Reliability Analysis of Water Distribution Networks Using Minimum Cut Set Approach

(Collaborative project funded by Qatar Foundation)

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Water Distribution Networks

Introduction

Background

Model Development

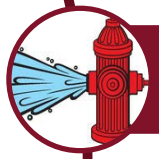
Model Implementation

Conclusion

Water Distribution Network (WDN)

Source

Pipes

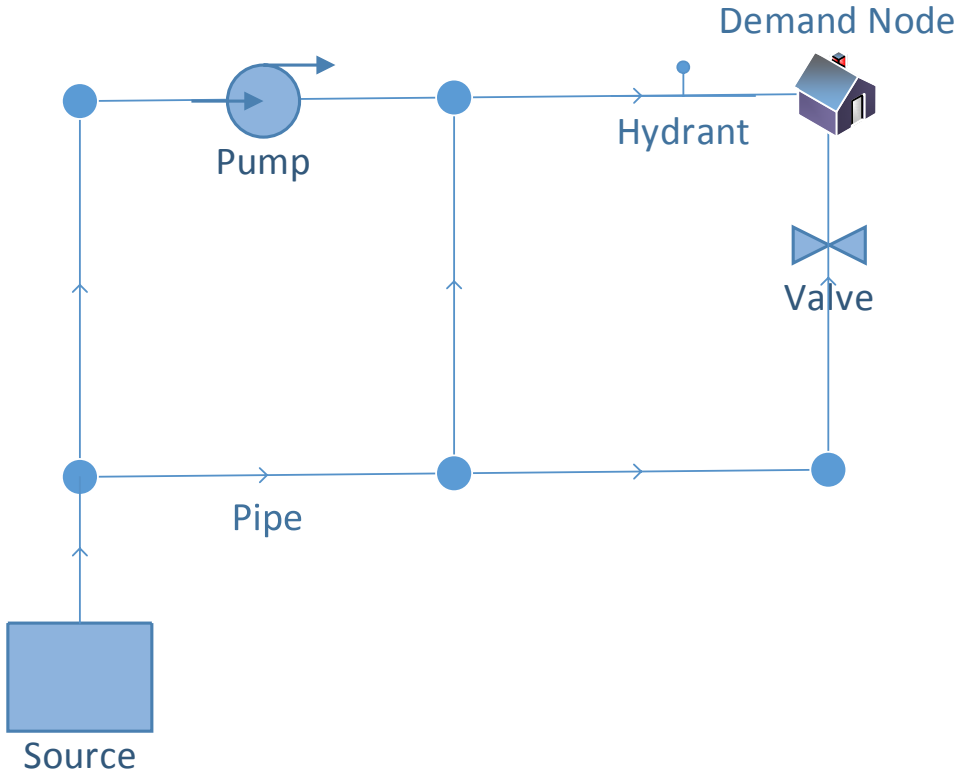


Hydrants

Valves

Pumps

Nodes/ Demand nodes



Water Distribution Networks

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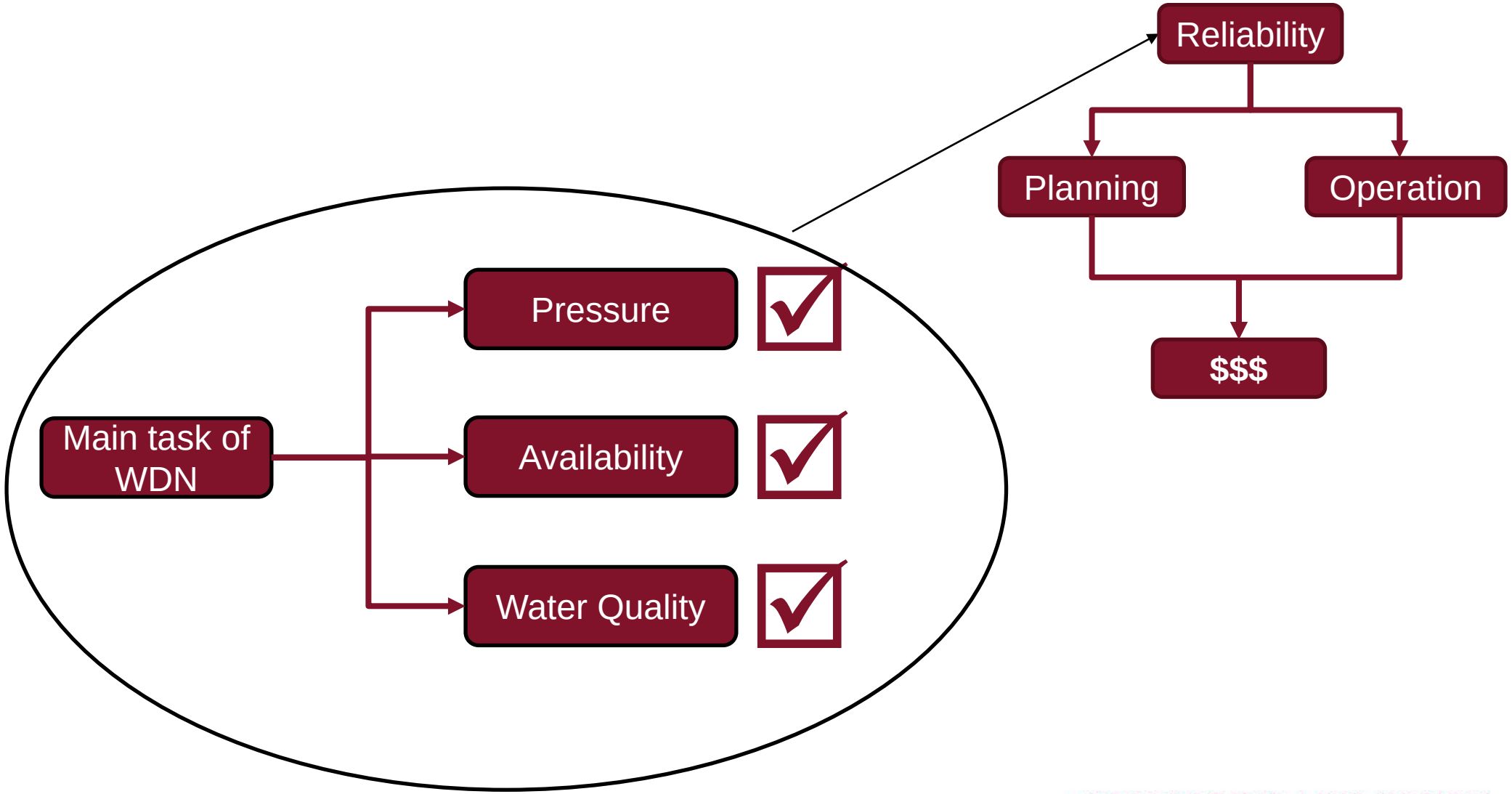
- 719630 km of water pipes in Canada
- 15.4% of linear assets rated “fair” to “very poor”
- 14.4% of non linear assets rated “fair” to “very poor”
- $25.9 billion estimated for rehabilitation

(Canadian Infrastructure Report Card, 2012)

Importance of Reliability



Types of Reliability

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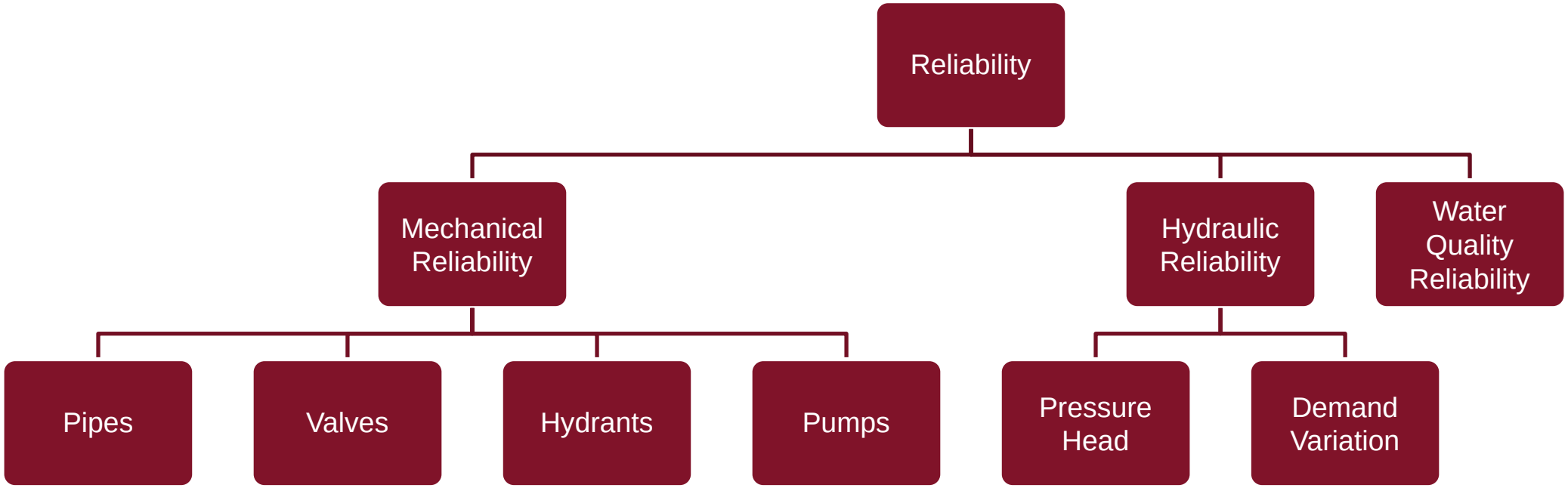

Objectives

- Introduction
- Background
- Model Development
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Mechanical Reliability

Component Reliability
- Pipes
- Valves
- Hydrants

→ **Segment Reliability** — Collection of components

→ **Network Reliability** — Collection of segments

Reliability Assessment Methods

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Connectivity/ Topological

- Shamsi (1990)
- Quimpo and Shamsi (1991)
- Ostfeld (2004)
- Yannopoulos and Spiliotis (2013)

Hydraulic

- Xu and Goulter (1999)
- Shinstine et al. (2002)
- Zhuang et al. (2011)

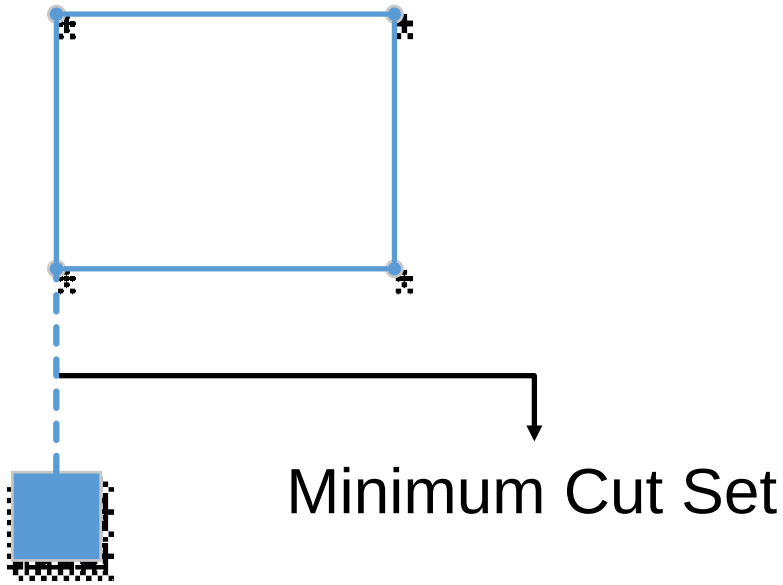
Entropy as a reliability surrogate

- Prasad and Tanyimboh (2008)
- Tanyimboh et al. (2011)
- Gheisi and Naser (2014)

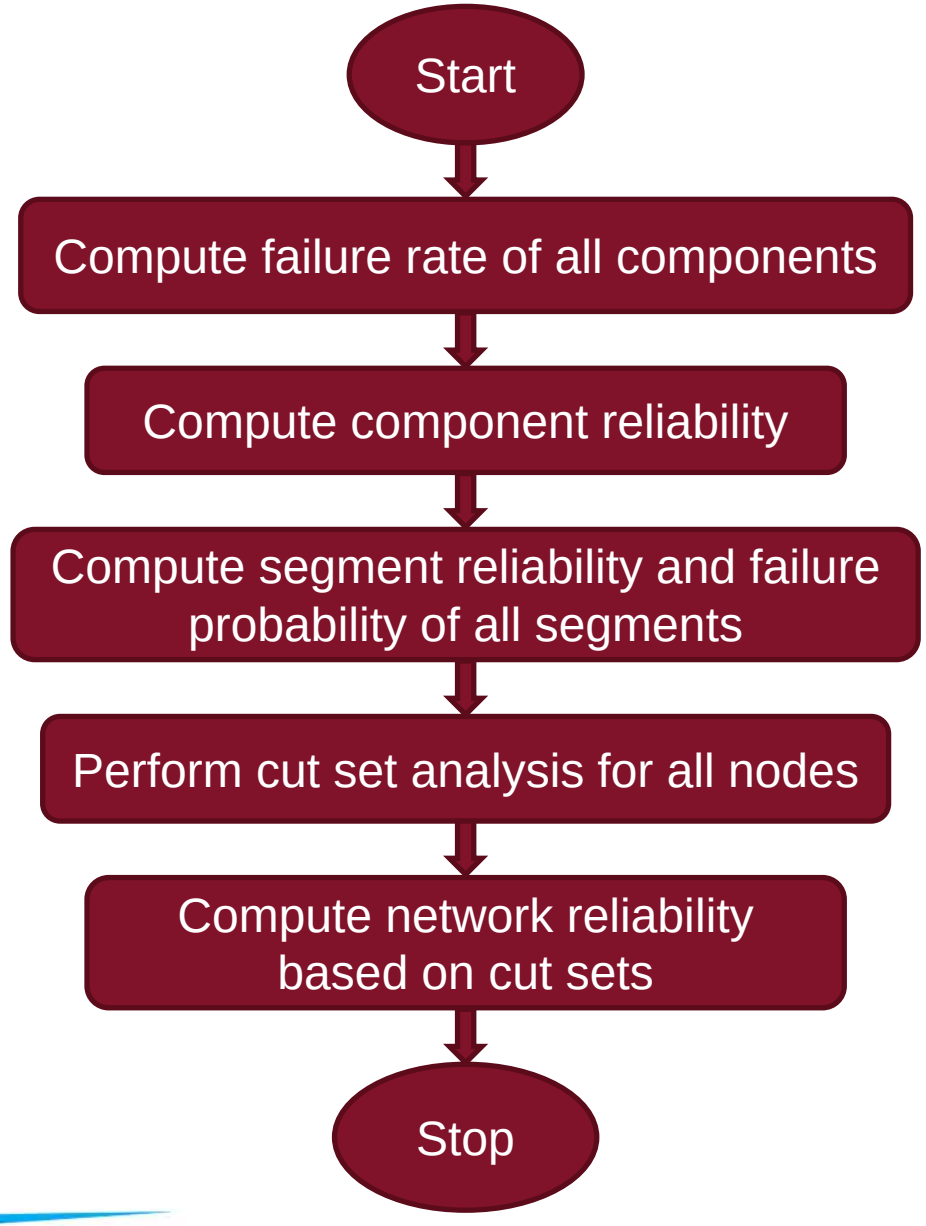
Reliability Assessment Methods

Tung (1985) discussed six techniques

- Conditional Probability Approach
- Tie Set Analysis
- Cut Set Method
- Connection Matrix Method
- Event Tree Technique
- Fault Tree Analysis



Network Reliability Flowchart



Reliability Assessment

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Failure Rate (λt)
$\lambda_{Pipe} = 6 \times 10^{-6} X^2 + 0.0004X + 0.0026$
X is Age of pipe
$\lambda_{Component} = \frac{N_f}{Length\ of\ Segment}$
N_f is Number of failures per year

Reliability Assessment

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Component Reliability

- $R_c = e^{-\lambda t}$
- R_c is Component Reliability

Segment Reliability

- $R_{Seg} = \sum_{i=1}^{n} R_c w_i$
- R_{seg} is Segment Reliability
- $Relative\ Weight\ (w_i) = \dfrac{Weight\ of\ Components}{Sum\ of\ Weights\ of\ all\ Components}$

Component Weights (Salman A., 2011)	
Pipe	38%
Hydrant	31%
Isolation Valve	28%
Control Valve	3%

Identification of Minimum Cut Sets

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Path Matrix

- Find all possible paths from source node to destination node.
- Create path matrix

First order cut sets

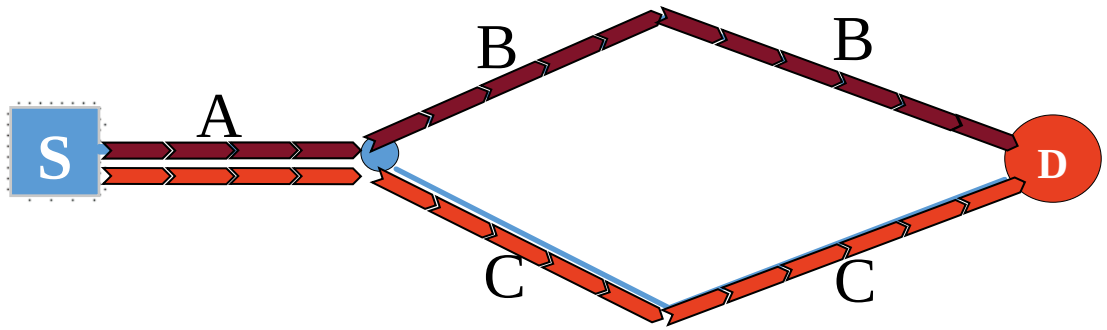
- From the path matrix, check if any column is non zero.
- Any non zero column is a first order cut set.

Second order cut sets

- Combine any two columns representing segments in a path matrix and check if their addition creates a non zero column.
- The resultant non zero column of combination of segments is second order cut set.

Identification of Minimum Cut Sets

Path Matrix



{A-B and A-C}

$$P = \begin{bmatrix} A & B & C \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

Identification of Minimum Cut Sets

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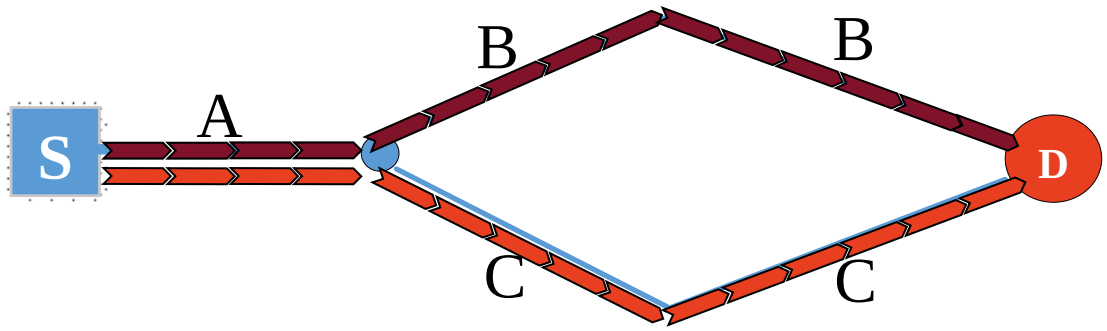
Second order cut sets



{A, B}, {B, C} and {C, A}

$$P = \begin{bmatrix} A+B & B+C & C+A \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

Reliability Assessment

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Network Reliability

Probability of Failure of Segments

$Q = 1 - e^{-\lambda t}$

Identification of Minimum Cut Sets

Path Matrix

First Order Cut Sets

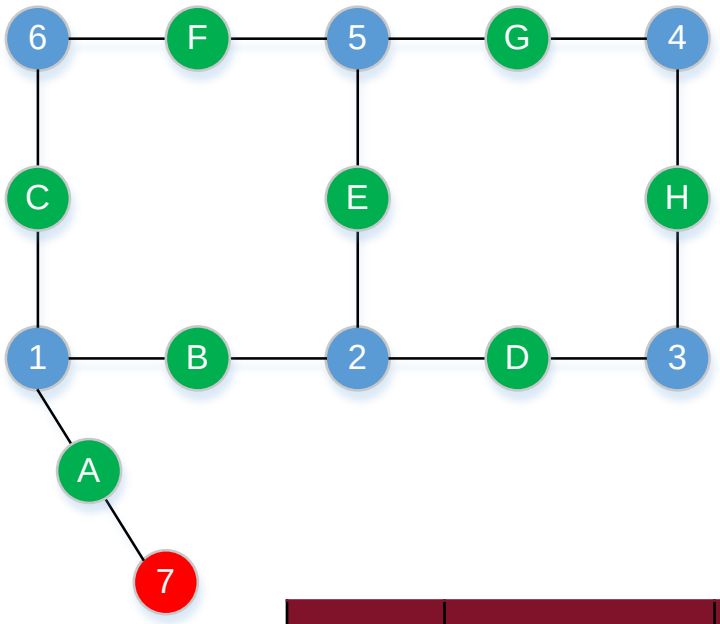
Second Order Cut Sets

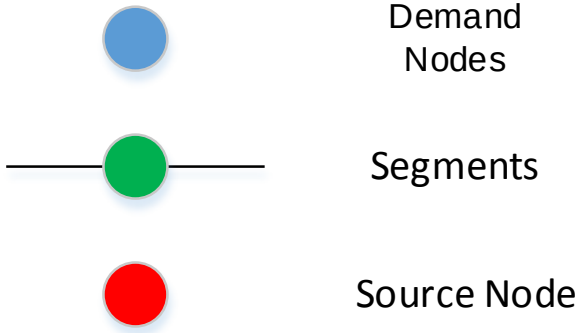
Mechanical Reliability based on Minimum Cut Sets

$Q(MC_i) = \prod_{j=1}^{n} Q_j$

$R_N = 1 - \sum_{i=1}^{M} Q(MC_i)$

Hypothetical Network





Seg.	Comp.	No. of Failures	Age X(yrs)	Seg. length(m)
A	I.Valve 1	5	N.A	400
	Pipe	3	8.4	
	I.Valve 2	5	N.A	

Results

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Seg.	Comp.	No. of Failures	Age X(yrs)	Seg. length(m)	Failure rate (λt) (Breaks/m)	Comp. reliability R_c	Weight	Relative weight w_i	Seg. reliability R_{seg}	Probability of failure Q
A	I.Valve 1	5	N.A	400	0.0125	0.9876	0.28	0.2979	0.990	**0.010**
	Pipe	3	8.4		0.0064	0.9936	0.38	0.4043		
	I.Valve 2	5	N.A		0.0125	0.9876	0.28	0.2979		

Results

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Segment	Seg. Reliability	Probability of failure $Q = 1 - R_{seg}$
Seg A.	0.989575987	0.010424013
Seg B.	0.986965692	0.013034308
Seg C.	0.994601779	0.005398221
Seg D.	0.988621382	0.011378618
Seg E.	0.993797096	0.006202904
Seg F.	0.985742613	0.014257387
Seg G.	0.982337837	0.017662163
Seg H.	0.981748611	0.018251389

Order of cut sets	List of cut sets
1	{A}
2	{B, C}, {B, F}, {D, G}, {D, H}, {C, F} and {G, H}
3	{B, D, E}, {B, E, G}, {B, E, H}, {C, D, E}, {C, E, H}, {C, F, G}, {D, E, F}, {E, F, H}, and {E, F, G}

$$R_N = 1 - Q_N = 1 - \sum_{i=1}^{M} Q(MC_i)$$

$$Q_N = Q(MC_1) + Q(MC_2) + Q(MC_3) = 0.0107$$

$$\therefore R_N = 1 - Q_N = \mathbf{0.9893}$$

Conclusion

- Requires very detailed historic break data of all the components including pipes
- Failure rate of pipes is based only on age
  - More parameters leads to more realistic predictions
  - Research should be extended to predict the failure rate of components other than pipe
- Assessed reliability assuming exponential distribution
  - More effective model is needed to assess reliability

Thank you

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