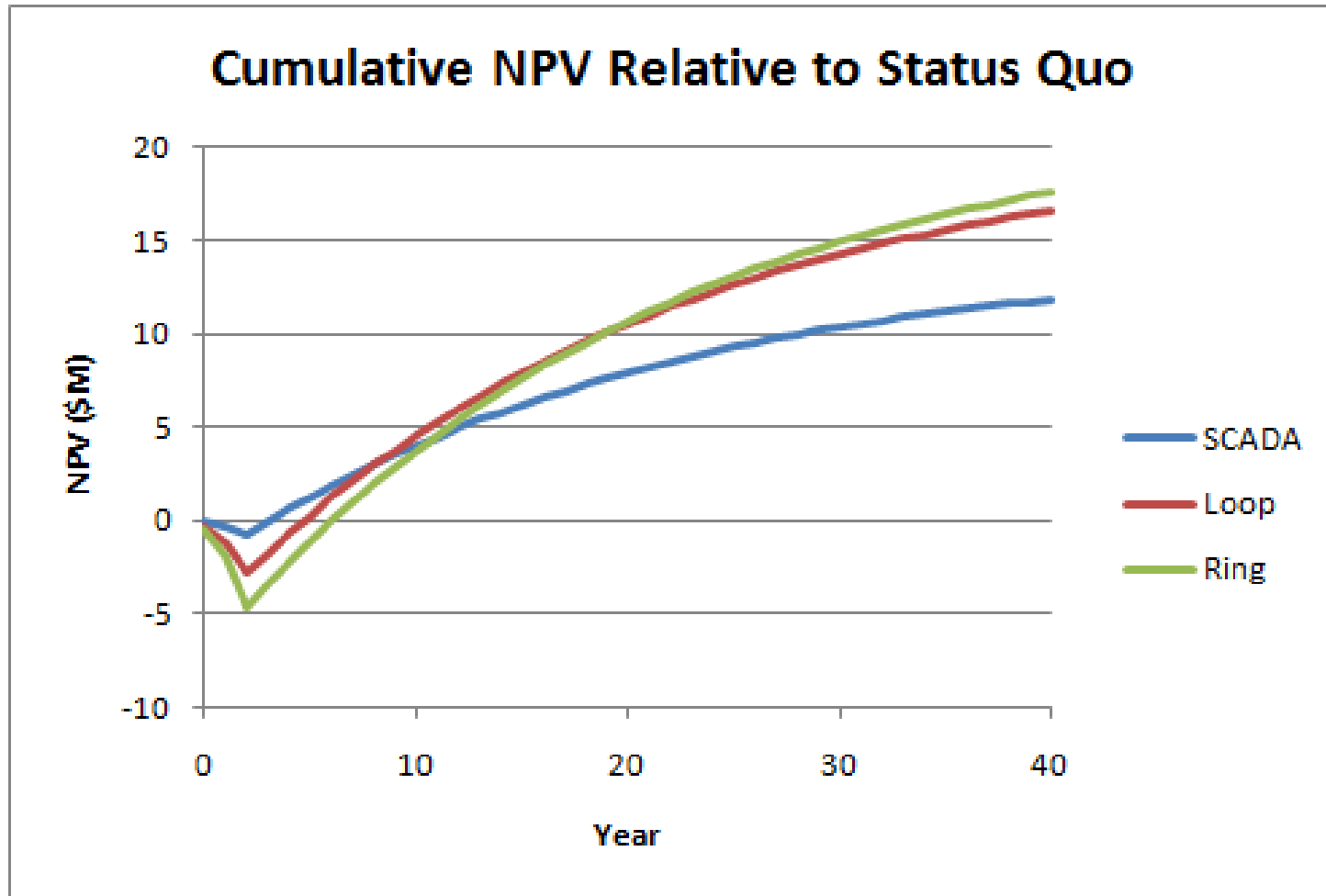
Cash Flow



Reliability Analysis

System Modeling – Transmission Line Example

Economic Comparison – Cumulative NPV Plot



Road Map For Today's Discussion

1. Reliability Analysis

- a. Cost of Customer Reliability
- b. Component Reliability Models
- c. Standard Analysis – Transmission Line Example, SCADA Switches vs. Line Sectionalizing
- d. **Advanced Analysis - How to quantify N-2, N-1-1, weather, load, maintenance and other events**
- e. Substation Reliability Analysis - Green and brown field decision matrices for Main/Aux, Double Bus Single Breaker and Breaker and a Half bus configurations

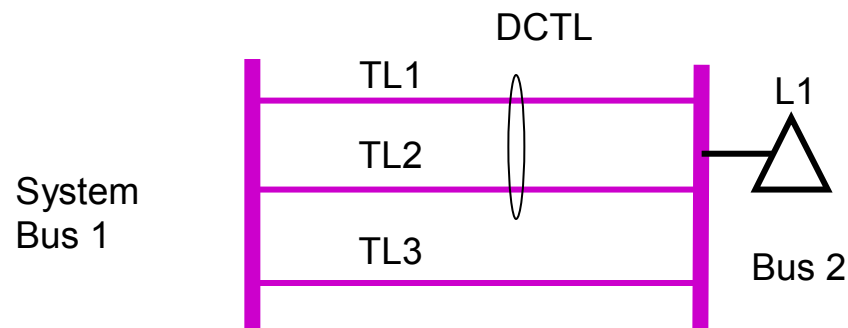
2. Artificial Intelligence

- a. Genetic Algorithm - transmission network expansion planning example
- b. Artificial Neural Networks – pattern recognition, time series forecasting and clustering examples

Reliability Analysis

Advanced Analysis – Common Mode Failures (N-2 Events) and Overlapping Outages (N-1-1 Events)

A car-pole accident that takes out 2 lines on the same structure is an example of a common mode failure (N-2). N-2 events are treated in much the same way as N-1 outages since they are both the result of a single point of failure. It is important to make the distinction between N-2 and N-1-1 events. N-1-1 events are the result of two independent outages overlapping. A reliability block diagram is a good way to visualize the difference between these events. As an Example, we'll draw the reliability block diagram for the following system considering N-1, N-1-1 and N-2 outages.



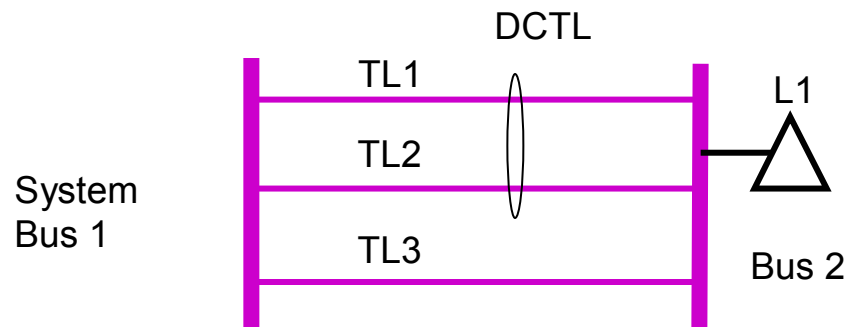
TL1 & TL2 are on the same tower

There is also an SPS that will drop load L1 any time 2 out of 3 lines are removed from service

Reliability Analysis

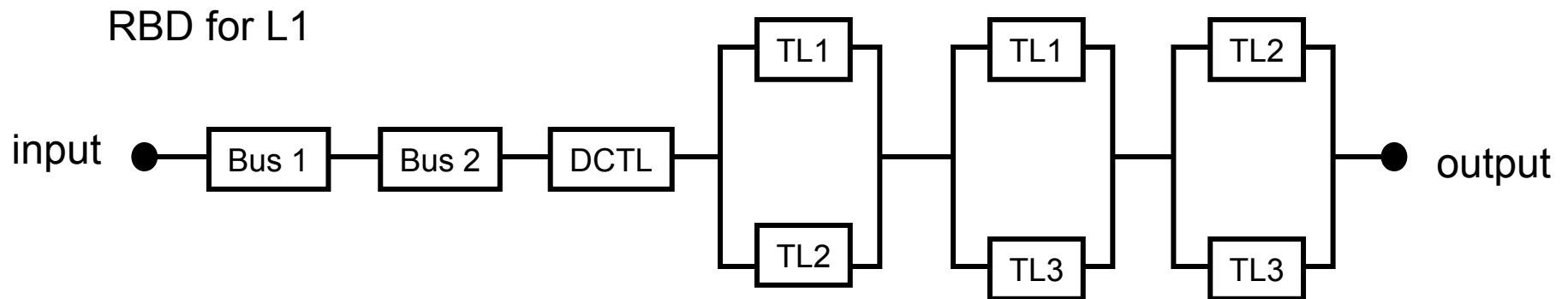
Advanced Analysis – Common Mode Failures (N-2 Events) and Overlapping Outages (N-1-1 Events)

A reliability block diagram (RBD) relates component failures to system failures. In this case the component failures are line outages and system failure is the interruption of load L1.



TL1 & TL2 are on the same tower

There is also an SPS that will drop load L1 any time 2 out of 3 lines are removed from service



Reliability Analysis

Advanced Analysis – Common Mode Failures (N-2 Events) and Overlapping Outages (N-1-1 Events)

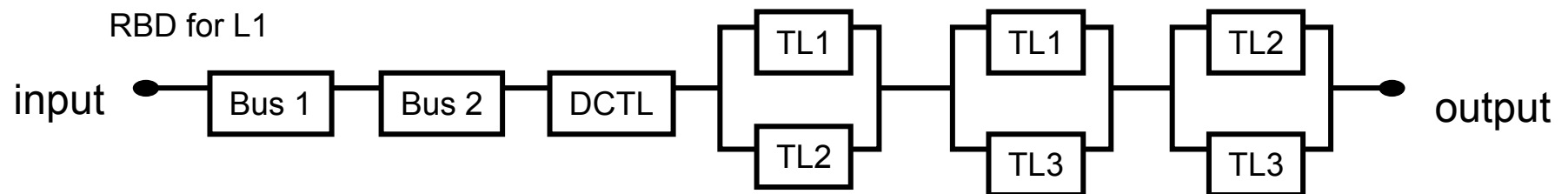
If a component fails and is removed from service it is removed from the RBD. If removing that component disconnects the input and output then the system fails. The RBD shows the logical relationship between component and system failures.

The RBD shown below can be read as follows:

If there is a failure of

Bus 1 OR Bus 2 OR DCTL OR (TL1 AND TL2) OR (TL1 AND TL3) OR (TL2 AND TL3)

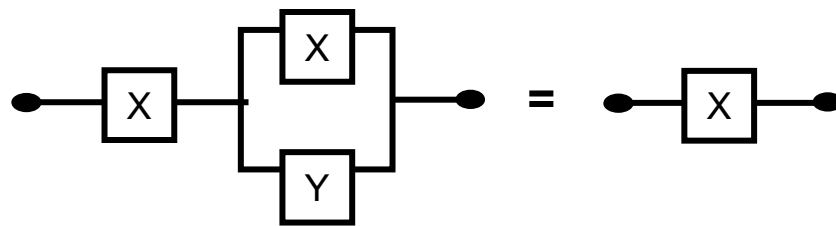
then load L1 is interrupted



Reliability Analysis

Advanced Analysis – Common Mode Failures (N-2 Events) and Overlapping Outages (N-1-1 Events)

Because the RBD can be thought of as a logic network the rules of Boolean algebra are often applied to reduce the network to its simplest form. This reduction is the basis for the minimum cut set approximation. A cut set is a set of outages that results in system failure. A minimum cut set is a cut set for which the restoration of any component restores the system. The minimum cut set can be thought of as an application of the following logical relationship.



$$X \text{ OR } (X \text{ AND } Y) = X$$

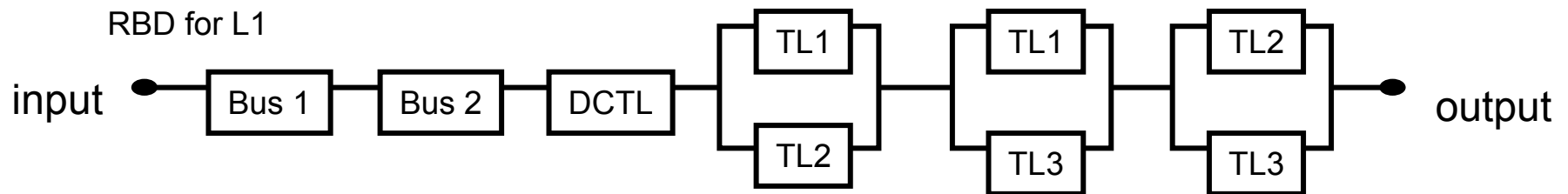
X	Y	X OR (X AND Y)
0	0	0
0	1	0
1	0	1
1	1	1

The minimum cut set approximation is valid for systems with highly reliable components such as power systems

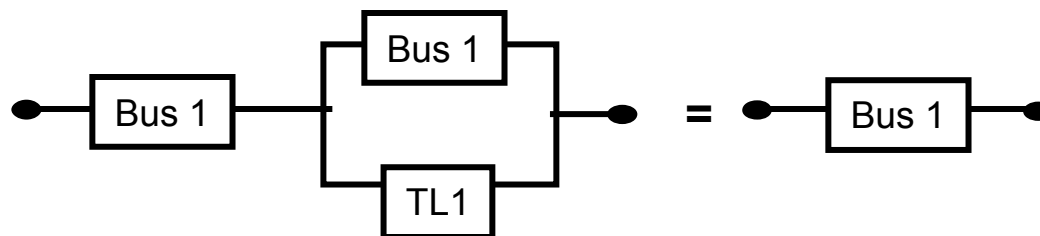
Reliability Analysis

Advanced Analysis – Common Mode Failures (N-2 Events) and Overlapping Outages (N-1-1 Events)

The RBD for the example system was created using the minimal cut set approximation.



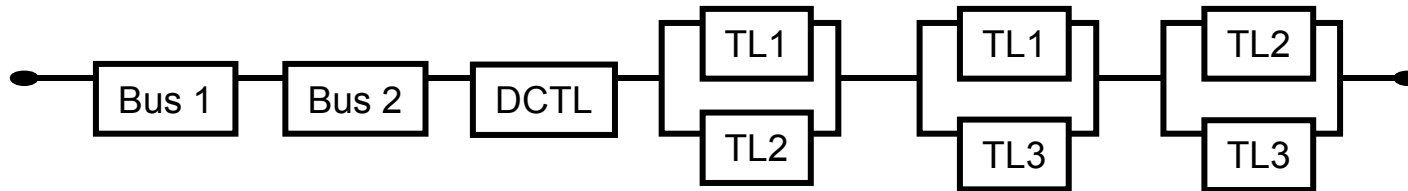
(Bus 1 AND TL1) are a cut set, but since the restoration of TL1 doesn't restore the system Bus 1 and TL1 aren't a minimal cut set and aren't shown in the final RBD.



Reliability Analysis

Advanced Analysis – Common Mode Failures (N-2 Events) and Overlapping Outages (N-1-1 Events)

Compute the equivalent failure rate, unavailability and average restoration time for L1.
Recall that each component has an unavailability of $U \approx \lambda r$.



Step 1) reduce each parallel block to an equivalent series block using

$$U_{eq} = U_1 * U_2 \quad \text{and} \quad \lambda_{eq} = \lambda_1 * U_2 + \lambda_2 * U_1$$

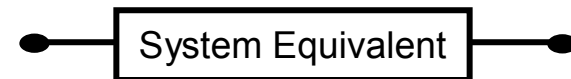


Step 2) reduce all series block to one equivalent block representing the system using

$$U_{sys} = \sum U_{eq}$$

and

$$\lambda_{sys} = \sum \lambda_{eq}$$



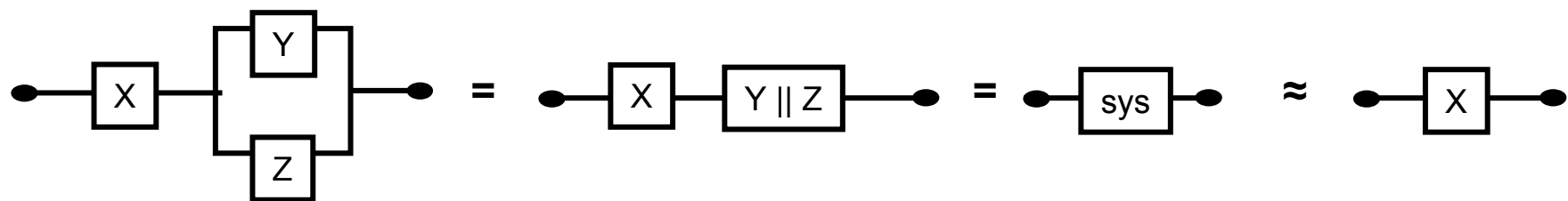
Step 3) compute the system average restoration time using $r_{sys} = U_{sys} / \lambda_{sys}$

Component unavailability should be converted to the unit-less quantify of year/year before performing calculations. Once the calculations are completed unavailability can always be converted back to hours/year or minutes/year. Reporting the wrong units is the most common error made in reliability analysis.

Reliability Analysis

Advanced Analysis – Common Mode Failures (N-2 Events) and Overlapping Outages (N-1-1 Events)

Because of the high reliability of power system components N-1 analysis is usually sufficient. Consideration of N-1-1 events is usually reserved for studies that include the effects of severe weather events that result in failure bunching. During severe weather events there is a high probability of having overlapping outages.



$$\lambda_X = \lambda_Y = \lambda_Z = 1 \text{ failures/yr}$$

$$r_X = r_Y = r_Z = 4 \text{ hr}$$

$$U_X = U_Y = U_Z = 0.0004566 \text{ yr/yr}$$

$$\lambda_{Y||Z} = 0.0009 \text{ failures/yr}$$

$$r_{Y||Z} = 2 \text{ hr}$$

$$U_{Y||Z} = 0.0000002 \text{ yr/yr}$$

$$\lambda_{\text{sys}} = 1.0009 \text{ failures/yr}$$

$$r_{\text{sys}} = 3.99 \text{ hr}$$

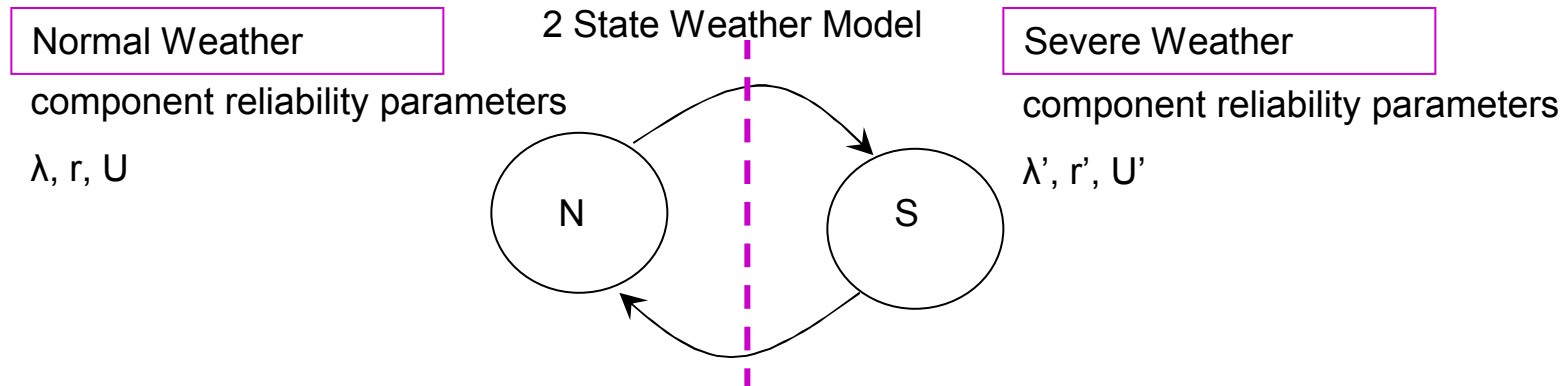
$$U_{\text{sys}} = 0.0004568 \text{ yr/yr}$$

For RBDs with 3 or more blocks in parallel conditional probabilities can be employed to calculate the series equivalent. If all 3 components have identical reliability parameters the binomial distribution may be used.

Reliability Analysis

Advanced Analysis – Severe Weather Events

During stormy periods line failure rates are often 100 times higher than during normal weather. This means that N-1-1 events become much more likely during these periods. A large number of outages occurring simultaneously also puts a strain on resources and increases restoration times. To capture the effect of the weather on system reliability two sets of component reliability parameters should be derived, one for normal weather and one for stormy weather periods.



For a two state weather model the overall ECOST is computed as

$$ECOST = P(N) * ECOST_N + P(S) * ECOST_S$$

where

$ECOST_N$ is ECOST calculated using normal weather component reliability parameters

$P(N)$ is the probability of normal weather

$ECOST_S$ is ECOST calculated using severe weather component reliability parameters and

$P(S)$ is the probability of severe weather

Reliability Analysis

Advanced Analysis – Severe Weather Events

Compute the outage rate, unavailability and average outage duration for the following system using the 2 state weather model. Consider only sustained transmission line outages. There are typically 2 severe weather events per year. The average event lasts 43.8 hours. Start by computing the probability of severe weather $P(S)$ and the probability of normal weather, $P(N)$.

$$P(S) = 2 * 43.8 / 8760 = 0.01$$

$$P(N) = 1 - P(S) = 1 - 0.01 = 0.99$$



Normal weather component
reliability parameters

$$\lambda_{TL1} = 0.7 \text{ failures/year}$$

$$r_{TL1} = 5 \text{ hours}$$

Severe weather component
reliability parameter

$$\lambda'_{TL1} = 120 \text{ failures/year}$$

$$r'_{TL1} = 19 \text{ hours}$$

$$\begin{aligned} U_{L1} &= U_{TL1} * P(N) + U'_{TL1} * P(S) = \lambda_{TL1} * r_{TL1} * P(N) + \lambda'_{TL1} * r'_{TL1} * P(S) \\ &= [0.7 * 5/8760 * 0.99 + 120 * 19/8760 * 0.01] * 8760 \\ &= 26.3 \text{ hours/year} \end{aligned}$$

$$\begin{aligned} \lambda_{L1} &= \lambda_{TL1} * P(N) + \lambda'_{TL1} * P(S) = 0.7 * 0.99 + 120 * 0.01 \\ &= 1.893 \text{ outages/year} \end{aligned}$$

$$\begin{aligned} r_{L1} &= U_{L1} / \lambda_{L1} = 26.3 / 1.893 \\ &= 13.9 \text{ hours/outage} \end{aligned}$$

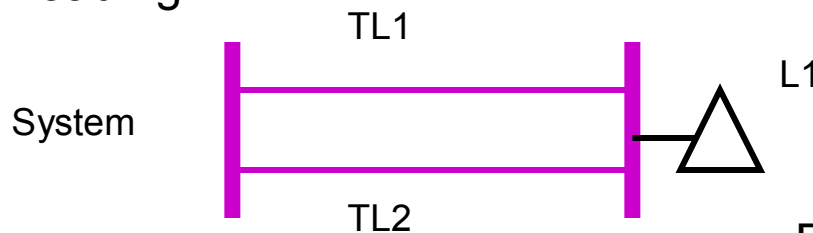
Make sure to use the
appropriate units.

(1 year = 8760 hours)

Reliability Analysis

Advanced Analysis – Load Duration Curves

TL1 is rated for 100 MVA and TL2 is rated for 50 MVA. TL2 is protected with a thermal relay set for 50 MVA. Compute the frequency and duration of outages to L1, λ_{L1} and r_{L1} . Consider sustained N-1 line outages and loading.



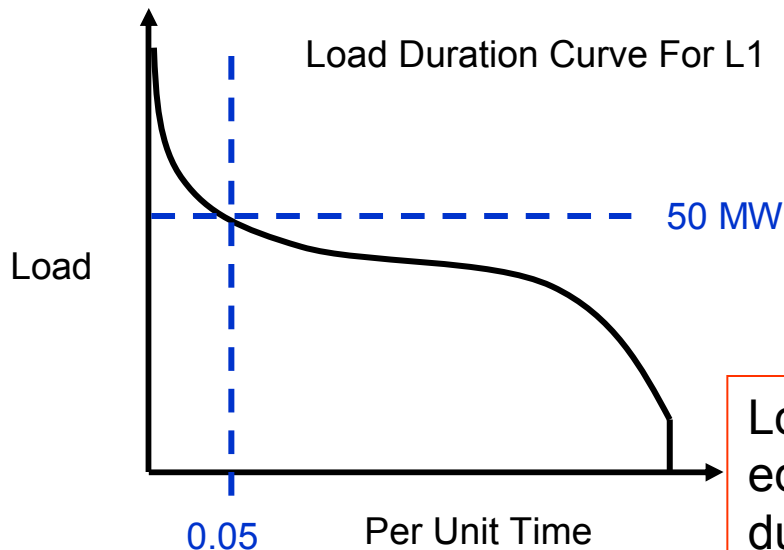
$$\lambda_{TL1} = 2 \text{ failure/year}$$

$$r_{TL1} = 5 \text{ hr}$$

Based on the load duration curve there is a 5% probability of the load being high enough to trip the thermal relay when line TL1 is out of service.

$$\lambda_{L1} = P(L1 > 50 \text{ MW}) * \lambda_{TL1} + U_{TL1} * ?$$

$$U_{L1} = ?, r_{L1} = ?$$

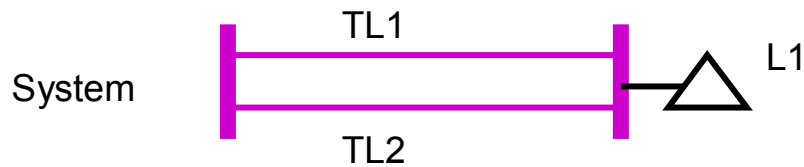


Load and line failures are independent so we use the equations for overlapping events, but the load duration curve doesn't supply all of the information we need to complete the calculations.

Reliability Analysis

Advanced Analysis – Utilizing Historical Load Data

To solve this problem look at historical loading to determine frequency and duration of peaks above 50 MW.



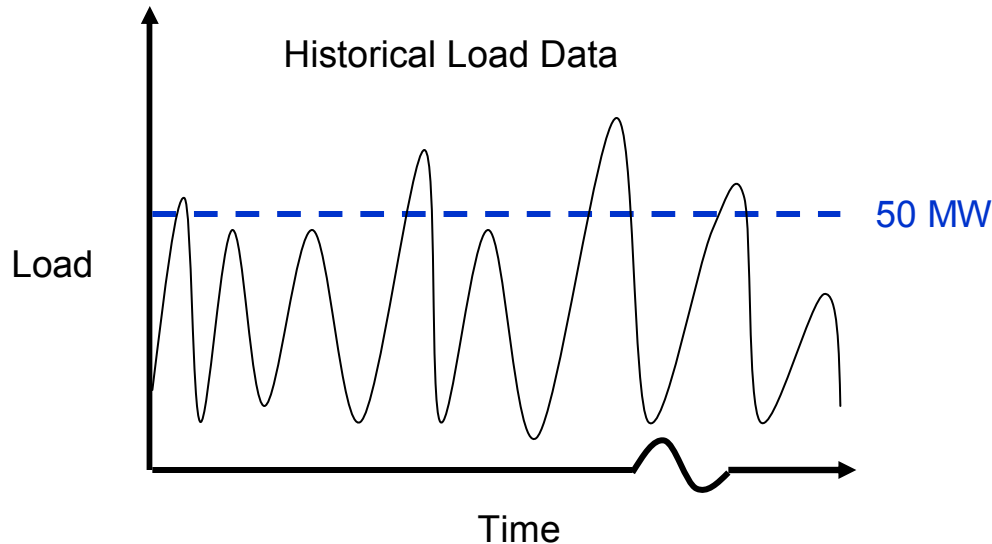
$$\lambda_{TL1} = 2 \text{ failure/year}$$

$$r_{TL1} = 5 \text{ hr}$$

Based on the load profile, the average peak above 50 MW lasts 4 hours and has a frequency of 109.5 times per year.

$$\lambda_{L1>50MW} = 109.5 \text{ peaks/year}$$

$$r_{L1>50MW} = 4 \text{ hours/peak}$$



$$\begin{aligned} \lambda_{L1} &= \lambda_{TL1} * P(L1>50MW) + \lambda_{L1>50MW} * U_{TL1} \\ &= \lambda_{TL1} * \lambda_{L1>50MW} * r_{L1>50MW} + \lambda_{L1>50MW} * \lambda_{TL1} * r_{TL1} \\ &= 2 * 109.5 * 4 / 8760 + 109.5 * 2 * 5 / 8760 \\ &= 0.225 \text{ failures/year} \end{aligned}$$

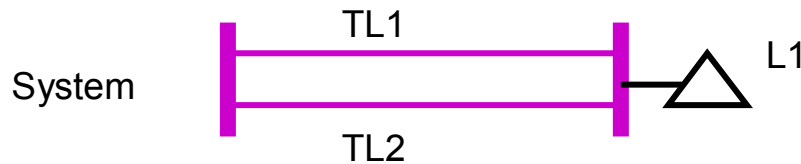
Make sure to use the appropriate units.

(1 year = 8760 hours)

Reliability Analysis

Advanced Analysis – Utilizing Historical Load Data

Computing unavailability and average restoration time.



$$\lambda_{TL1} = 2 \text{ failure/year}$$

$$r_{TL1} = 5 \text{ hr}$$

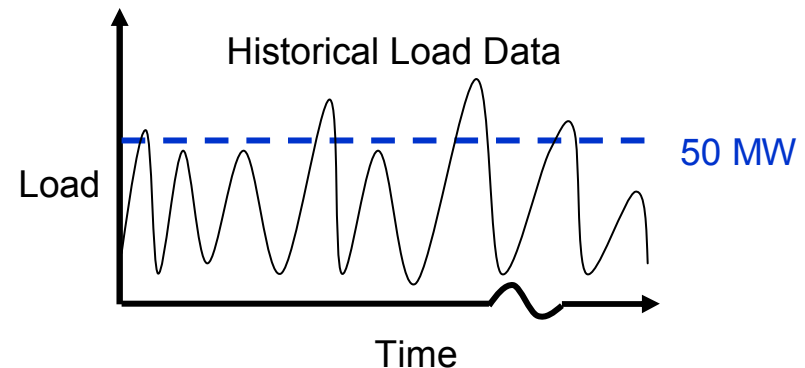
$$\lambda_{L1>50MW} = 109.5 \text{ peaks/year}$$

$$r_{L1>50MW} = 4 \text{ hours/peak}$$

$$\lambda_{L1} = 0.225 \text{ outages/year}$$

$$\begin{aligned} U_{L1} &= P(L1>50MW) * U_{TL1} \\ &= \lambda_{L1>50MW} * r_{L1>50MW} * \lambda_{TL1} * r_{TL1} \\ &= [109.5 * (4 / 8760) * 2 * (5 / 8760)] * 8760 \\ &= 0.5 \text{ hours/year} \end{aligned}$$

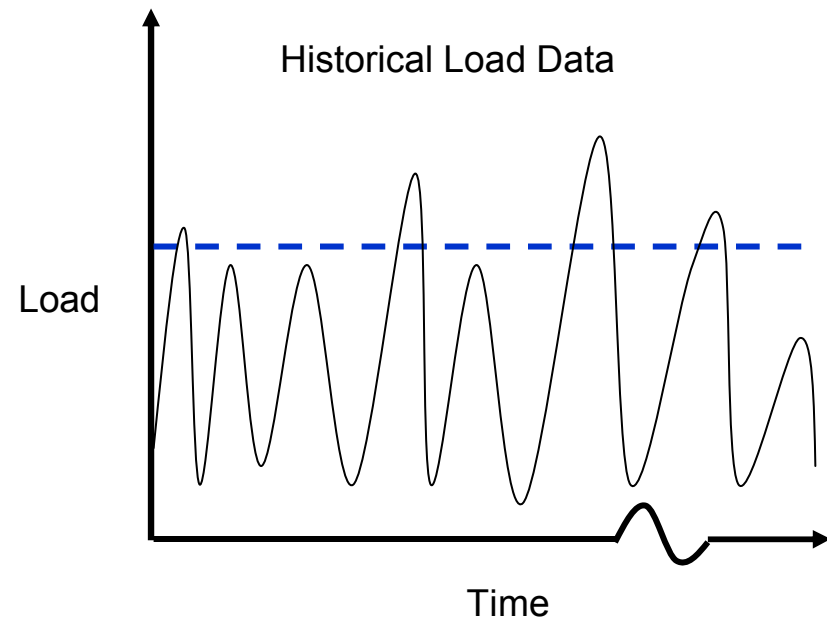
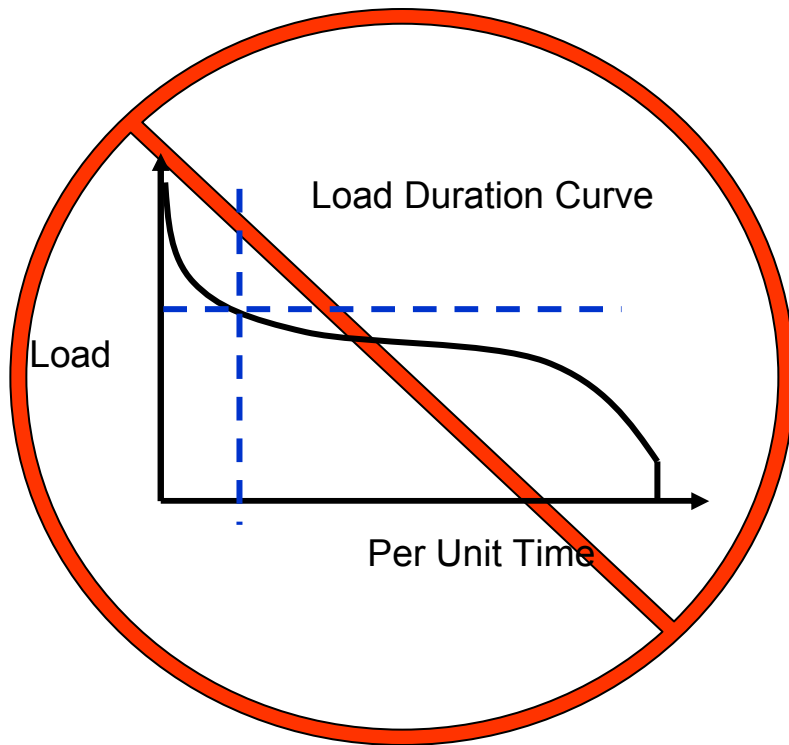
$$\begin{aligned} r_{L1} &= U_{L1} / \lambda_{L1} = 0.5 / 0.225 \\ &= 2.22 \text{ hours/outage} \end{aligned}$$



Reliability Analysis

Advanced Analysis – Loading

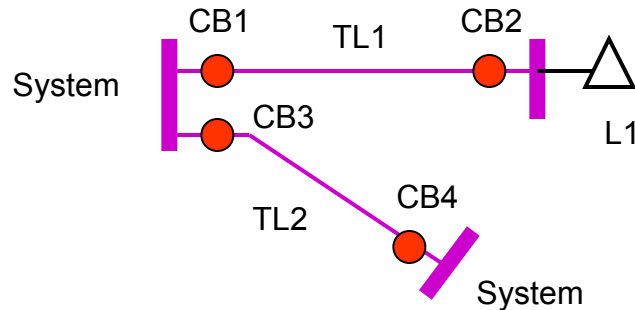
To include the effect of loading in your reliability analysis use historical data to determine frequency and duration of peak events



Reliability Analysis

Advanced Analysis – Operational Failures

Compute the outage rate, unavailability and average outage duration for load L1 considering sustained N-1 line faults and operational failures.



$$\lambda_{TL1} = 0.9 \text{ failures/year}$$

$$r_{TL1} = 5 \text{ hours}$$

$$\lambda_{TL2} = 0.5 \text{ failures/year}$$

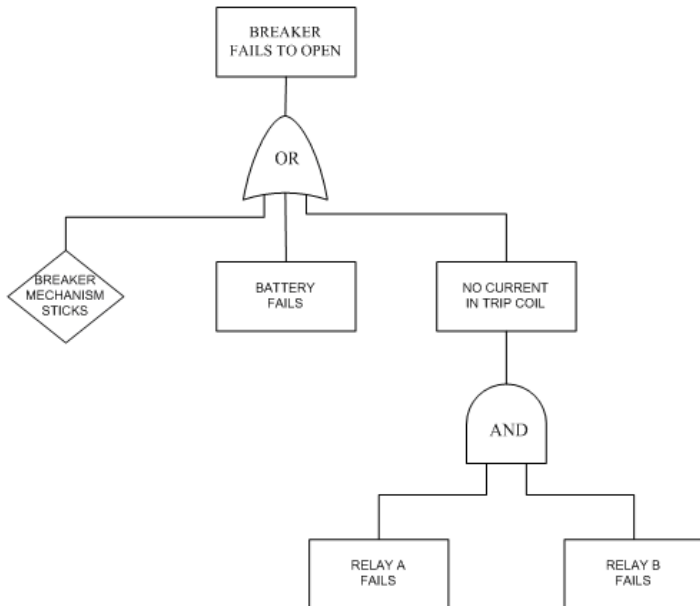
$$r_{TL2} = 4 \text{ hours}$$

Probability of operational failure

$$P(O.F.) = 0.02$$

$$MTTS = 2 \text{ hours}$$

Breaker Fault Tree
- Operational Failure



$$\lambda_{L1} = \lambda_{TL1} + \lambda_{TL2} * P(O.F.)_{CB3} = 0.9 + 0.5 * 0.02$$

$$= 0.91 \text{ failures/year}$$

$$U_{L1} = \lambda_{TL1} * r_{TL1} + \lambda_{TL2} * MTTS * P(O.F.)_{CB3} = 0.9 * 5 + 0.5 * 2 * 0.02$$

$$= 4.52 \text{ hours/year}$$

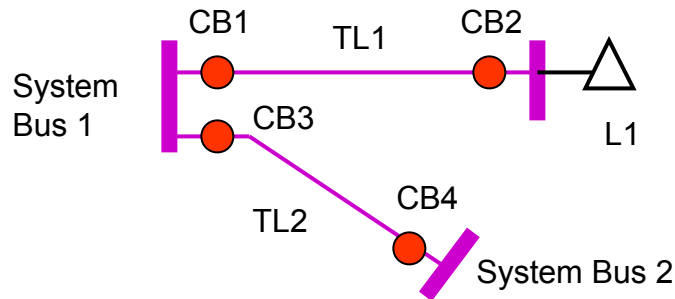
$$r_{L1} = U_{L1} / \lambda_{L1} = 4.52 / 0.91$$

$$= 4.97 \text{ hours/outage}$$

Reliability Analysis

Advanced Analysis – Security Failures

Compute the outage rate, unavailability and average outage duration for load L1 in the system shown below. Consider only security failures that result in breakers opening unnecessarily (false trips). All breakers connected to System Bus 1 have SCADA

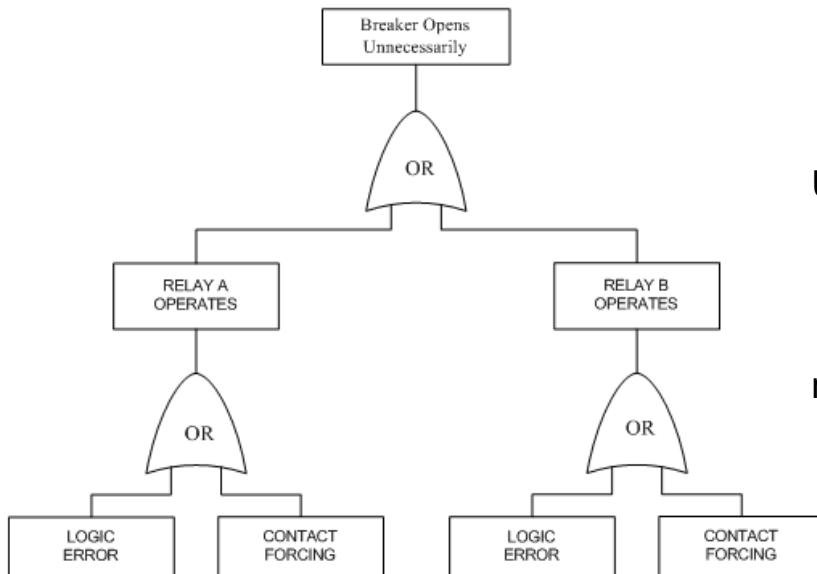


$$\lambda_{FT} = 0.01 \text{ false operations/year}$$

$$MTTS = 2 \text{ hours for manual operation}$$

$$MTTS_S = 0.25 \text{ hours for SCADA operation}$$

Security Failure Fault Tree



$$\lambda_{L1} = \lambda_{FT \text{ CB1}} + \lambda_{FT \text{ CB2}} = 0.01 + 0.01$$

$$= 0.02 \text{ failures/year}$$

$$U_{L1} = \lambda_{FT \text{ CB1}} * MTTS_S + \lambda_{FT \text{ CB2}} * MTTS = 0.01 * 0.25 + 0.01 * 2$$

$$= 0.0225 \text{ hours/year}$$

$$r_{L1} = U_{L1} / \lambda_{L1} = 0.0225 / 2$$

$$= 1.125 \text{ hours/outage}$$

Reliability Analysis

Advanced Analysis – Maintenance Events

Like severe weather periods, during maintenance events customers have significantly higher risk of interruption than during normal periods. However, unlike storms we have control over when we do maintenance. It's usually safe to assume that maintenance clearances won't be taken during outages, peak loading, severe weather events, or other times that put customers at unnecessary risk.

Maintenance often requires switching the system into a less reliable configuration especially in systems that use sub-standard, low reliability, bus configurations.

During maintenance human error also becomes a major concern. In systems with sub-standard bus designs approximately one third of substation outages are caused by work procedure errors.

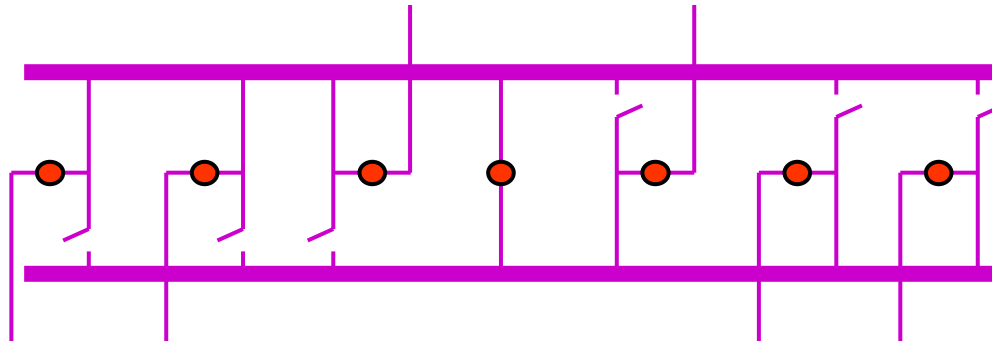
Reliability Analysis

Advanced Analysis – Maintenance Events

Double Bus Single Breaker – Normal Operating Configuration

Any bus or line breaker fault or failure to operate takes out about half the substation

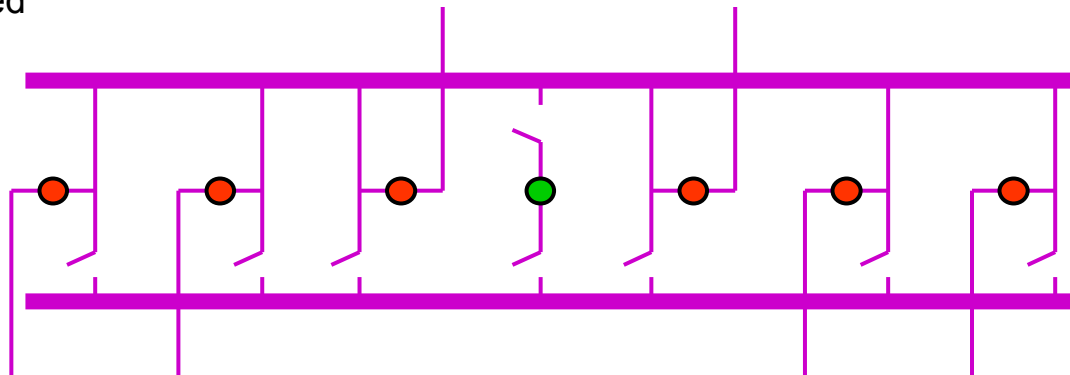
A tie-breaker fault or failure to operate takes out the entire substation



Double Bus Single Breaker – Maintenance Configuration

A bus fault or any line breaker fault or failure to operate takes out the entire substation.

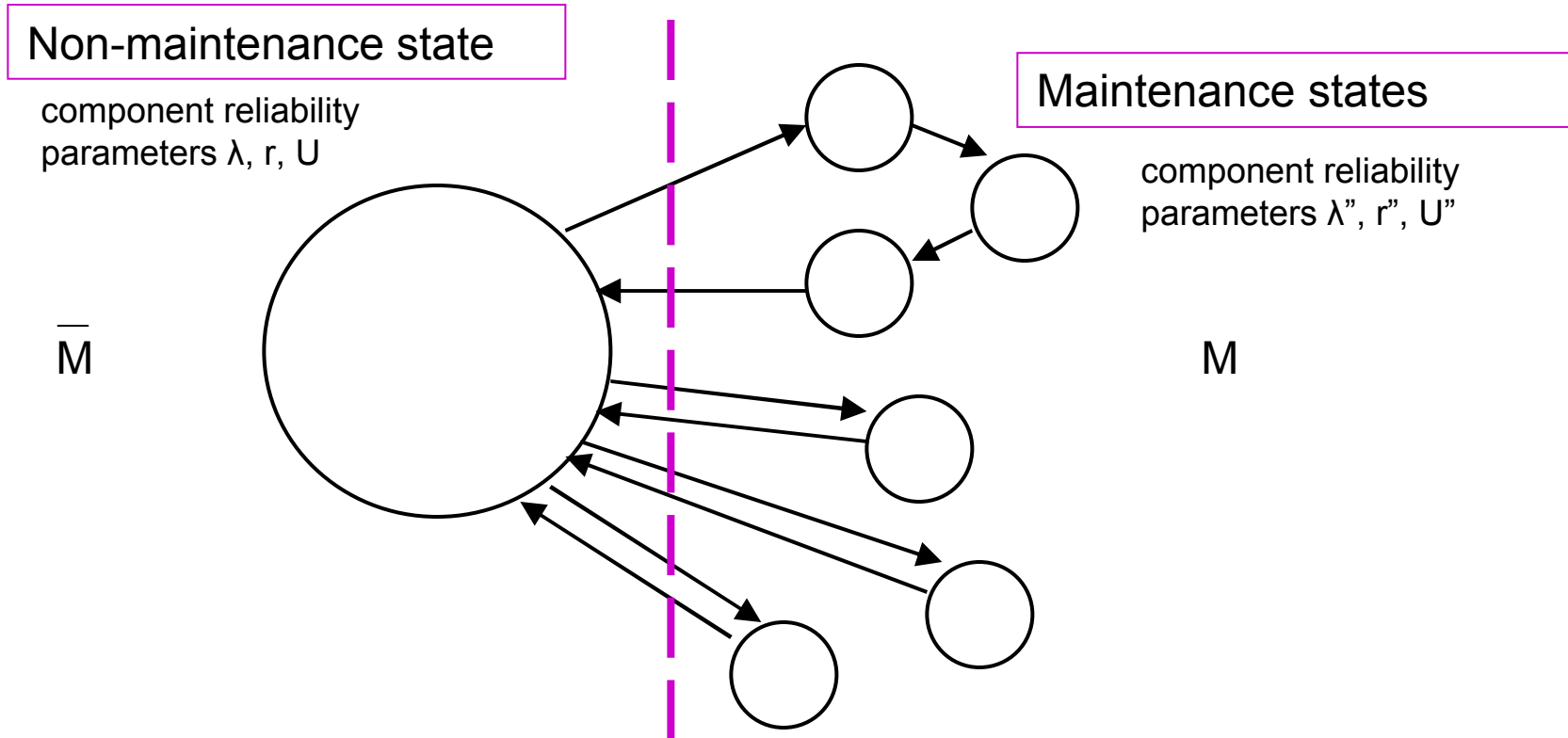
Failure rates also increase by orders of magnitude due to the large number of switching steps involved



Reliability Analysis

Advanced Analysis – Maintenance Events

Maintenance events can be modeled in much the same way as normal and severe weather periods.

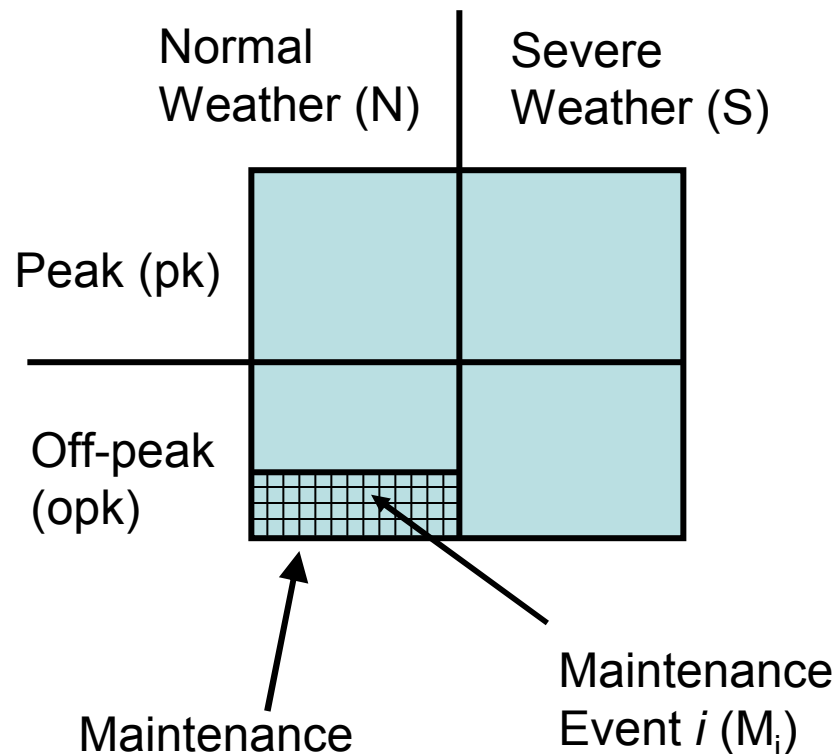


$$ECOST = P(\bar{M}) * ECOST_{\bar{M}} + \sum P(M_i) * ECOST_{M_i}, \text{ for all maintenance configurations } i$$

Reliability Analysis

Advanced Analysis – General Model

General model for maintenance, weather and loading effects



$$\begin{aligned}
 ECOST = & P(N \cap pk) * ECOST_{N \cap pk} \\
 & + P(N \cap opk \cap \bar{M}) * ECOST_{N \cap opk \cap \bar{M}} \\
 & + P(S \cap pk) * ECOST_{S \cap pk} \\
 & + P(S \cap opk) * ECOST_{S \cap opk} \\
 & + \sum P(N \cap opk \cap M_i) * ECOST_{N \cap opk \cap M_i}, \\
 & \text{for all maintenance configurations } i
 \end{aligned}$$

Note: Weather, load and component failures are all random events, but maintenance is not.

Reliability Analysis

Advanced Analysis – Alternative Methods

See [Markov Modeling.doc](#)

See [Monte Carlo Simulation.doc](#)

Reliability Analysis

Advanced Analysis – Economics, Reliability Costs

In addition to the cost of customer interruptions, the following costs are also commonly included in the economic evaluation of discretionary projects: maintenance, repair, replacement, labor and other operating costs.

For bulk electric system studies the largest costs are often managing congestion and buying energy on the spot market following the unexpected loss of critical infrastructure. The forced outage of a large nuclear unit could easily cost millions of dollars an hour. To capture these costs a production cost simulation should be run.

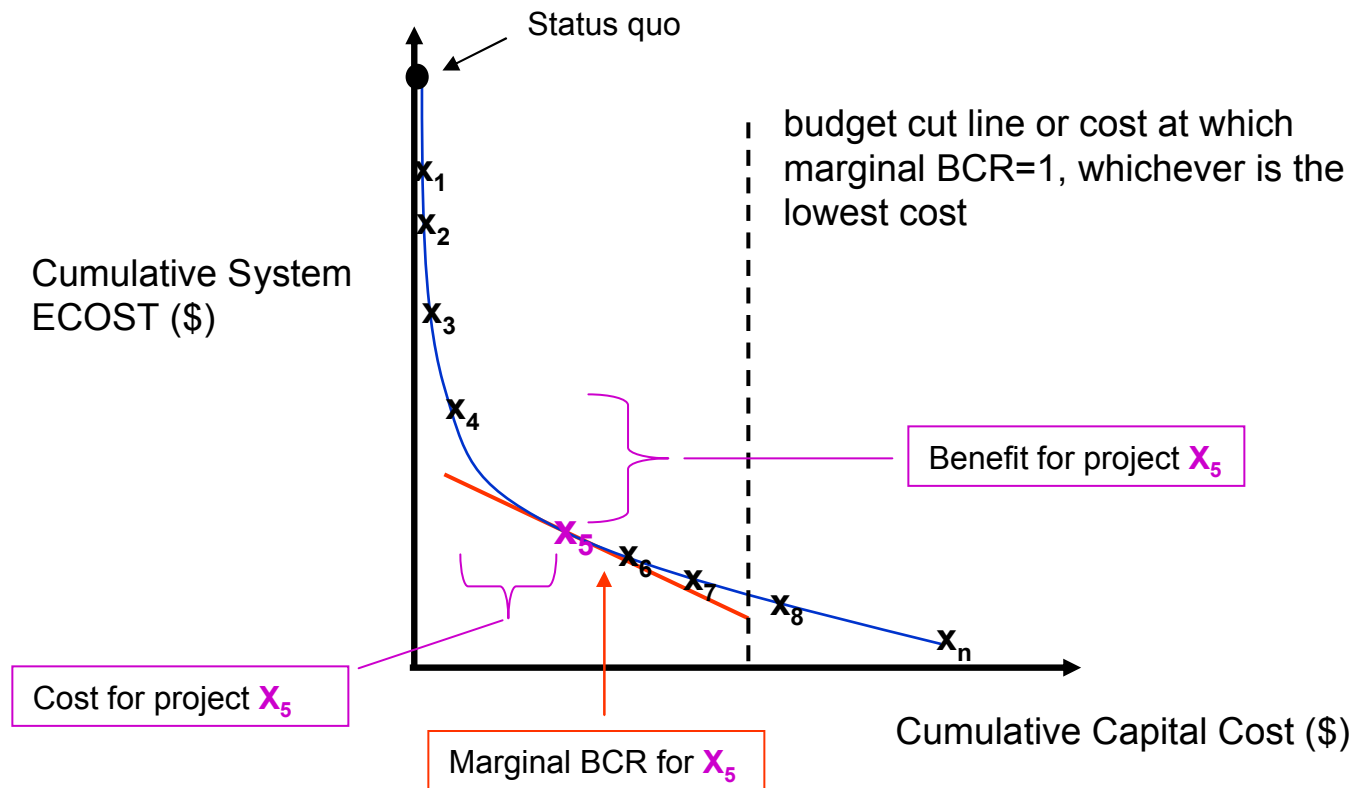
Production cost simulations typically employ sequential Monte Carlo style simulations. They model loads and both forced and planned transmission and generator outages in hourly increments over the course of a year. Many programs still use traditional security constrained economic dispatch or optimal power flow within security constrained unit commitment to compute production costs based on generator cost curves, but market simulation is becoming more common.

(Side note: when the shift from economic dispatch to markets was made the argument was markets would drive down costs and improve reliability. However, the opposite effect has been observed in many markets.)

Reliability Analysis

Advanced Analysis – Economics, Program Management

The most common method for prioritizing discretionary spending is marginal benefit to cost ratio analysis.



BCR ranking methods encounter difficulties when projects have dependence relationships. Network expansion planning optimization programs can model these complex relationships and succeed where BCR ranking fails.

Reliability Analysis

Common Reliability Indices

Definitions

N_i = number of customers interrupted by outage i
 NT = total number of customers in the system
 CN = total number of customers in the system experiencing 1 or more sustained outages
 $CN(k>n)$ = total number of customers in the system experiencing more than n sustained outages
 $CNT(k>n)$ = total number of customers in the system experiencing more than n outages
 L_i = connected kVA of customers interrupted by outage i
 $Lave\ i$ = average load of customers interrupted by outage i
 LT = total connected kVA of the system
 r_i = duration of interruption to customers interrupted by outage i
 T = period, usually one year, (8760 hours or 525600 minutes)
 ID_i = interrupting device operations
 IDE = interruption device events

Sustained Customer Interruption Indices

System Average Interruption Frequency Index
 System Average Interruption Duration Index
 Customer Average Interruption Duration Index
 Customer Total Average Interruption Duration Index
 Customer Average Interruption Frequency Index
 Average Service Availability Index
 Customers Experiencing Multiple Interruptions

Momentary Customer Interruption Indices

Momentary Average Interruption Frequency Index
 Momentary Average Interruption Frequency Event Index
 Customers Experiencing Multiple Sustained and Momentary Interruptions

Load and Energy Based Indices

Average System Interruption Frequency Index
 Average System Interruption Duration Index
 Expected Energy Not Supplied
 Average Energy Not Supplied
 Average Customer Curtailment Index

Economic Indices

Sector Customer Damage Function
 Composite Customer Damage Function
 Expected Customer Outage Cost
 Interrupted Energy Assessment Rate

Miscellaneous Terms

Customer Minutes
 Customers Experiencing Sustained Outages
 Customer Experiencing Momentary Outages

Generation Adequacy Indices

Loss of Load Probability
 Loss of Load Expectation
 Loss of Energy Expectation

$SAIFI = (\sum N_i)/NT$
 $SAIDI = (\sum r_i * N_i)/NT$
 $CAIDI = SAIDI/SAIFI$
 $CTAIDI = (\sum r_i * N_i)/CN$
 $CAIFI = (\sum N_i)/CN$
 $ASAI = (NT * T - \sum r_i * N_i)/(NT * T)$
 $CEMIn = CN(k>n)/NT$

$MAIFI = (\sum ID_i * N_i)/NT$
 $MAIFIE = (\sum IDE * N_i)/NT$
 $CEMSMin = CNT(k>n)/NT$

$ASIFI = (\sum L_i)/LT$
 $ASIDI = (\sum r_i * L_i)/LT$
 $EENS = \sum Lave\ i * r_i$
 $AENS = (\sum Lave\ i * r_i)/NT$
 $ACCI = (\sum Lave\ i * r_i)/CN$

$SCDF$
 $CCDF = \sum Lave\ i * SCDF$
 $ECOST = \sum CCDF(r)$
 $IEAR = ECOST/EENS$

$CMin$
 $CES0$
 $CEMO$

$LOLP$
 $LOLE$
 $LOEE$

Road Map For Today's Discussion

1. Reliability Analysis

- a. Cost of Customer Reliability
- b. Component Reliability Models
- c. Standard Analysis – Transmission Line Example, SCADA Switches vs. Line Sectionalizing
- d. Advanced Analysis - How to quantify N-2, N-1-1, weather, load, maintenance and other events
- e. Substation Reliability Analysis - Green and brown field decision matrices for Main/Aux, Double Bus Single Breaker and Breaker and a Half bus configurations

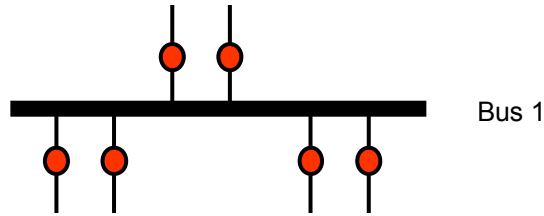
2. Artificial Intelligence

- a. Genetic Algorithm - transmission network expansion planning example
- b. Artificial Neural Networks – pattern recognition, time series forecasting and clustering examples

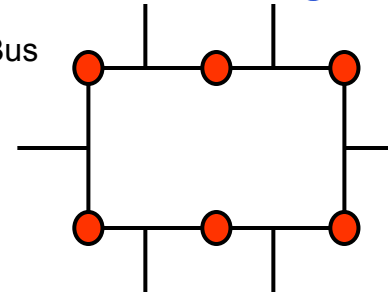
Reliability Analysis

Substation Reliability - Standard Bus Configurations

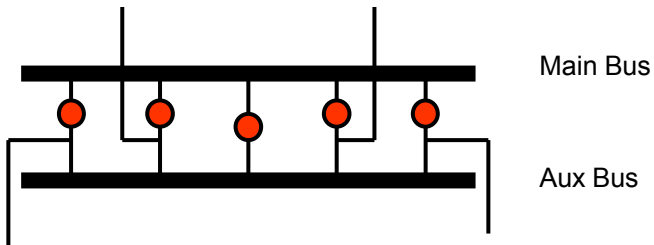
SBSB - Single Bus Single Breaker



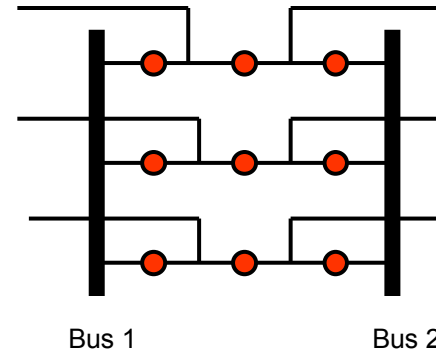
Ring Bus



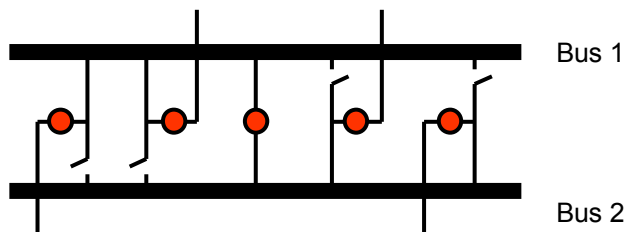
MA - Main and Aux (Transfer)



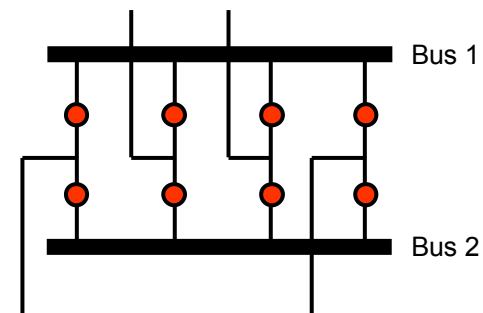
BAAH - Breaker and a Half



DBSB - Double Bus Single Breaker



DBDB - Double Bus Double Breaker



Reliability Analysis

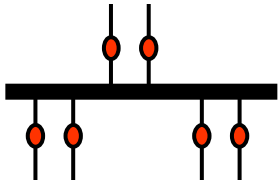
Substation Reliability – Bus Configuration Pros and Cons

Switching Scheme	Advantages	Disadvantages
1. Single Bus Single Breaker	1. Lowest Cost	1. Failure of bus or any circuit breaker results in shutdown of entire substation. 2. Difficult to do any maintenance. 3. Bus cannot be extended without completely de-energizing the substation. 4. Can be used only where loads can be interrupted or have other supply arrangements
2. Main and Transfer	1. Low initial and ultimate cost. 2. Any breaker can be taken out of service for maintenance. 3. Potential devices may be used on the main bus for relaying.	1. Requires one extra breaker for the bus-tie. 2. Switching is complicated when maintaining a breaker. 3. Failure of bus or CB results of shutdown of entire substation.
3. Double Bus Single Breaker	1. Permits some flexibility with two operating buses. 2. Either main bus may be isolated for maintenance. 3. Circuit can be transferred readily from one bus to the other by use of bus-tie breaker and bus selector disconnect switches.	1. One extra breaker is required for the bus-tie. 2. Four switches are required per circuit. 3. Bus protection scheme may cause loss of substation when it operates if all circuits are connected to that bus. 4. High exposure to bus faults. 5. Line breaker failure takes all circuits connected to that bus out of service. 6. Bus-tie failure takes entire substation out of service.
4. Ring Bus	1. Low initial and ultimate cost. 2. Flexible operation for breaker maintenance. 3. Any breaker can be removed for maintenance without interrupting load. 4. Requires only one breaker per circuit. 5. Does not use main bus. 6. Each circuit is fed by two breakers. 7. All switching is done with breakers.	1. If fault occurs during maintenance period, ring can be separated into two sections. 2. Automatic reclosing and relaying is complex. 3. If single set of relays is used, the circuit must be taken out of service to maintain the relays. 4. Requires potential devices on all circuits since there is no definite potential reference point. 5. Breaker failure during a fault on one of the circuit causes loss of one additional circuit.
5. Breaker and a Half	1. Most flexible operation. 2. High reliability. 3. Breaker failure of bus side breakers removes only one circuit from service. 4. All switching is done by breakers. 5. No disconnect switching is required for normal operation 6. Either main bus can be taken out of service at any time for maintenance 7. Bus failure does not remove any feeder circuits from service.	1. One-and-a-half breakers per circuit 2. Relaying and automatic reclosing are somewhat involved since the middle breaker must be responsive to either of its associated
6. Double Bus Double Breaker	1. Each circuit has two dedicated breakers. 2. Has flexibility in permitting feeder circuits to be connected to either bus. 3. Any breaker can be taken out of service for maintenance. 4. High reliability	1. Most expensive 2. Would lose half the circuits for breaker failure if circuits are not connected to both buses.

Reliability Analysis

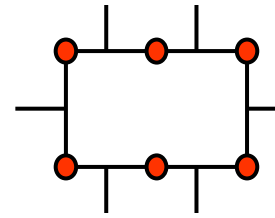
Substation Reliability - Key Points

SBSB - Single Bus Single Breaker



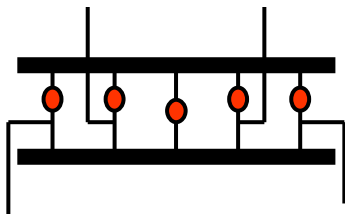
Any N-1 fault takes out the entire substation.
Can't clear bus or breakers.

Ring Bus



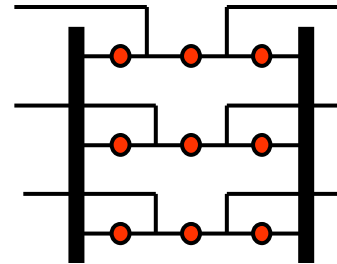
Each position subject to loss of continuity for two N-1 breaker faults.
Any N-1 fault takes out 2 positions simultaneously.
Limited to six positions or less.

MA - Main and Aux (Transfer)



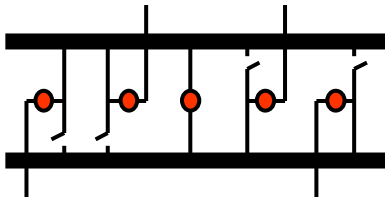
Any N-1 fault takes out the entire substation.
Can't clear bus.

BAAH - Breaker and a Half



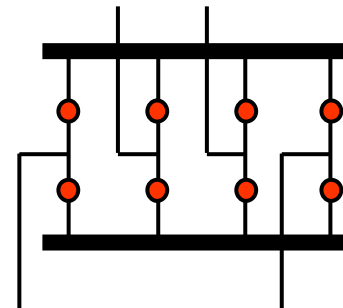
Each position subject to loss of continuity for two N-1 breaker faults.
Only middle breaker faults take out 2 positions simultaneously.
Highest operating flexibility.

DBSB - Double Bus Single Breaker



All but one N-1 fault take out half the substation.
Bus tie breaker fault takes out the entire substation.
Can clear bus and breakers, but complicated switching leads to high incidence of work procedure errors.

DBDB - Double Bus Double Breaker



Each position subject to loss of continuity for two N-1 breaker faults.
No N-1 fault takes out 2 positions simultaneously.

Reliability Analysis

Substation Reliability – Study Assumptions

- Circuit breaker, switch, CT, PT and bus failures are modeled.
- N-1 active failures and N-1-1 active failures overlapping passive failures are considered, even though N-1-1 events contribute less than 1% to reliability indices.
- Delivery point failure occurs whenever there is a loss of continuity between source and load.
- The minimum cut-set approximation is employed.
- Maintenance events are not modeled. This is conservative since maintenance outages are far more likely to happen on the lower reliability bus configurations (SBSB, MA and DBSB).
- MA, DBSB and BAAH bus configurations will be modeled. Reliability results for MA and SBSB will be similar, although reliability is worse for SBSB due to maintenance outages. Reliability results for Ring, BAAH and DBDB will be very similar.
- The switching sequences inside the substation during restoration are modeled.
- Reliability results are calibrated to realistic system averages, implicitly capturing restoration outside the substation.
- Only a single voltage level is modeled.
- Depreciation was neglected in the economic analysis.
- For green field studies load is modeled with an S-curve but the sequence of substation expansions is not taken into account (all costs are up front). For brown field studies the load is assumed to have already saturated.
- Lifetime average failure rates are used for the analysis.

Failure Rates (failures/year):

CB = 0.0075

Source and Load nodes = 0.005 to account for CTs, PTs and switches

Buses = $0.005 + 0.005 * \# \text{ of elements attached to bus (accounts for CTs, PTs \& switches)}$

Restoration Times:

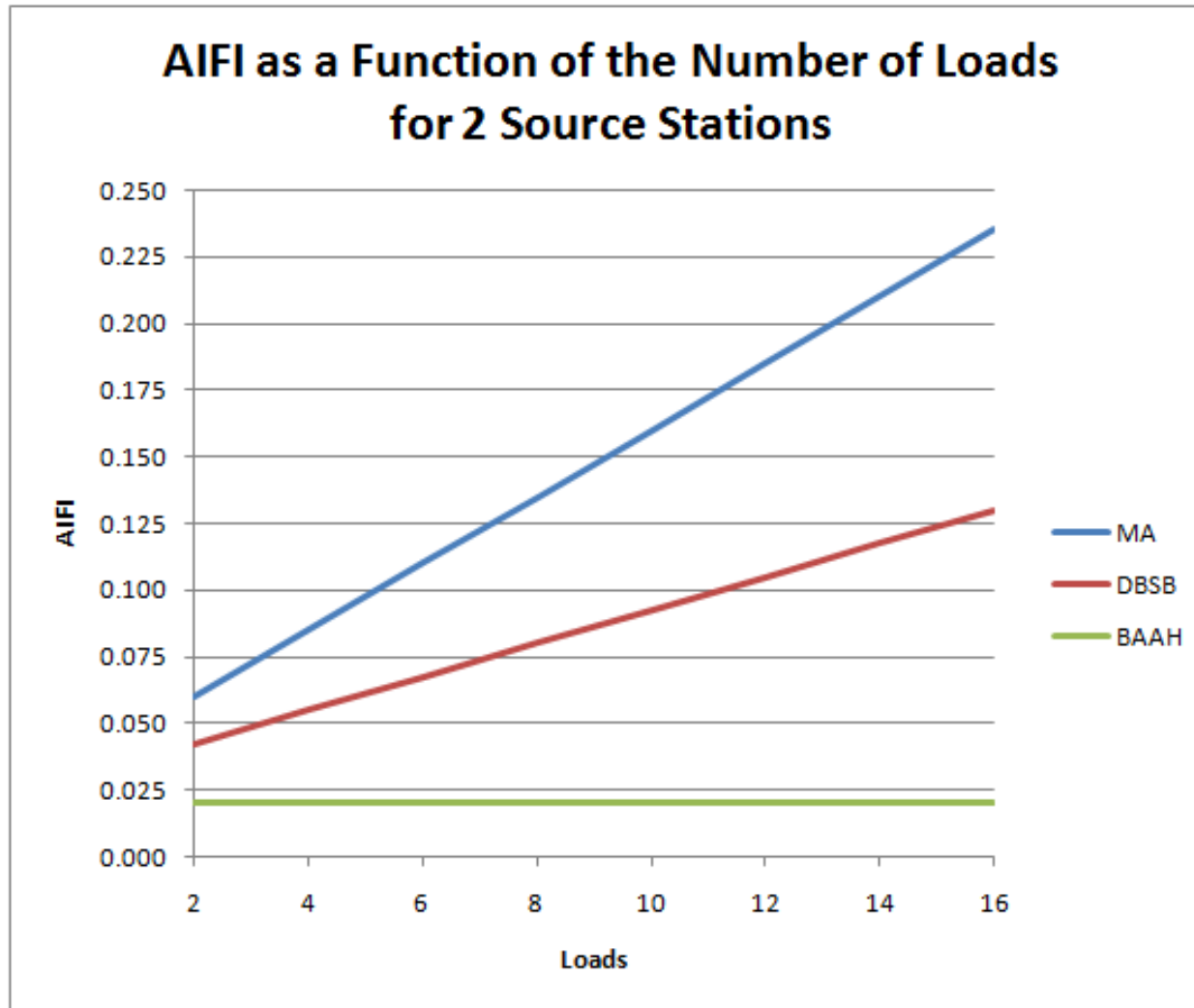
90 minutes to travel and perform 1 restoration step

30 minutes for each additional restoration step

Average Load Point Reliability Statistics	Bus Structure	# of Sources	2 Loads	4 Loads	6 Loads	8 Loads	10 Loads	12 Loads	14 Loads	16 Loads
AIDI - Unavailability (customer outage minutes/year)	BAAH	1 Source	3.3	3.4	3.5	3.5	3.5	3.5	3.6	3.6
	DBSB		6.0	8.3	10.9	13.7	16.8	20.0	23.5	27.2
	MA		5.6	9.2	13.4	18.2	23.6	29.6	36.2	43.4
	BAAH	2 Sources	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	DBSB		4.3	5.9	7.6	9.5	11.5	13.7	16.0	18.5
	MA		6.9	10.8	15.3	20.4	26.1	32.4	39.3	46.8
	BAAH	3 Sources	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	DBSB		5.5	7.2	9.1	11.1	13.3	15.6	18.1	20.7
	MA		8.8	13.0	17.8	23.2	29.2	35.8	43.0	50.8
	BAAH	4 Sources	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	DBSB		5.9	7.6	9.5	11.5	13.7	16.0	18.5	21.1
	MA		10.8	15.3	20.4	26.1	32.4	39.3	46.8	54.9
AIFI - Failure Rate (customer outages/year)	BAAH	1 Source	0.0363	0.0381	0.0388	0.0391	0.0393	0.0394	0.0395	0.0395
	DBSB		0.0588	0.0775	0.0963	0.1150	0.1338	0.1525	0.1713	0.1900
	MA		0.0525	0.0775	0.1025	0.1275	0.1525	0.1775	0.2025	0.2275
	BAAH	2 Sources	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200
	DBSB		0.0425	0.0550	0.0675	0.0800	0.0925	0.1050	0.1175	0.1300
	MA		0.0600	0.0850	0.1100	0.1350	0.1600	0.1850	0.2100	0.2350
	BAAH	3 Sources	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200
	DBSB		0.0513	0.0638	0.0763	0.0888	0.1013	0.1138	0.1263	0.1388
	MA		0.0725	0.0975	0.1225	0.1475	0.1725	0.1975	0.2225	0.2475
	BAAH	4 Sources	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200
	DBSB		0.0550	0.0675	0.0800	0.0925	0.1050	0.1175	0.1300	0.1425
	MA		0.0850	0.1100	0.1350	0.1600	0.1850	0.2100	0.2350	0.2600
CAIDI - Average Restoration Time (customer minutes/outage)	BAAH	1 Source	90	90	90	90	90	90	90	90
	DBSB		101	107	113	119	125	131	137	143
	MA		107	119	131	143	155	167	179	191
	BAAH	2 Sources	90	90	90	90	90	90	90	90
	DBSB		101	106	112	118	124	130	136	142
	MA		115	127	139	151	163	175	187	199
	BAAH	3 Sources	90	90	90	90	90	90	90	90
	DBSB		108	114	120	126	132	138	144	150
	MA		121	133	145	157	169	181	193	205
	BAAH	4 Sources	90	90	90	90	90	90	90	90
	DBSB		106	112	118	124	130	136	142	148
	MA		127	139	151	163	175	187	199	211

Reliability Analysis

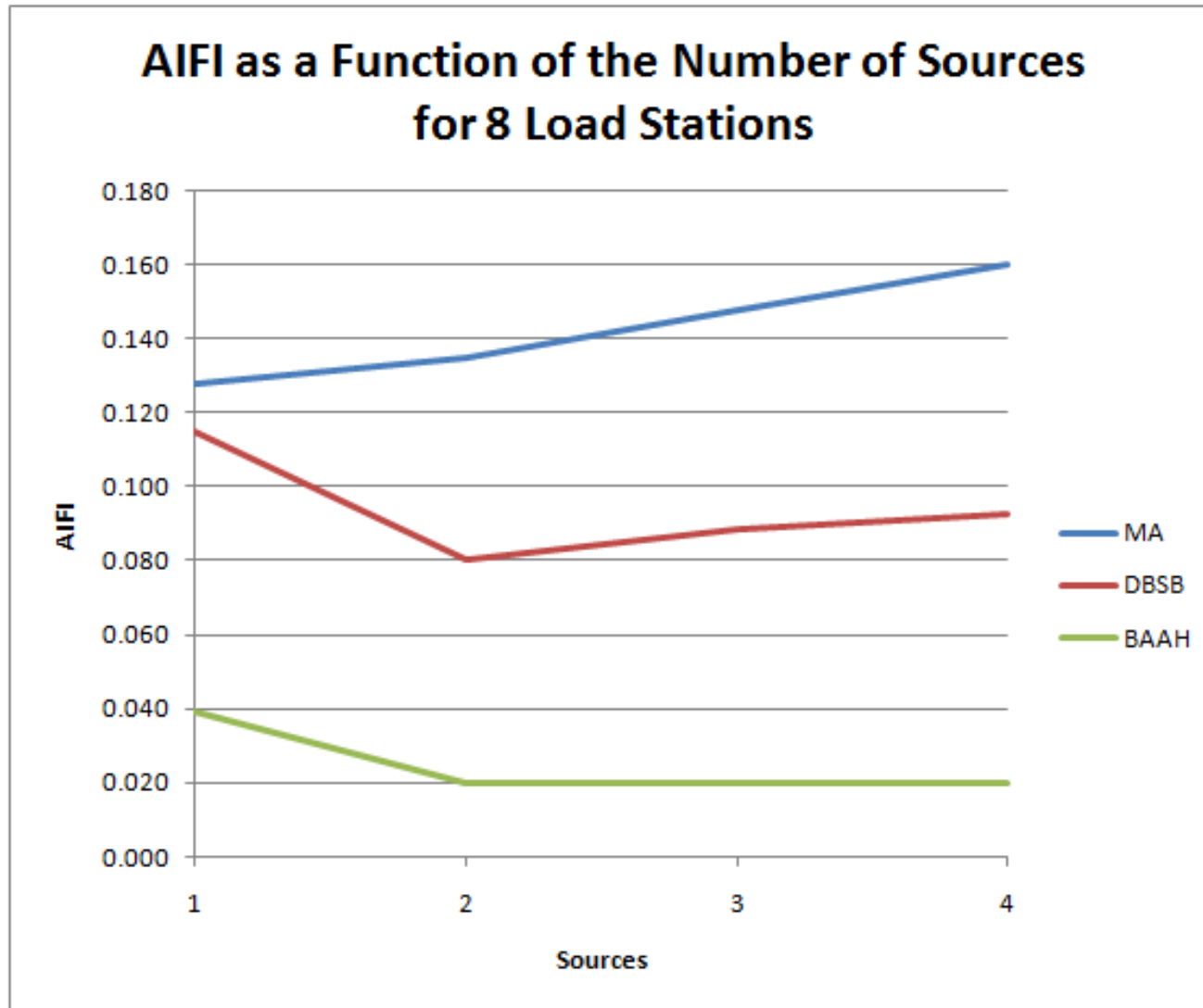
Substation Reliability Results



Note: AIDI and CAIDI plots show the same general relationship

Reliability Analysis

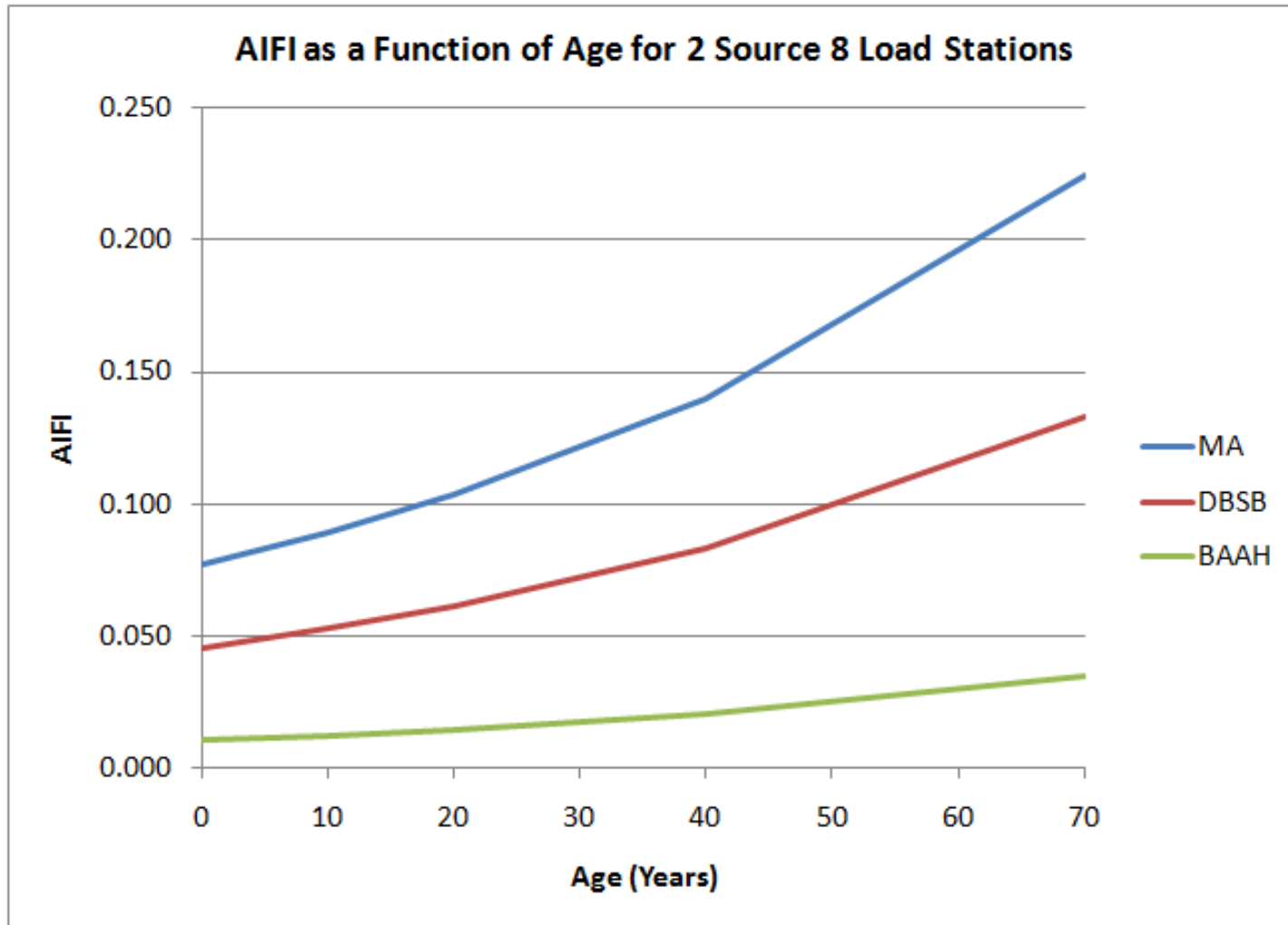
Substation Reliability Results



Note: AIDI and CAIDI plots show the same general relationship

Reliability Analysis

Substation Reliability Results



Note: AIDI and CAIDI plots show the same general relationship

Reliability Analysis

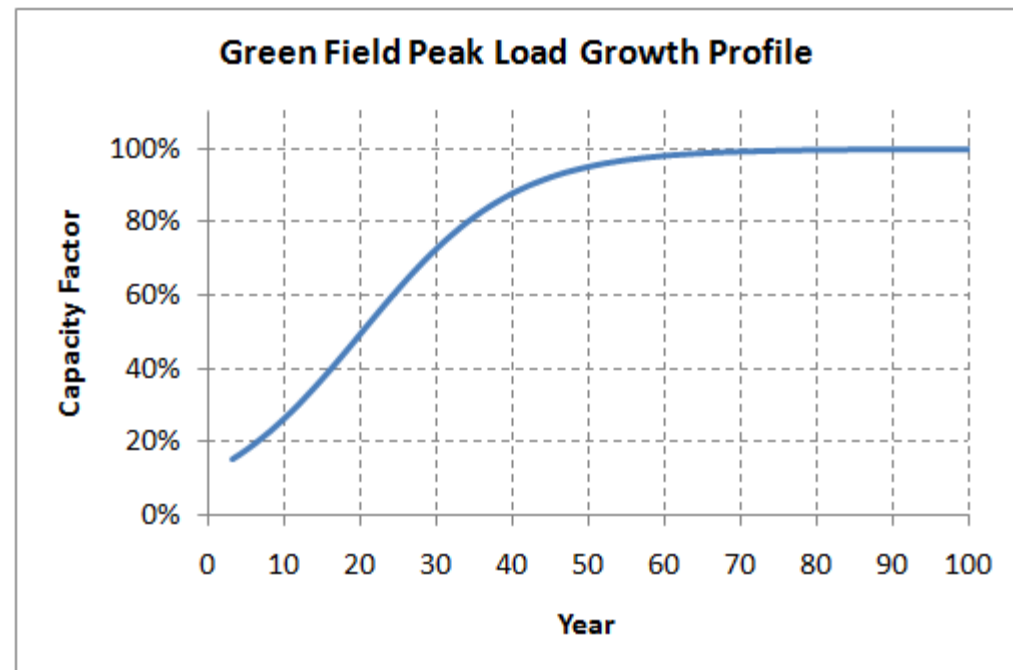
Substation Reliability – Economic Parameters

Value of Service Data	DOM	COM	IND	AGR	Average
\$/int/peak kW	0.53	7.47	11.00	0.00	5.18
\$/hr/peak kW	0.15	27.56	5.64	10.56	7.22
Load Composition	40%	15%	35%	10%	N/A

Capital Schedule	% of Total Cost
Year 0	10%
Year 1	30%
Year 2	60%

Unit Costs	\$M/element (Green Field)	\$M/element (Brown Field)
BAAH	2	2.6
DBSB	1.2	1.6
MA	1	N/A

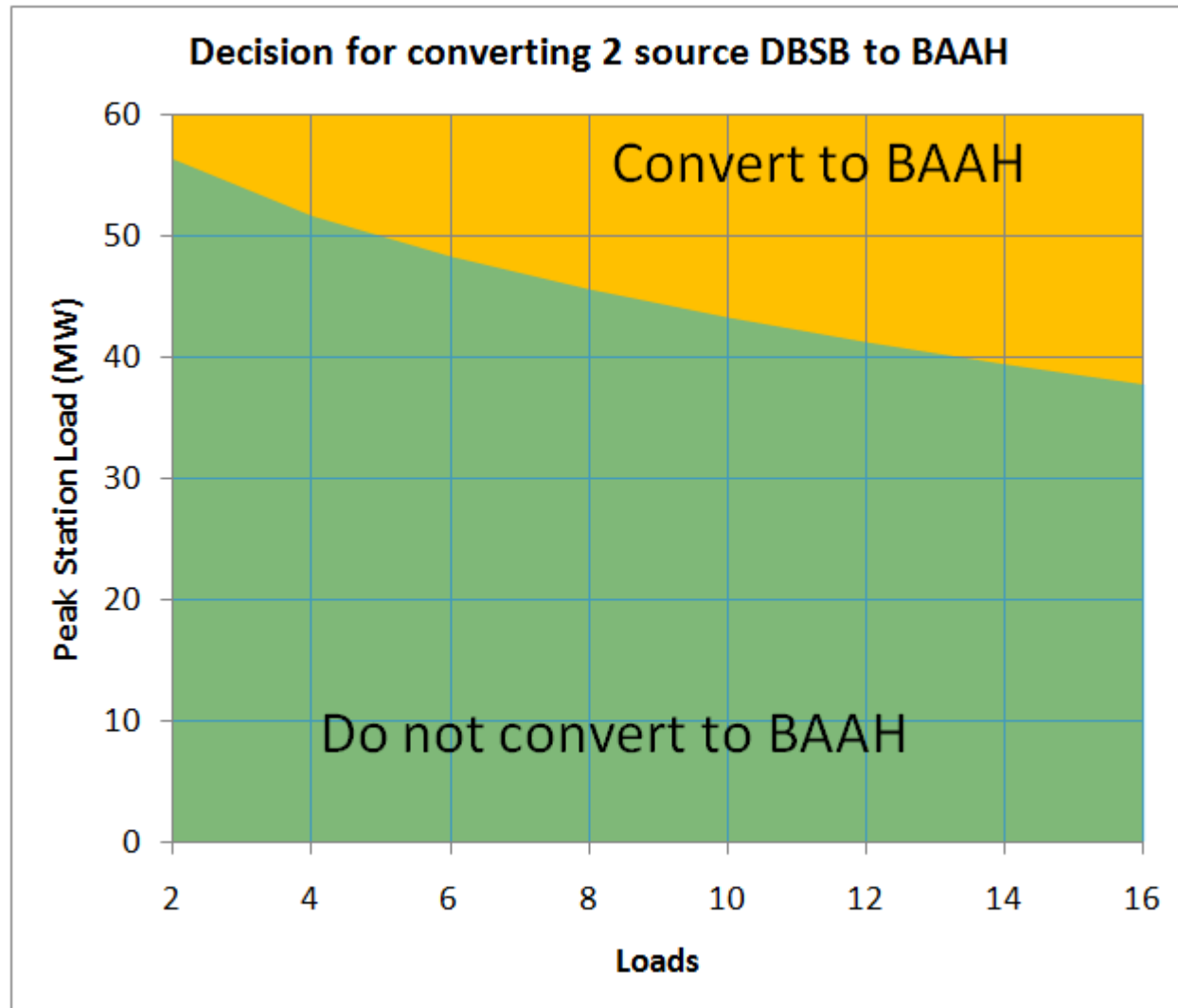
Economic Parameters	
Discount Rate	7.6%
Escalation Rate	2.5%
Tax Rate	40%
Study Period (years)	40



Substation Reliability – Decision Matrices

Green Field Decision Matrix									
Select the most reliable bus configuration whenever ultimate station load is greater than or equal to the values in this table									
Station Load (MW) for NPV=0	2 Loads	4 Loads	6 Loads	8 Loads	10 Loads	12 Loads	14 Loads	16 Loads	
BAAH vs. MA	1 Source	41	28	23	20	18	16	15	14
BAAH vs. DBSB		29	27	25	23	22	21	20	19
DBSB vs. MA		Never	36	18	13	11	9	8	7
BAAH vs. MA	2 Sources	26	22	19	18	16	15	14	13
BAAH vs. DBSB		42	39	36	34	32	31	29	28
DBSB vs. MA		10	8	7	6	5	5	4	4
BAAH vs. MA	3 Sources	23	20	18	17	16	14	14	13
BAAH vs. DBSB		35	34	32	31	29	28	27	26
DBSB vs. MA		10	8	7	6	5	5	4	4
BAAH vs. MA	4 Source	22	19	18	16	15	14	13	12
BAAH vs. DBSB		39	36	34	32	31	29	28	27
DBSB vs. MA		8	7	6	5	5	4	4	4
Brown Field Decision Matrix									
Convert to a more reliable bus configuration whenever station load is greater than or equal to the values in this table									
Station Load (MW) for NPV=0	2 Loads	4 Loads	6 Loads	8 Loads	10 Loads	12 Loads	14 Loads	16 Loads	
MA to BAAH	1 Source	44	30	25	21	19	17	16	15
DBSB to BAAH		39	36	33	31	29	28	26	25
MA to DBSB		Never	120	60	43	35	29	25	23
MA to BAAH	2 Sources	27	23	21	19	17	16	15	14
DBSB to BAAH		56	52	48	46	43	41	39	38
MA to DBSB		33	26	22	20	18	16	15	14
MA to BAAH	3 Sources	25	22	20	18	17	15	14	14
DBSB to BAAH		47	45	43	41	39	38	36	35
MA to DBSB		33	26	22	20	18	16	15	14
MA to BAAH	4 Source	23	21	19	17	16	15	14	13
DBSB to BAAH		52	48	46	43	41	39	38	36
MA to DBSB		26	22	20	18	16	15	14	13

Substation Reliability – Graphical Interpretation of a Row in a Decision Matrix



Road Map For Today's Discussion

1. Reliability Analysis

- a. Cost of Customer Reliability
- b. Component Reliability Models
- c. Standard Analysis – Transmission Line Example, SCADA Switches vs. Line Sectionalizing
- d. Advanced Analysis - How to quantify N-2, N-1-1, weather, load, maintenance and other events
- e. Substation Reliability Analysis - Green and brown field decision matrices for Main/Aux, Double Bus Single Breaker and Breaker and a Half bus configurations

2. Artificial Intelligence

- a. Genetic Algorithm - transmission network expansion planning example
- b. Artificial Neural Networks – pattern recognition, time series forecasting and clustering examples

Artificial Intelligence

Artificial intelligence (AI) is the intelligence of machines and the branch of computer science that aims to create it. The field is defined as the study and design of intelligent agents where an intelligent agent is a system that perceives its environment and takes actions that maximize its chances of success.

Problems artificial intelligence aims to solve include perception, deduction, reasoning, planning, learning, language processing, motion, social intelligence and ultimately general intelligence.

The approaches taken to achieve AI include symbolic, sub-symbolic and statistical processing.

The tools used include search, optimization, logic, statistical learning and control theory, among others.

Nature is often the inspiration behind many fields of research in artificial intelligence. See [particle swarm optimization demo.xls](#)

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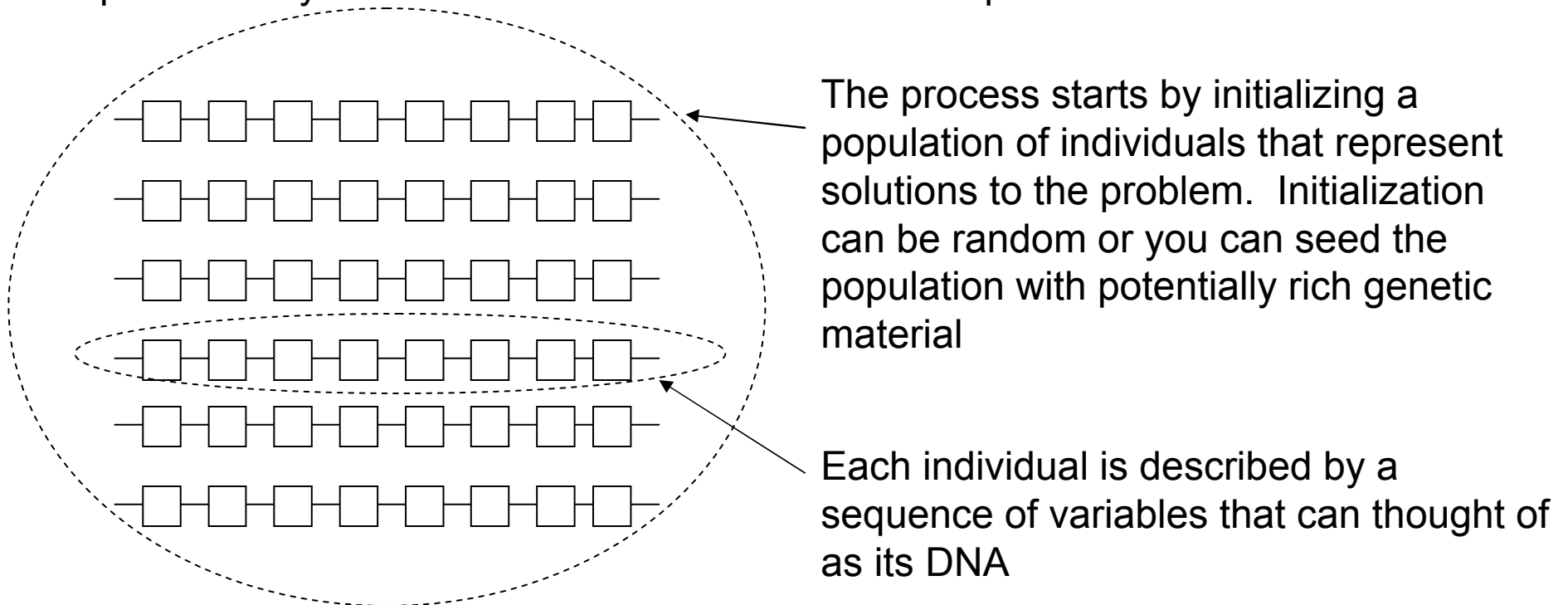
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Artificial Intelligence

Genetic Algorithms

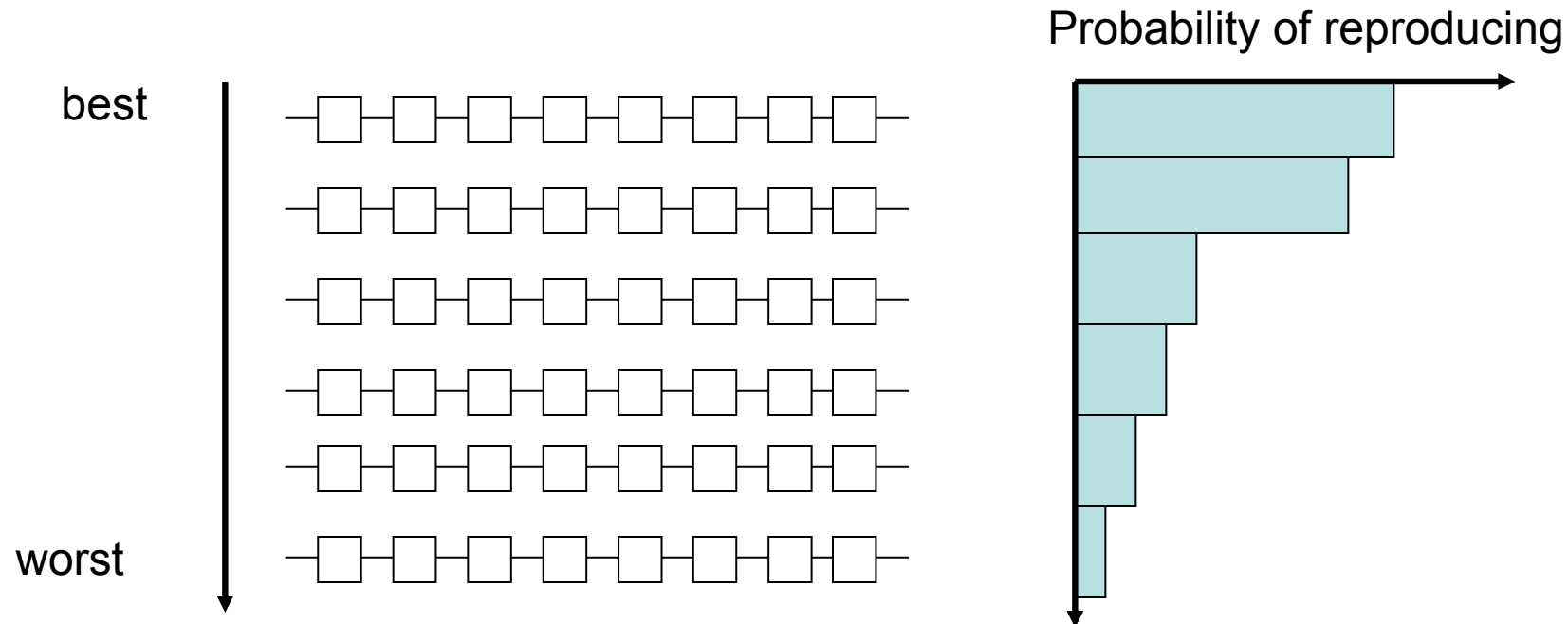
Genetic algorithms are one of the power full optimization tools used in artificial intelligence. They work by mimicking the process of evolution and can be used to solve virtually any type of problem. They are most frequently employed for problems the classical optimization techniques perform poorly on. For example, gradient techniques are sensitive to initial conditions and can get trapped on local optima. On such problems genetic algorithms can be used to find global optima. They are also well suited for combinatorial problems.



Artificial Intelligence

Genetic Algorithms

Each individual's genetic sequence produces certain traits that determine its fitness, the objective function is used to evaluate each potential solution and assign it a score.



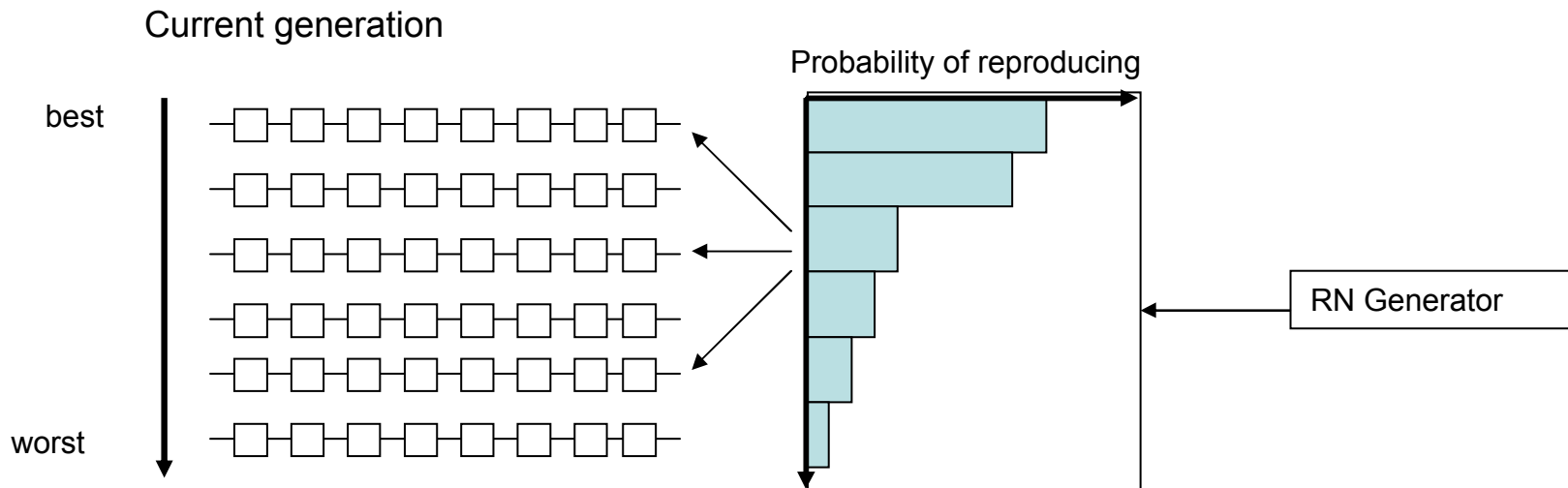
An individual's fitness determines its likelihood of surviving and successfully reproducing.

The best solution is often carried over to the next generation to insure that the process approaches the optimal solution monotonically

Artificial Intelligence

Genetic Algorithms – Selection

The next generation of individuals is produced by applying standard genetic operators - selection, recombination and mutation.

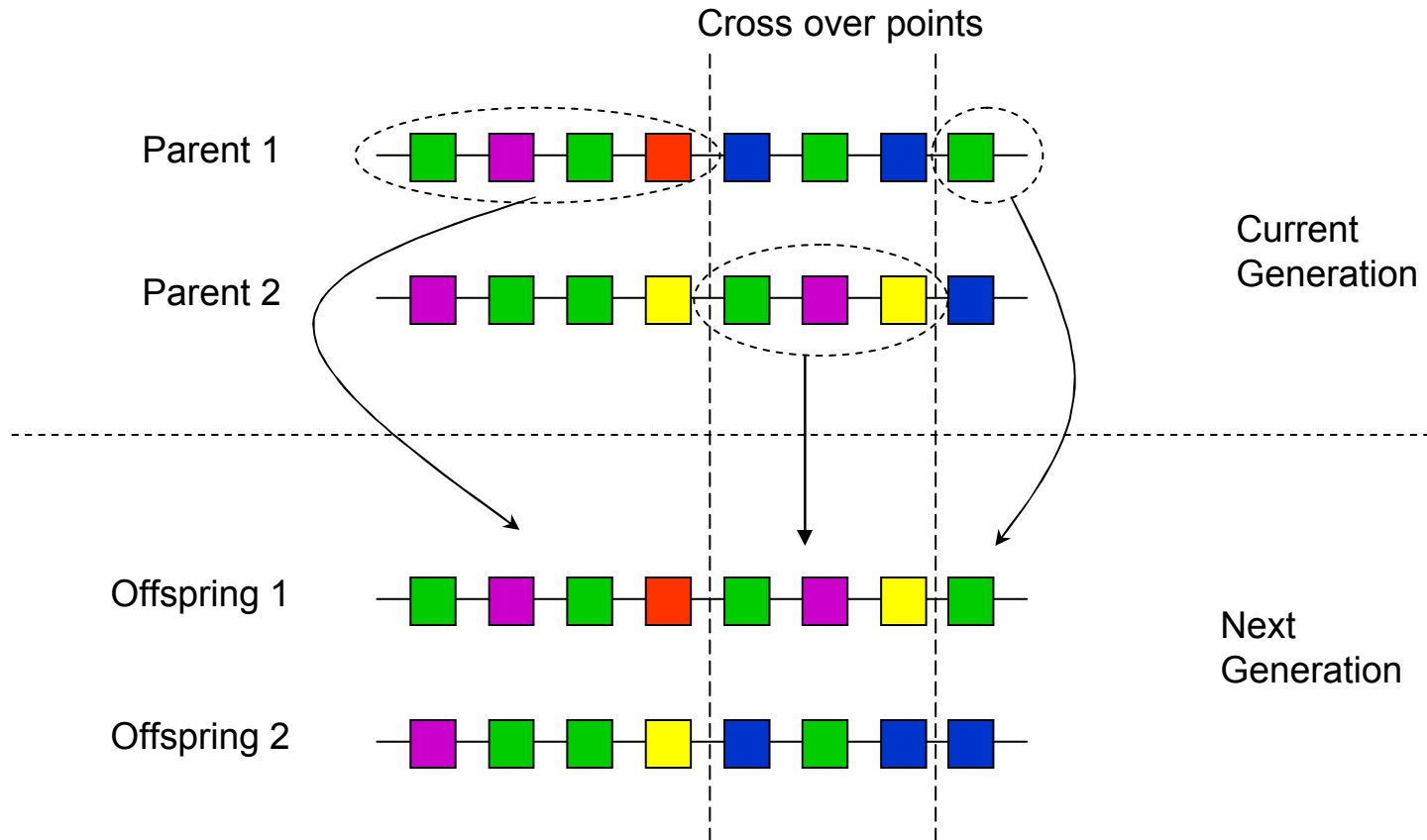


Individuals are selected using via random number generation.
The fitter an individual is, the more likely it is to be selected.

Artificial Intelligence

Genetic Algorithms - Recombination

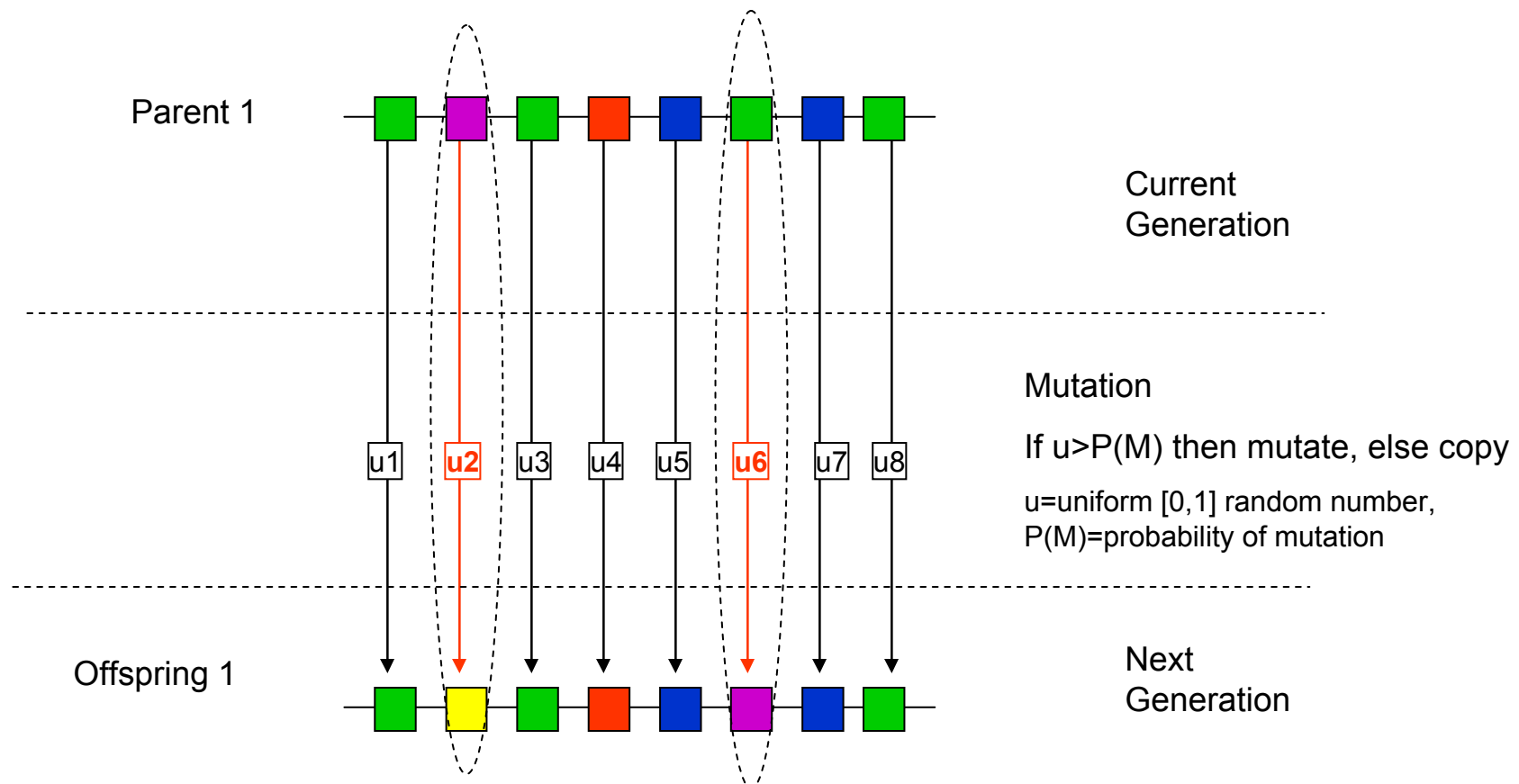
The recombination is similar to chromosome cross over.



Two point cross over is common approach. Cross over points can be random.

Artificial Intelligence

Genetic Algorithms - Mutation

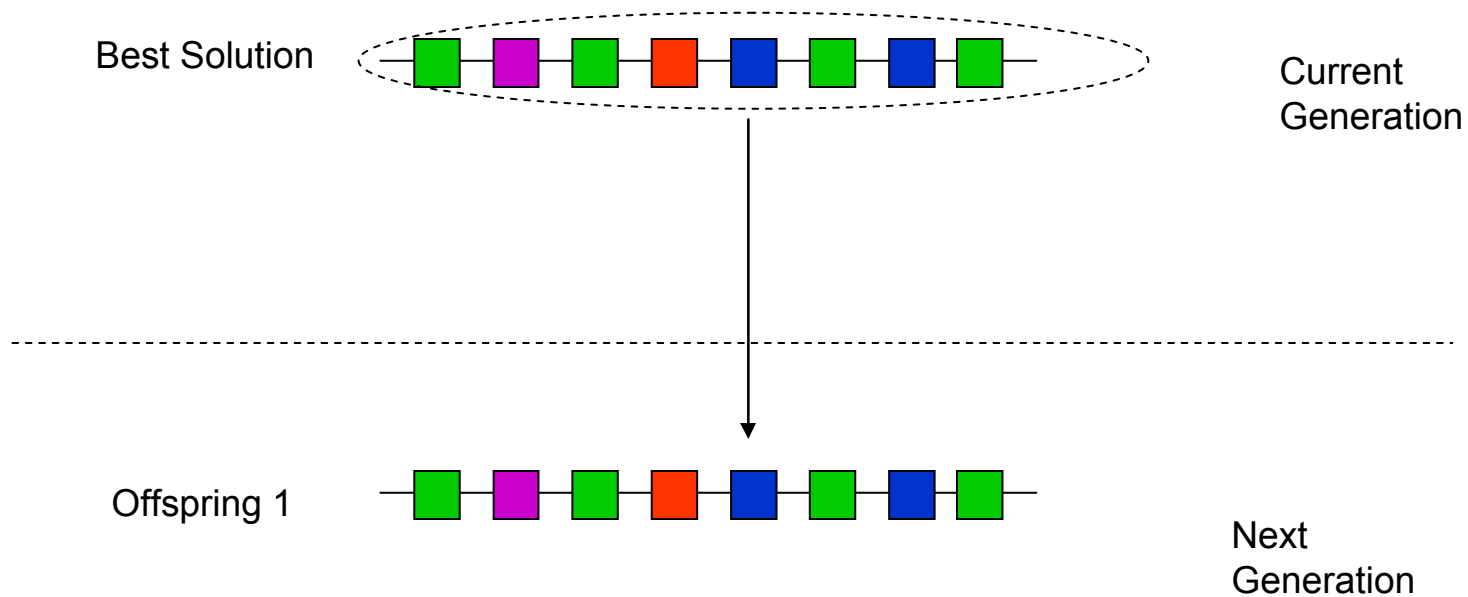


In sophisticated implementations all the genetic operators are varied automatically during the optimization based on their effectiveness. The probability of mutation can also be varied during the optimization.

Artificial Intelligence

Genetic Algorithms – Carry Over

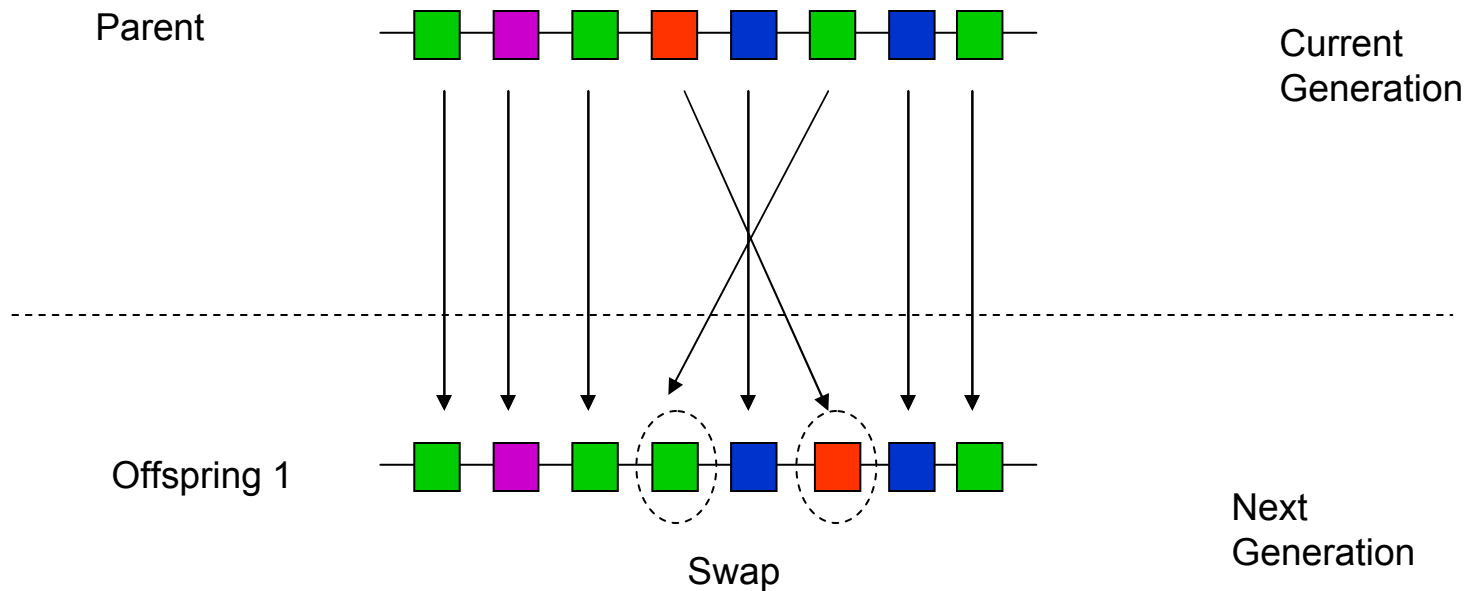
Carry over is just copying the best solution from the current generation to the next generation



The best solution may be carried over to the next generation to force the solution process to approach the optima monotonically

Artificial Intelligence

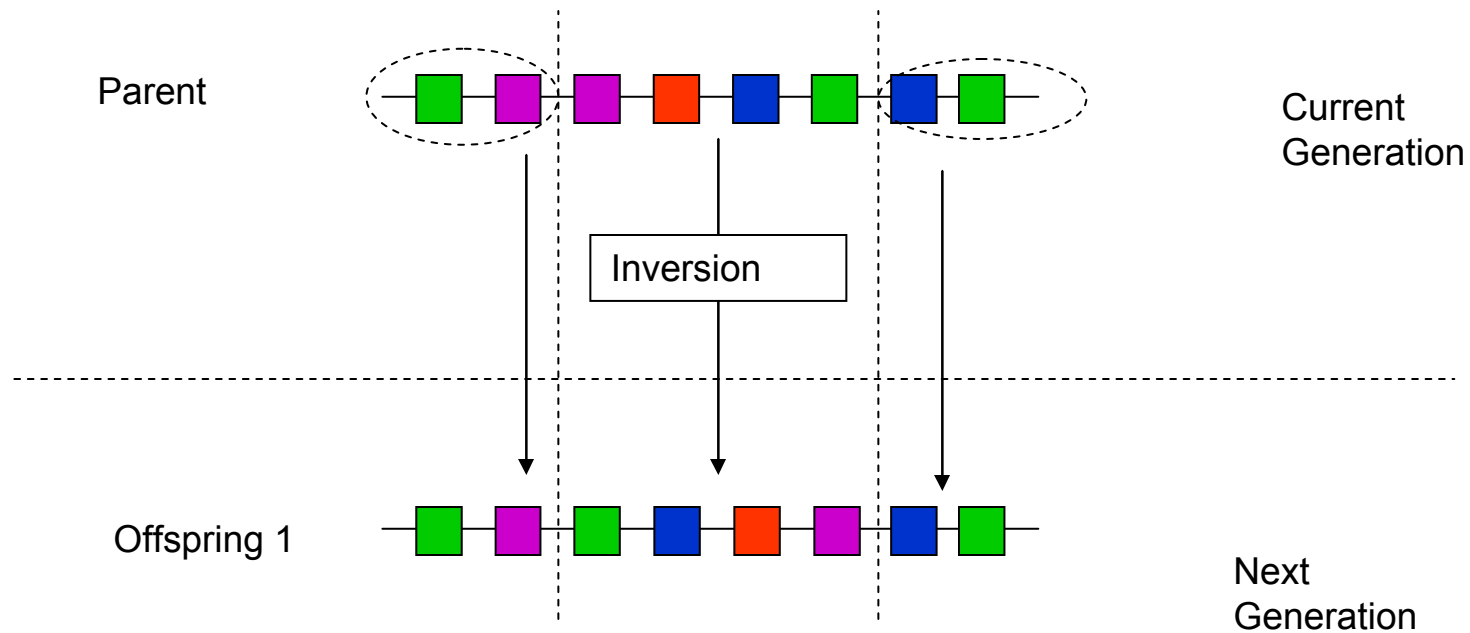
Genetic Algorithms – Swaps



For combinatorial problems swapping can be effective

Artificial Intelligence

Genetic Algorithms – Inversion

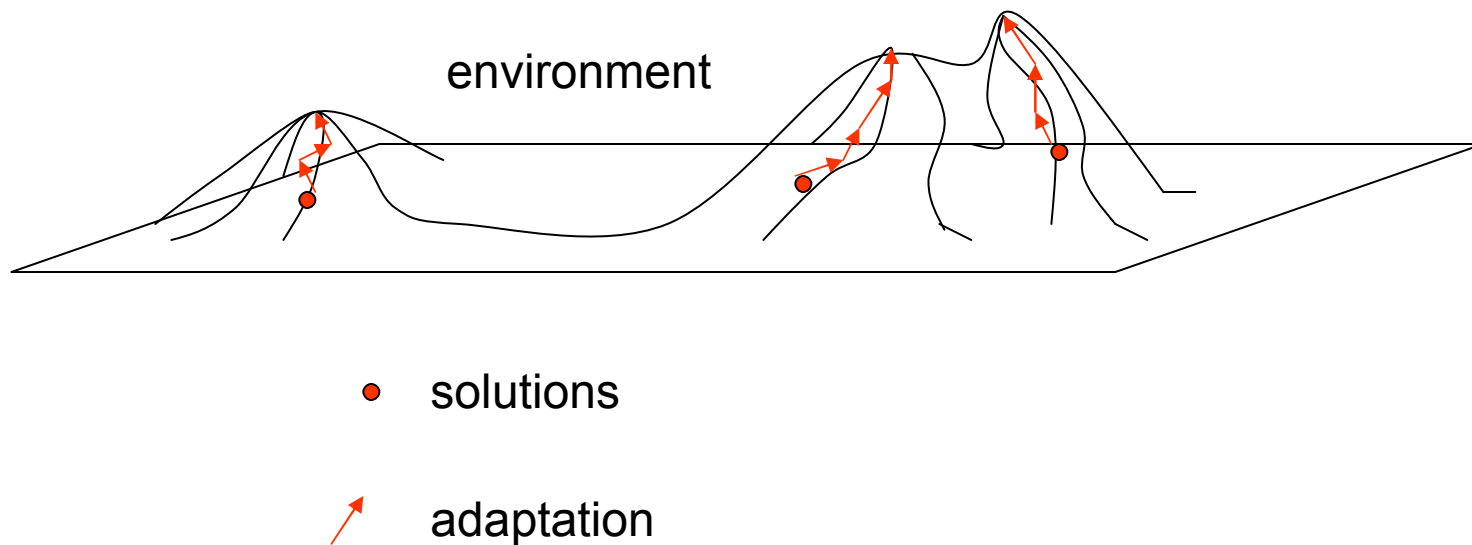


For combinatorial problems inverting portions of the sequence may be effective.

Artificial Intelligence

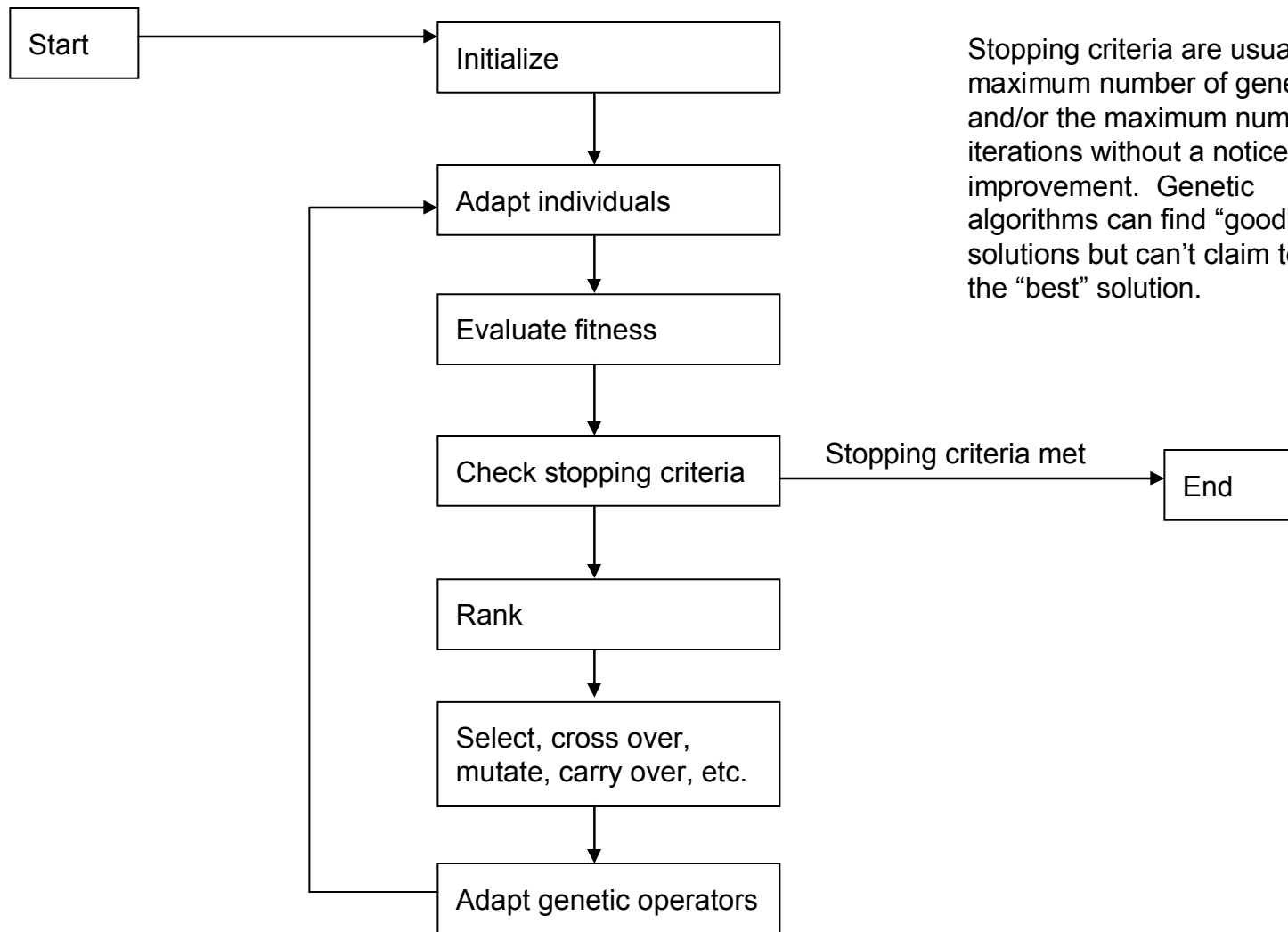
Genetic Algorithms - Adaptation

Other optimization techniques can be incorporated easily within the genetic algorithm to allow individuals to adapt to the environment



Artificial Intelligence

Genetic Algorithms – Flow Chart



Stopping criteria are usually the maximum number of generations and/or the maximum number of iterations without a noticeable improvement. Genetic algorithms can find “good” solutions but can’t claim to find the “best” solution.

Artificial Intelligence

Genetic Algorithms – Demonstration

Traveling salesman problem.

A traveling salesman has to visit 50 cities every month. To minimize his expenses he's trying to find the shortest possible route that goes through each city exactly once. The route must begin and end in the same city. To solve this problem he wrote a genetic algorithm.

Can you find a better route?

See [traveling salesman game.xls](#)

Artificial Intelligence

Genetic Algorithms – Potential Power System Applications

Genetic algorithms have been applied to many problems in science and engineering. Some examples include:

Transmission Network Expansion Planning (TNEP). The goal of TNEP is to plan for additions to the transmission system that optimize some criteria. For example, a TNEP problem could be to find the minimum cost combination of capital projects that will allow the transmission system to remain in compliance with NERC standards in each of the next 10 years.

Transient (or Operational) Reliability Optimization. Following an outage, find the sequence of switching steps that minimizes ECOST while making sure that all voltages and branch flows are within ratings. Results could be used to create the appearance of a “Smart Grid”.

Optimal control. Find an optimal strategy for bidding into the CAISO markets. Fit generator, governor and exciter models to test data. Tune controls to damp unstable systems.

Road Map For Today's Discussion

1. Reliability Analysis

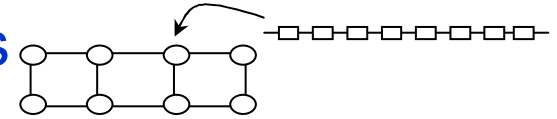
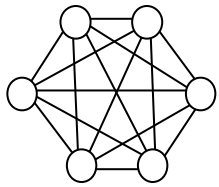
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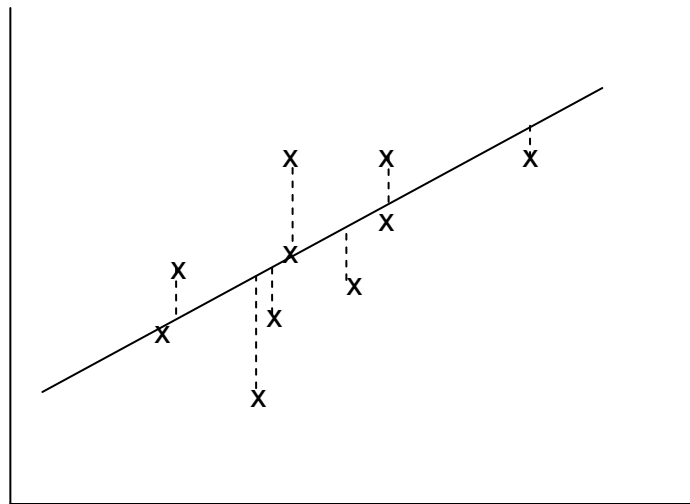
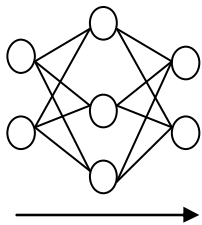
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Artificial Intelligence

Artificial Neural Networks



As the name clearly states, artificial neural networks draw their inspiration from their biological counterparts. They are highly connected, massively parallel, nonlinear networks. The equations that they generate are not intuitive or easy for a person to understand but they are very powerful and easy to use. They can be used for regression analysis, classification, clustering, etc. and have the additional advantage of being adaptive. To start we'll refresh on the idea of regression analysis.



Linear regression -
determine the parameters
for the line that minimize the
sum of square error terms
between the line and all of
the data points

Artificial Intelligence

Artificial Neural Networks

The line of best fit is solved by setting the derivatives of the error function to zero and solving for the minimum.

$$s^2 = \sum (mx + b - y)^2$$

$$\frac{\partial \varepsilon^2}{\partial m} = \sum (2mx^2 + 2xb - 2xy) = 0$$

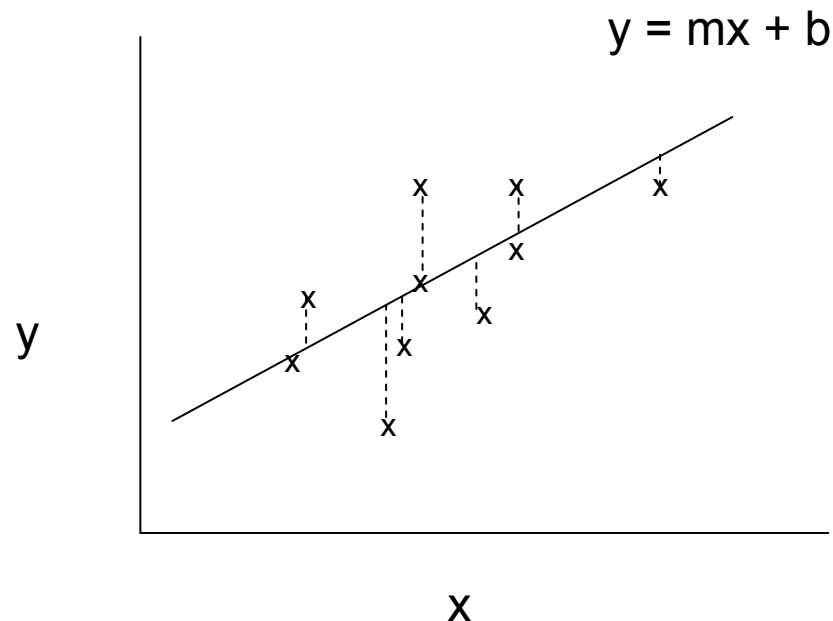
$$\frac{\partial \varepsilon^2}{\partial b} = \sum (2mx + 2b - 2y) = 0$$

$$2 \begin{bmatrix} \sum x^2 & \sum x \\ \sum x & \sum 1 \end{bmatrix} \begin{bmatrix} m \\ b \end{bmatrix} = 2 \begin{bmatrix} \sum xy \\ \sum y \end{bmatrix}$$

$$m = \frac{\Delta_1}{\Delta} = \frac{n \sum xy - \sum x \sum y}{n \sum x^2 - (\sum x)^2}$$

$$b = \frac{\Delta_2}{\Delta} = \frac{\sum x^2 \sum y - \sum x \sum xy}{n \sum x^2 - (\sum x)^2}$$

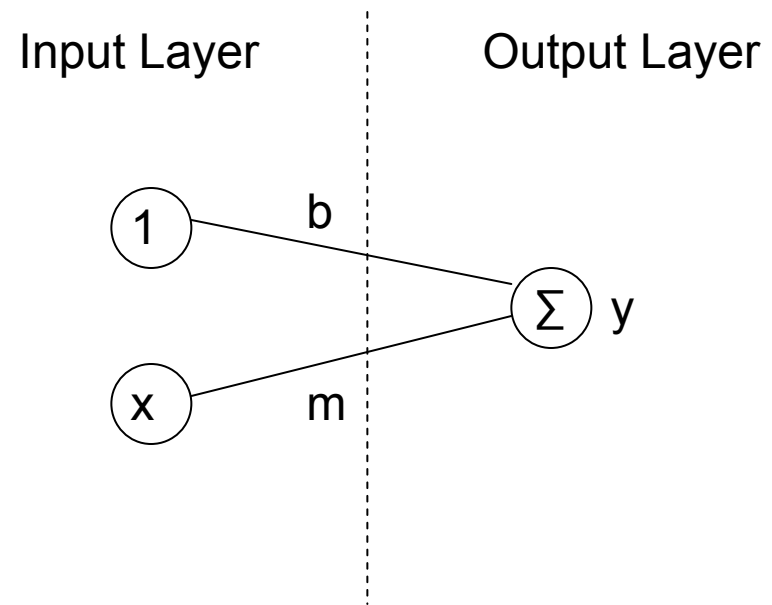
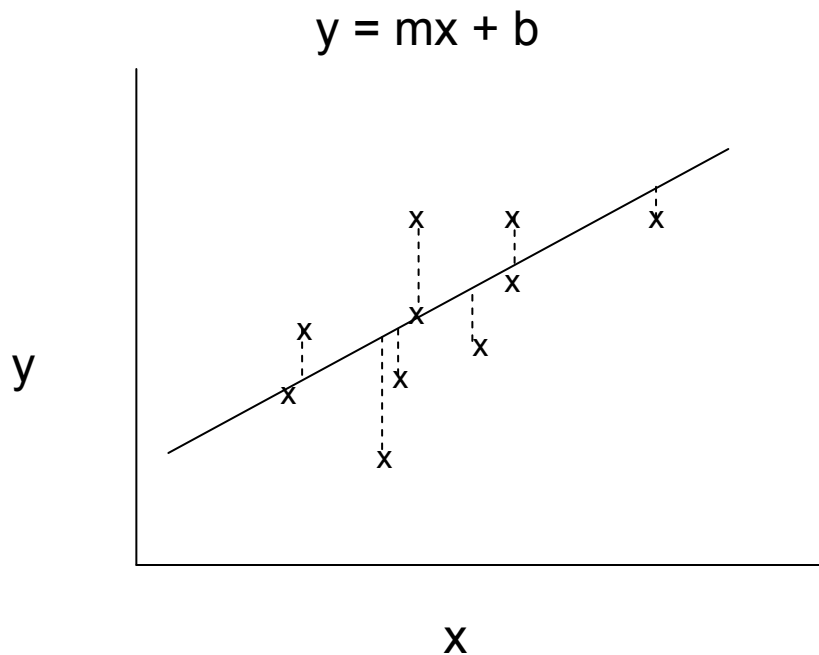
$$b = \bar{y} - m\bar{x}$$



Artificial Intelligence

Artificial Neural Networks – Linear Regression

The linear regression model can be expressed as one of the simplest neural networks. This network is simple, but not very useful.

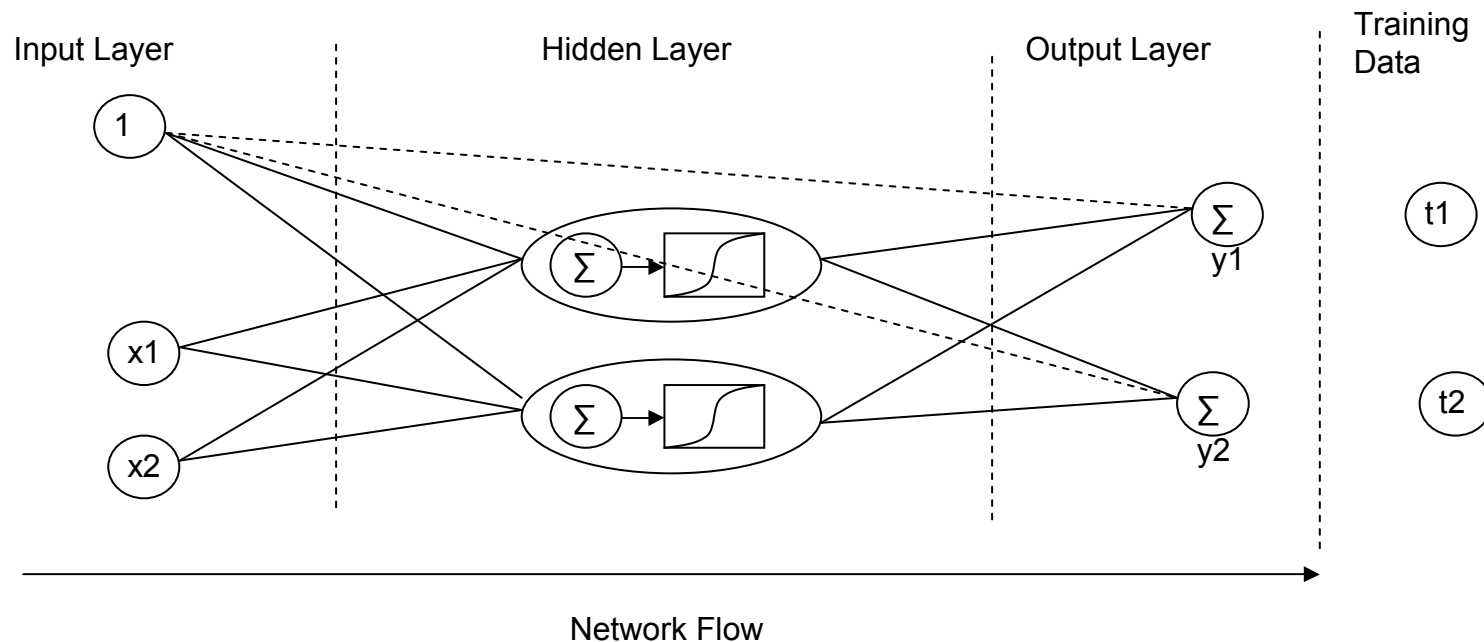


In this model the input layer has one input neuron and one bias neuron whose activation is always 1. the output layer has one neuron which act which forms the sum of the input layer neurons time their connection weights

Artificial Intelligence

Artificial Neural Networks – Feed Forward Neural Network

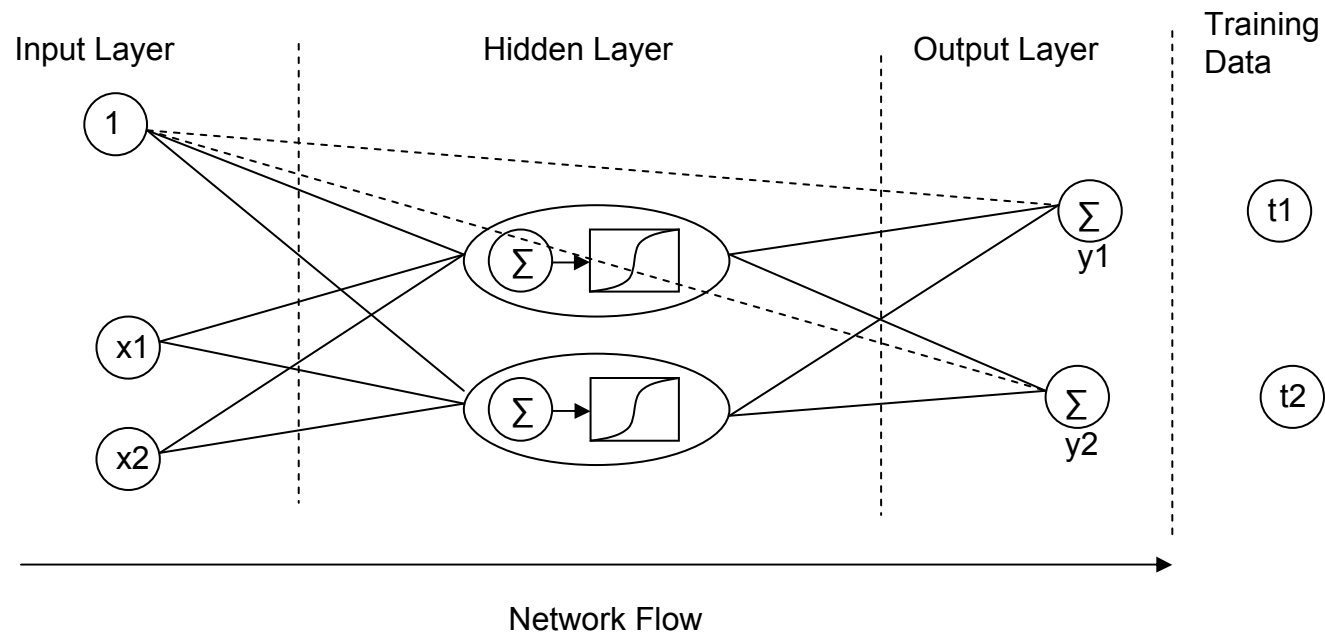
A general regression model is known as the feed forward neural network. It has an input layer, a hidden layer and an output layer. It also utilizes non-linear activation functions, bias terms and is typically fully connected. The non-linear activation functions and the hidden layer let this network model almost any type of function, continuous, discrete, logical, linear separable and non-linearly separable. The activation function used is typically a sigmoid ($1/(1+e^{-x})$)



Artificial Intelligence

Artificial Neural Networks – Feed Forward Neural Network

Network is trained using supervised learning. For each training set the inputs are propagated forward and the outputs are compared to the target values. The error is computed and propagated backwards through the network using the derivatives of the error with respect to the weights to fit the model much like a linear regression. However, in this case the equations are nonlinear and a stochastic gradient descent is employed.



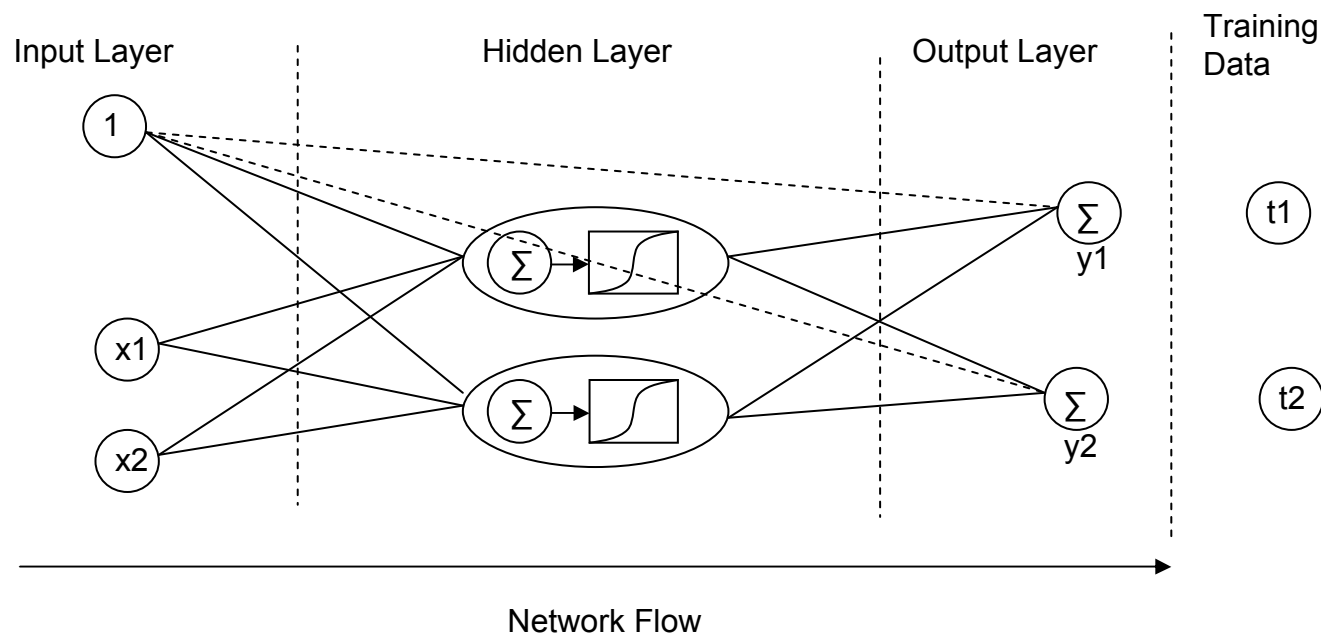
Artificial Intelligence

Artificial Neural Networks – Feed Forward Neural Network

The feed forward network can be used for pattern recognition and time series forecasting among other things. Time series would be useful for a short term load forecasting program. One that forecasted a day ahead in 24 one hour time steps. Other uses could be failure prediction and/or fault classification for power transformers.

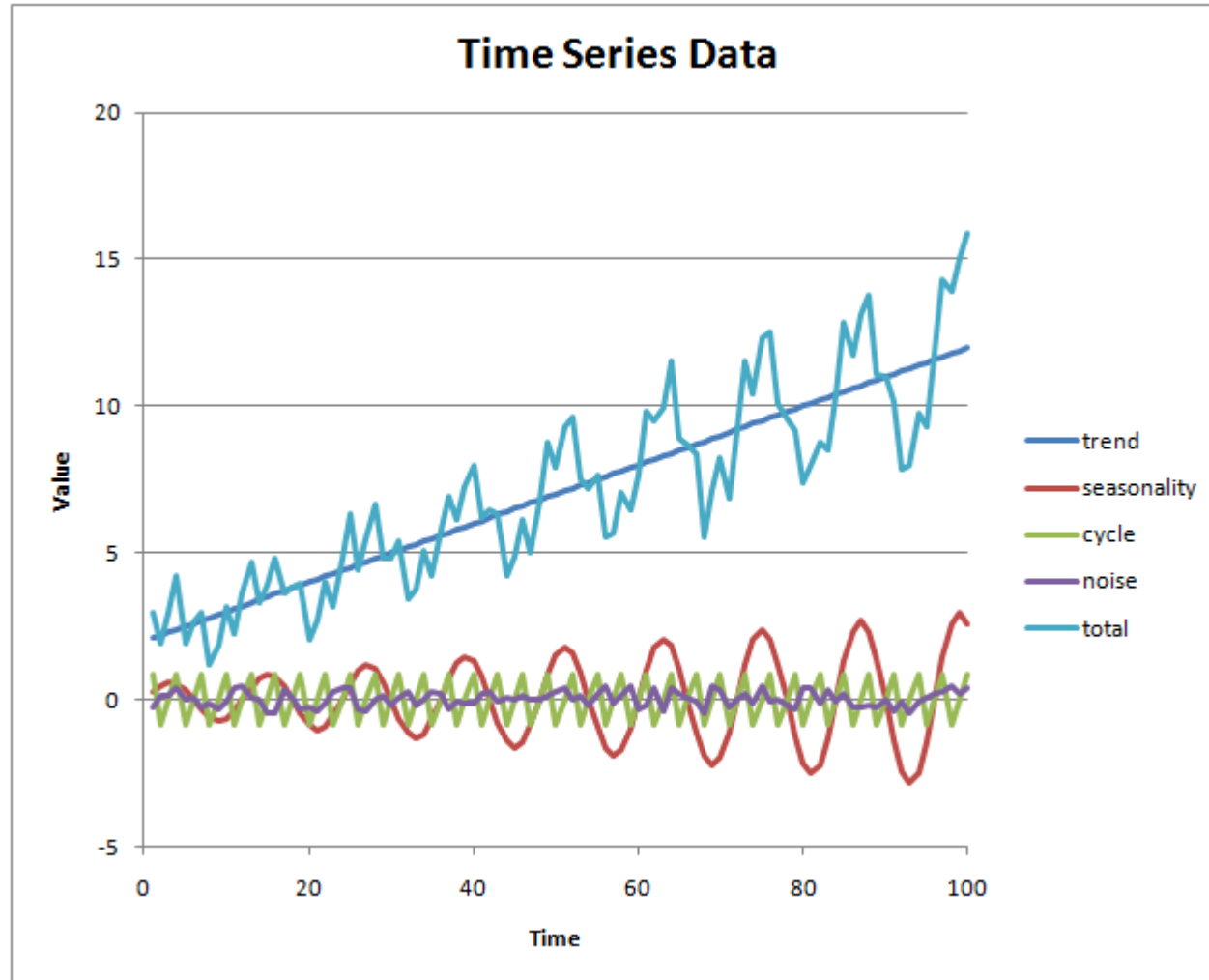
Example pattern recognition:

See [FFNN 0-9 recognition V2.xls](#)



Artificial Intelligence

Time Series Forecasting



Artificial Intelligence

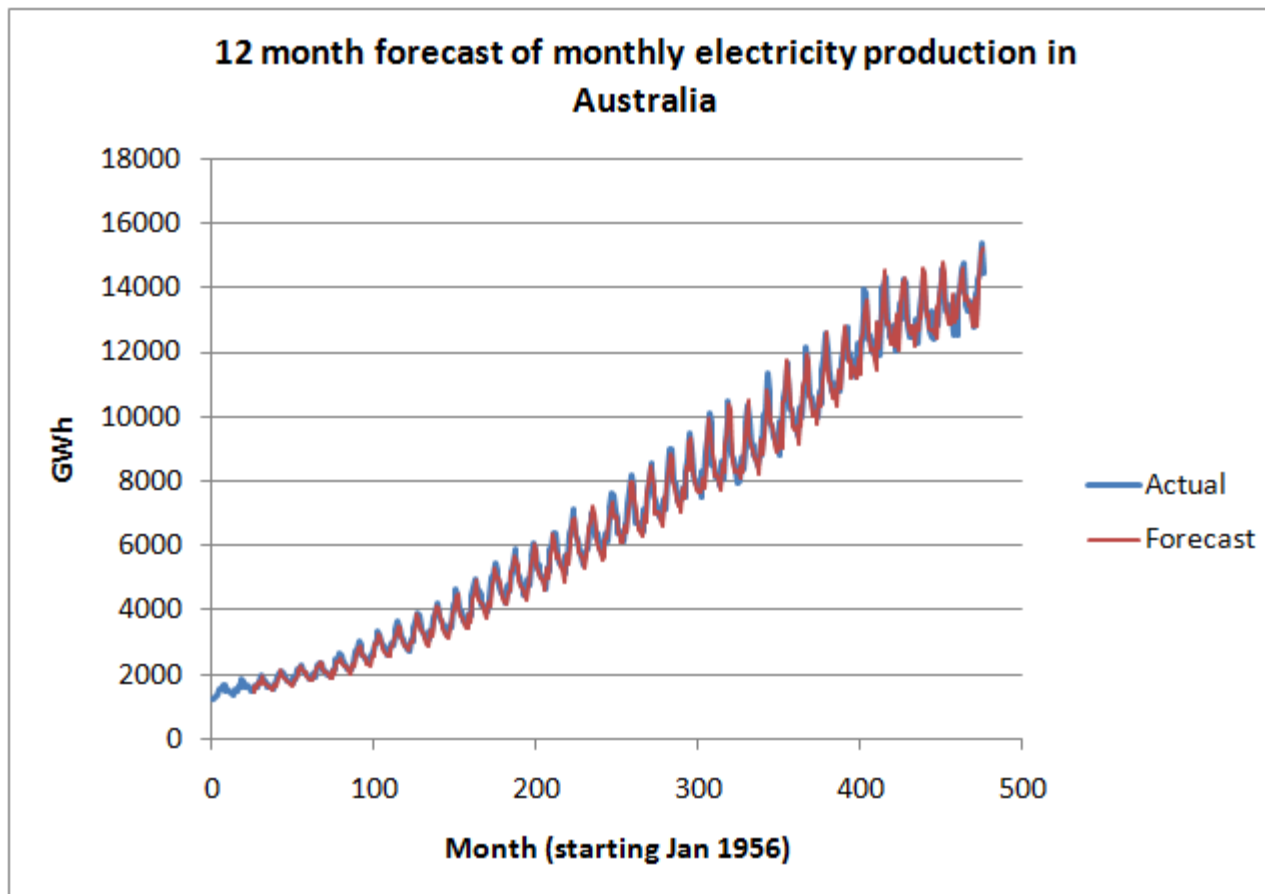
Time Series Forecasting

Monthly electricity production in Australia: giga-watt hours. Jan 1956 – Aug 1995.

Mean Absolute Percent Error (MAPE)

FFNN – MAPE = 3.7% (structure of FFNN was not optimized)

Auto-regressive Model – MAPE = 2.6%



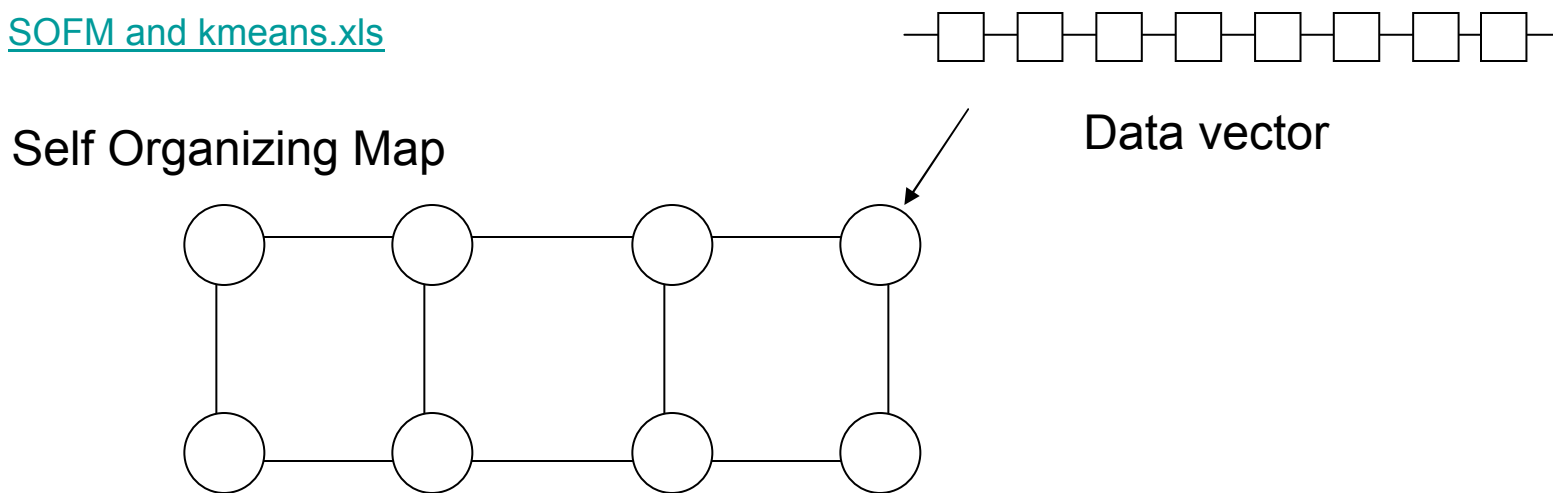
Artificial Intelligence

Artificial Neural Networks – Kohonen Neural Network

This type of network is also known as a self organizing map. It is trained using unsupervised learning.

Example cluster analysis:

See [SOFM and kmeans.xls](#)



Each node on the map has a vector associated with it. Input vectors are assigned to the node with the smallest Euclidean distance. The network learns by making its vectors move towards the nearest data clusters. When a node moves it pulls on its neighbors. The strength of the pull on neighboring nodes is inversely proportional to distance. The strength of attraction also decreases with time. This type of network is used for cluster analysis and data mining that tries to discover meaningful correlations and display them in a way that is easy to visualize.

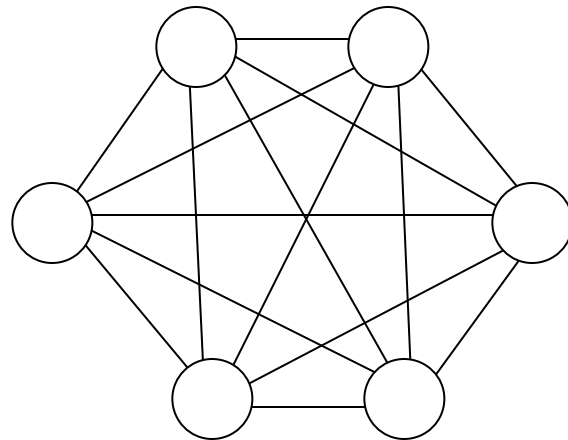
Artificial Intelligence

Artificial Neural Networks – Hopfield Neural Network

A Hopfield neural network is fully connected, every neuron is connected to every other neuron, besides itself. This type of network auto-associates. When presented with a pattern it iterates until it reaches a stable state. Recognition is achieved when an input pattern returns one of the patterns the network was trained for.

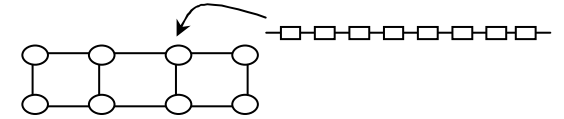
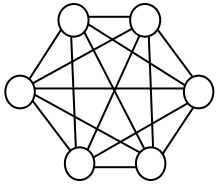
Example pattern recognition:

See [HNN pattern recognition.xls](#)

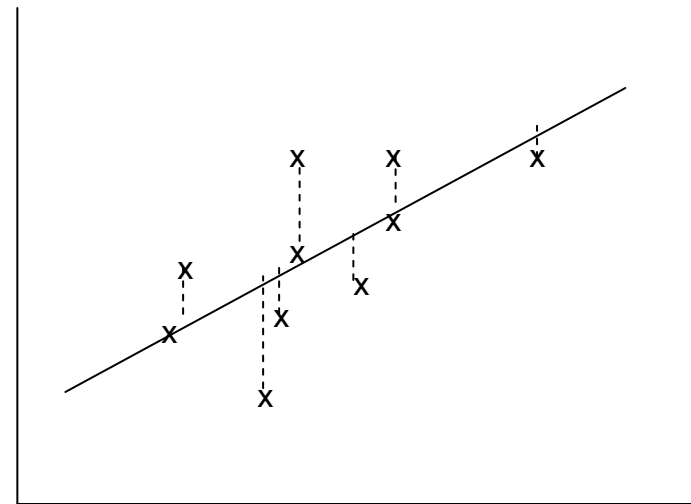
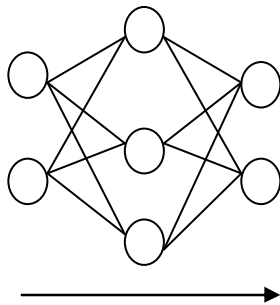


Artificial Intelligence

Artificial Neural Networks



Artificial neural networks have a wide variety of applications to power system operation and planning. These include, short, medium and long term load forecasting, online DGA monitoring and transformer fault classification, component failure rate predictions, control systems and many others. They are especially useful as black box models for situations where there is very little insight into the nature of the problem.



Questions??