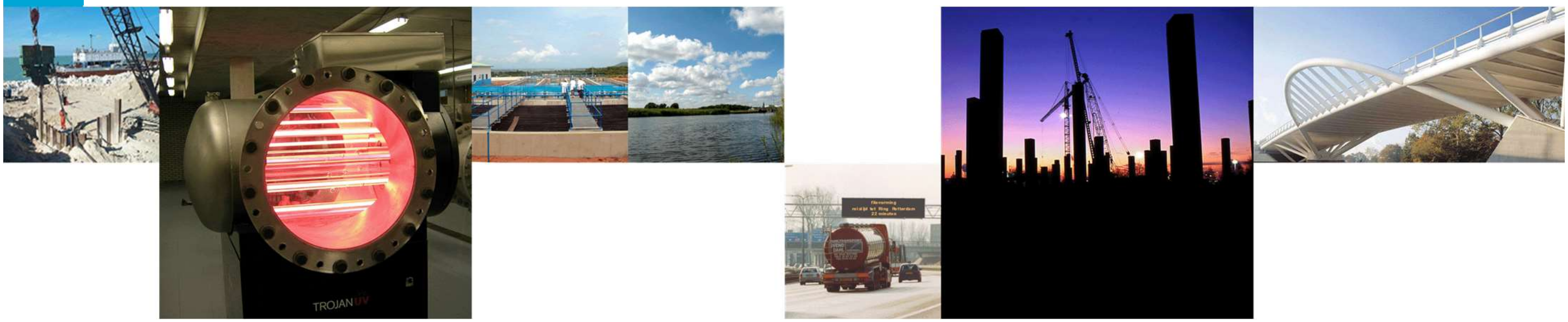
Risk based design of hydraulic structures
Fault Tree Workshop



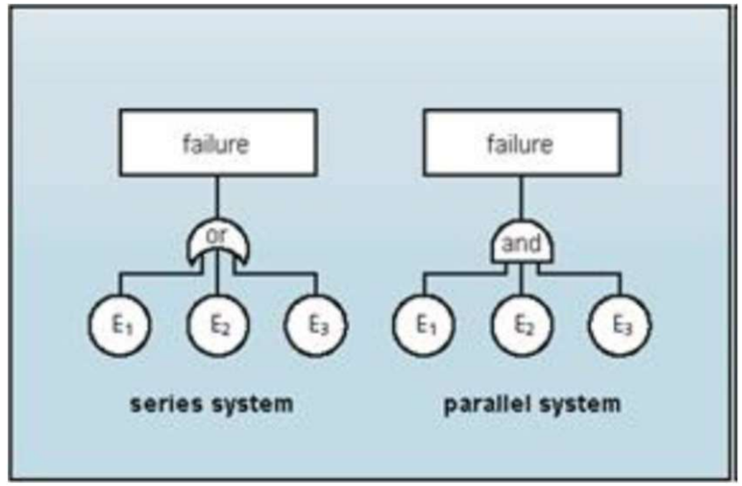
In cooperation with

Aalberts, Verheijen, Le
Lanzafame, Jonkman, Breedveld, and Co.

System reliability – Fault trees

- Graphical method for evaluating system failure probability

- Lecture notes Chapter 9



$P_{f,system}$ (with n components):

system	gate	operator	components		
			mutually exclusive	independent	fully dependent
series	OR	$\bigcup$	$\sum_{i=1}^{n} P_i$ (upper bound)	$1-\prod_{i=1}^{n}(1-P_i)$	$\max\{P_i\}$ (lower bound)
parallel	AND	$\bigcap$	0 (lower bound)	$\prod_{i=1}^{n} P_i$	$\min\{P_i\}$ (upper bound)

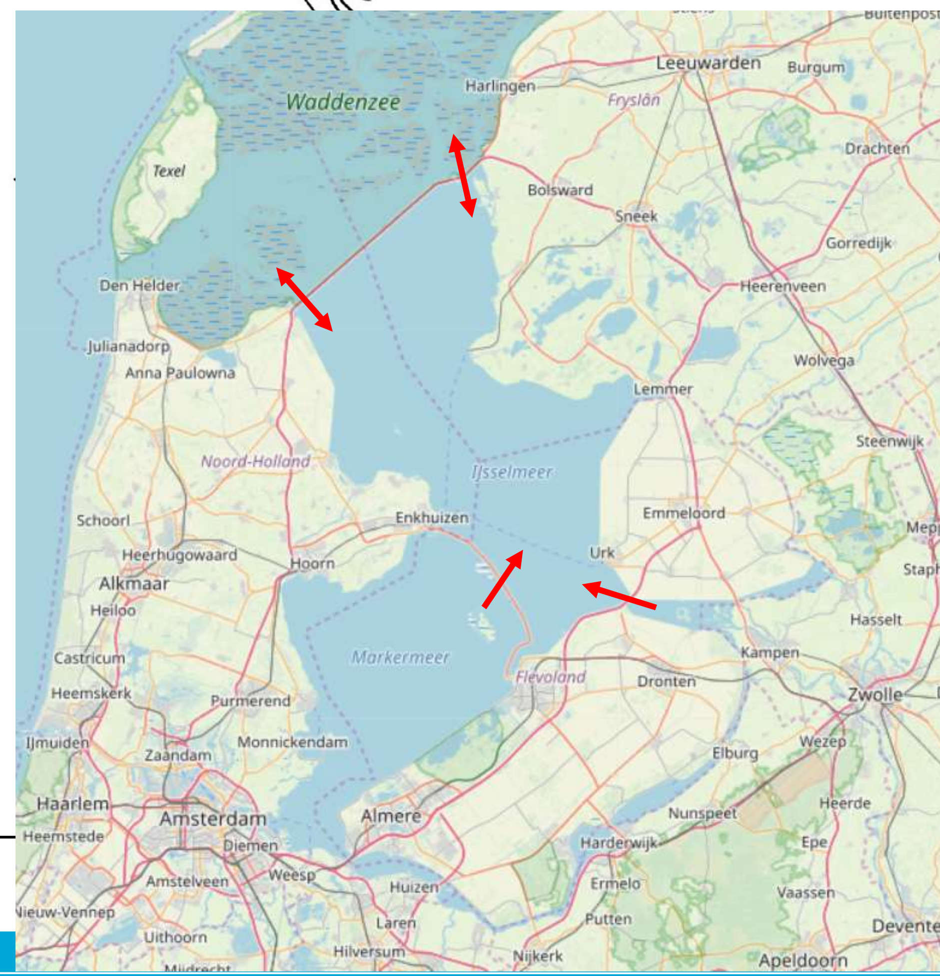
Overview of fault tree workshop

- Introduction to case study (this video)
- Case study: work on assignment in groups of 4-5
- Presentation by groups and discussion
- Wrap-up and conclusions

Documents:

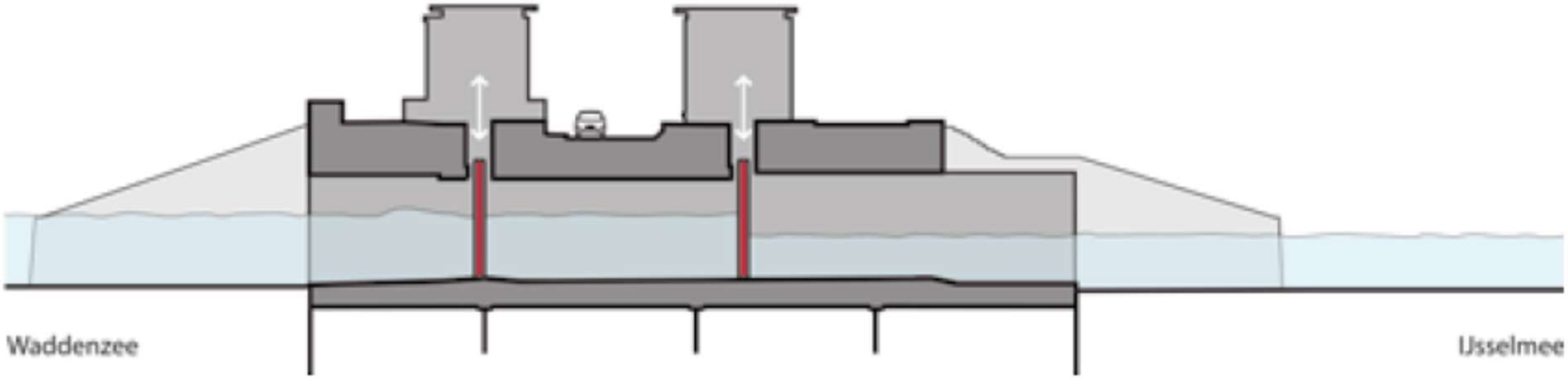
- Fault tree workshop introduction (these slides)
- Fault tree workshop handout
- Calculation template (online Google sheet)
- Fault tree diagram template (optional, also online Google sheet)

Afsluitdijk and IJsselmeer



Afsluitdijk inlet/outlet culverts

Culverts close to limit IJsselmeer level



Normal operation:

- prevent water from Waddenzee entering IJsselmeer

Failure:

- Culvert does not close when asked, *and*
- Water flow into IJsselmeer exceeds critical amount

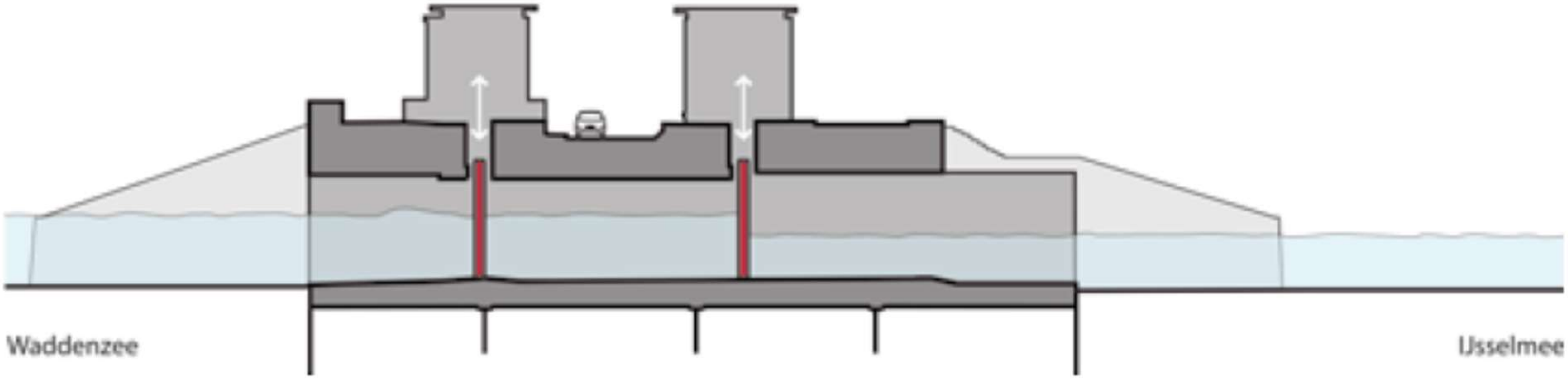
$$P_{f,system} = P(nc) \cdot P(Q > Q_{\max} | nc)$$

Derivation of norm for the Afsluitdijk

- Maximum allowable failure probability = 1/3000 = 0.00033
- Non-closure failure mechanism portion = 0.04
- Norm =
  0.04 * 0.0033 = 1.3e-5

$$P_{f,system} < 1.3e^{-5}$$

System failure (critical hydraulic conditions)

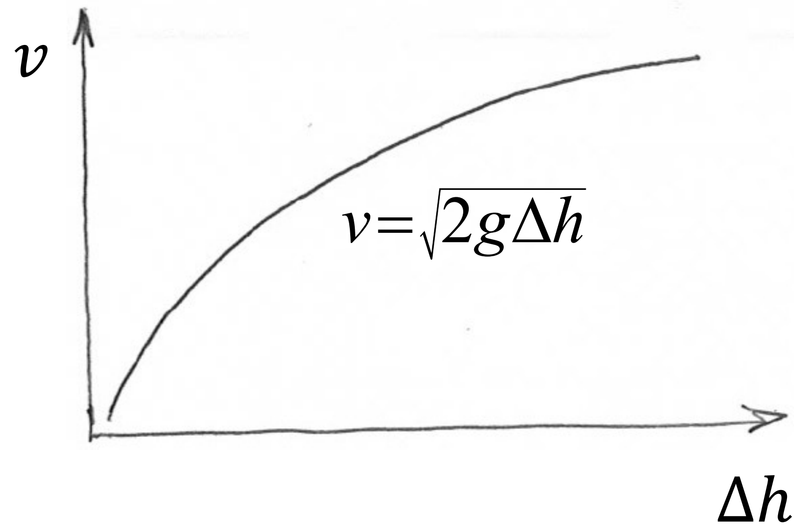


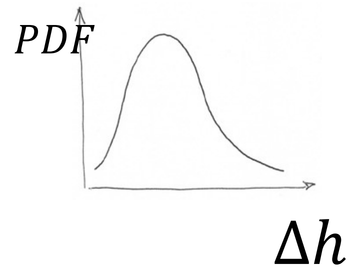
Governed by:

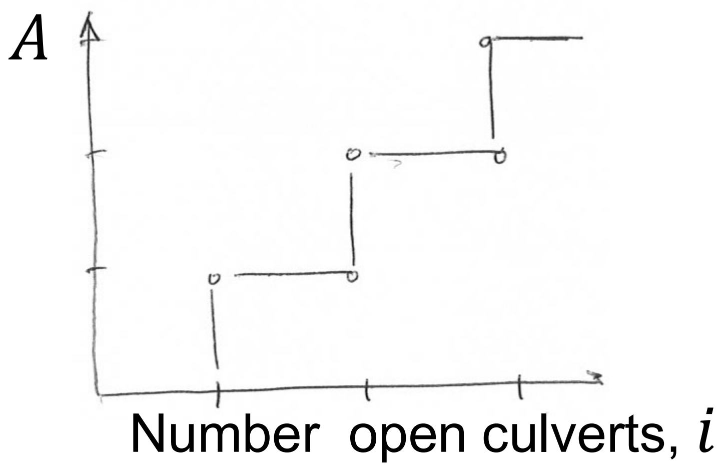
1. Critical hydraulic conditions in Ijsselmeer and Waddenzee
2. Number of open culverts, *i* (non-closure, *nc*)

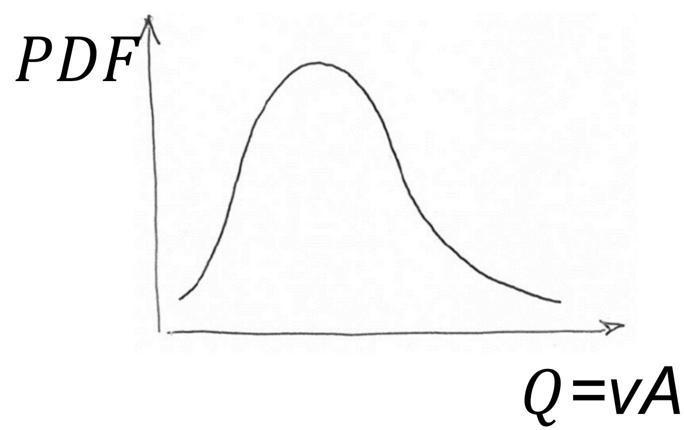
$$P_{f,system} = P(nc) \cdot P(Q > Q_{\max} | nc)$$

1. Critical hydraulic conditions Q_{max}









1. Critical hydraulic conditions Q_{max}

- 3 cases of non-closure
- Sum all scenarios (OR case)

Number of open culverts, *i*	$P(Q>Q_{max})$
1	6.39 E-3
2	3.27 E-2
3	1.89 E-1

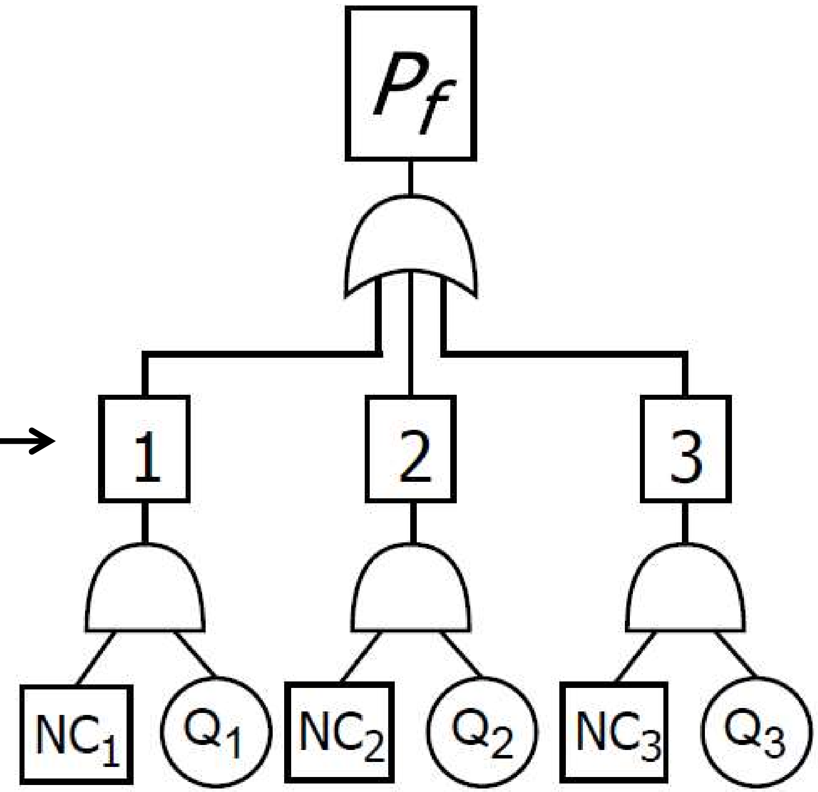
$$P_{f,system} = \sum_{i=1,2,3} P_{nc,i} \cdot P(Q<Q_{max,i}) < 1.3e^{-5}$$

1. Critical hydraulic conditions Q_{max}

Hint: top level of fault tree

Flooding through culverts (3 cases) →

Non-closure of 1, 2 or 3 culverts →



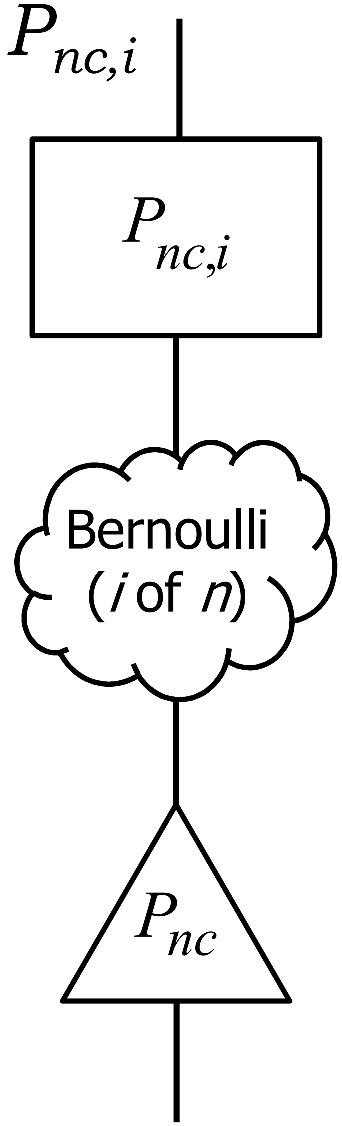
$$P_{f,system} = \sum_{i=1,2,3} P_{nc,i} \cdot P(Q < Q_{\max,i}) < 1.3e^{-5}$$

Probability of 1, 2 or 3 non-closures, $P_{nc,i}$

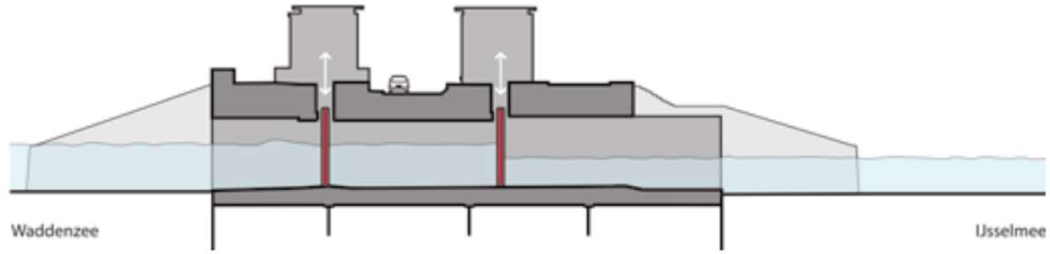
- All 3 culverts are always asked to close together (n=3)
- Bernoulli: probability of i failures in n trials
- Need probability of single culvert non-closure, P_{nc}

$$P_i = \frac{n!}{i!(n-i)!} * p^i * (1-p)^{(n-i)}$$

$$P_{f,system} = \sum_{i=1,2,3} P_{nc,i} \cdot P(Q < Q_{\max,i}) < 1.3e^{-5}$$



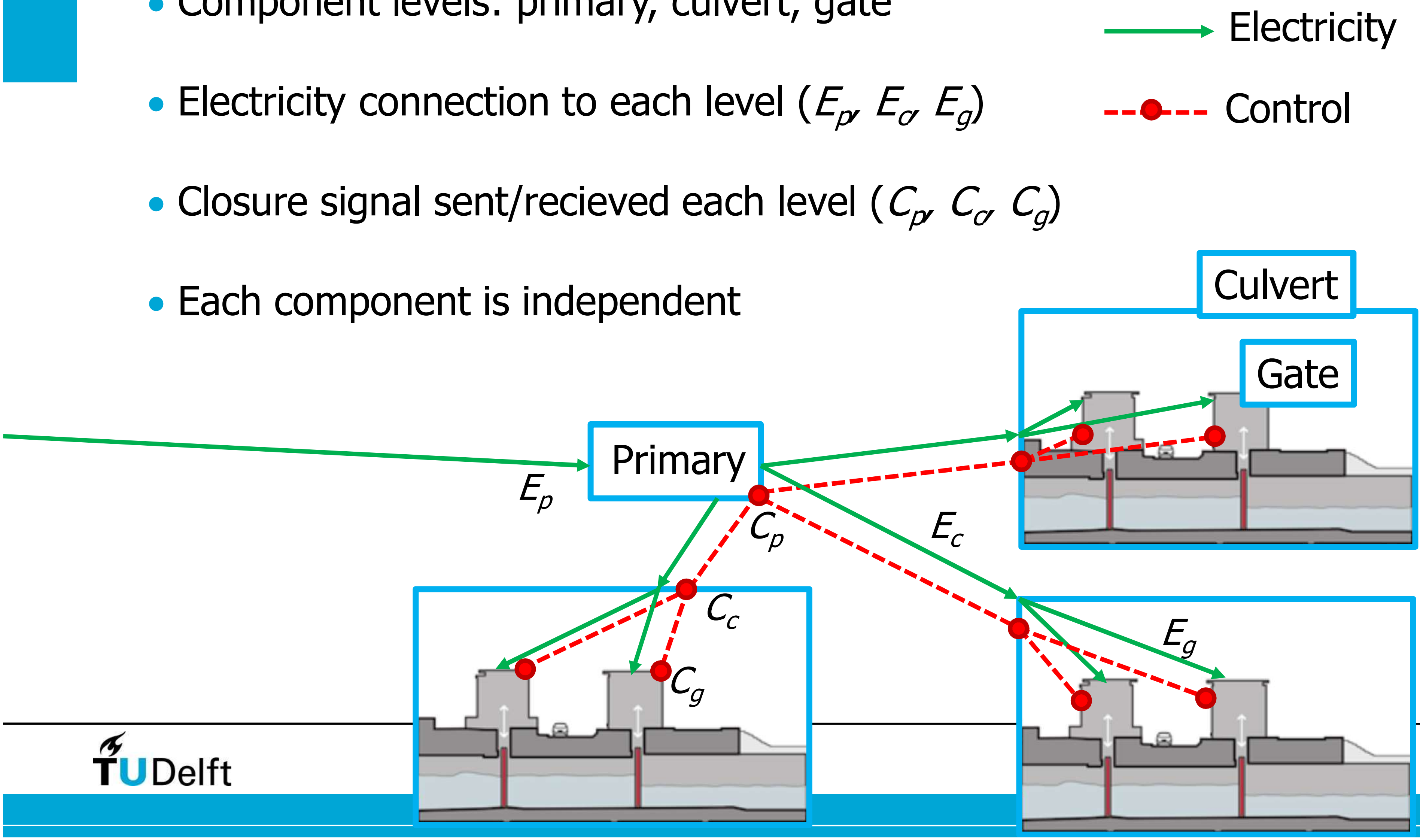
Single culvert non-closure, P_{nc}



- System contains: 3 culverts, each with 2 gates
- Failure modes:
  - Gates can jam
  - Culvert fails due to a construction problem
  - Electrical and control system between components
  - Human error (causes all 3 culverts to stay open)

Electricity and control system

- Component levels: primary, culvert, gate
- Electricity connection to each level (E_p, E_c, E_g)
- Closure signal sent/recieved each level (C_p, C_c, C_g)
- Each component is independent

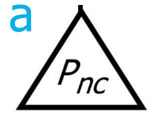


Failure modes and probability for fault tree

Symbol	Component	Consequence	Probability
C_p	Primary control system	All culverts open	3.5E-05
E_p	Primary electrical supply	All culverts open	7.3E-05
C_c	Culvert control system	Culvert open	3.8E-04
E_c	Culvert electrical supply	Culvert open	9.6E-06
C_g	Gate control system	Gate open	8.7E-06
E_g	Gate electrical supply	Gate open	1.5E-04
CC	Construction failure of culvert	Culvert open	2.0E-09
HE	Human error	All culverts open	2.5E-06
J_g	Jammed gate	Gate open	2.4E-03

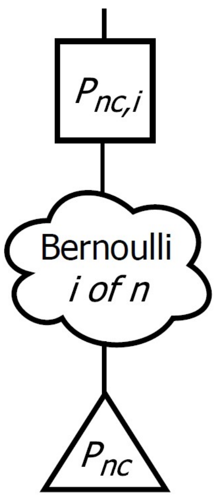
Assignment – 1. System failure

a



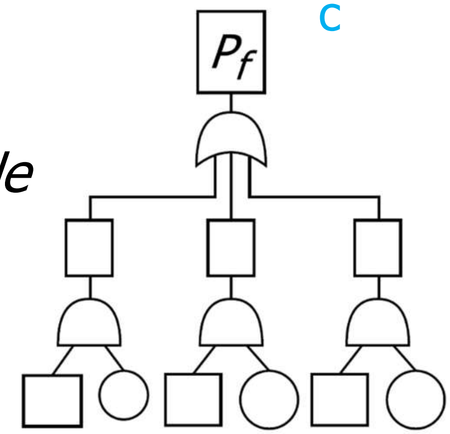
1. Find probability of culvert system failure $P_{f,system}$
   a. Fault tree for single culvert non-closure, P_{nc}
   b. Evaluate $P_{nc,i}$ for i non-closure cases using Bernoulli
   c. Fault tree for $P_{f,system}$ that includes 3 non-closure cases

b



Remember to use all events from the table

c



Assignment – 2. Design optimization (if time)

What part of the fault tree influences system failure the most?

- Get as close to norm as possible (but still below) while minimizing the expected projects costs

- "Investment points" = proxy for costs

Design option	Points
At gate level	1
At culvert level	3
At central level	5
Extra gate construction	5
Removing second gate	-5

Rules for optimization:

- Don't introduce new components
- Add or remove redundancy within the existing system
- If number of culverts changes, $P_{nc,i}$ will also change

Assignment

1. Find probability of culvert system failure $P_{f,system}$

2. Optimize design (if time allows)

Form groups of 4-5, prepare fault tree and results for discussion

Documents:

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