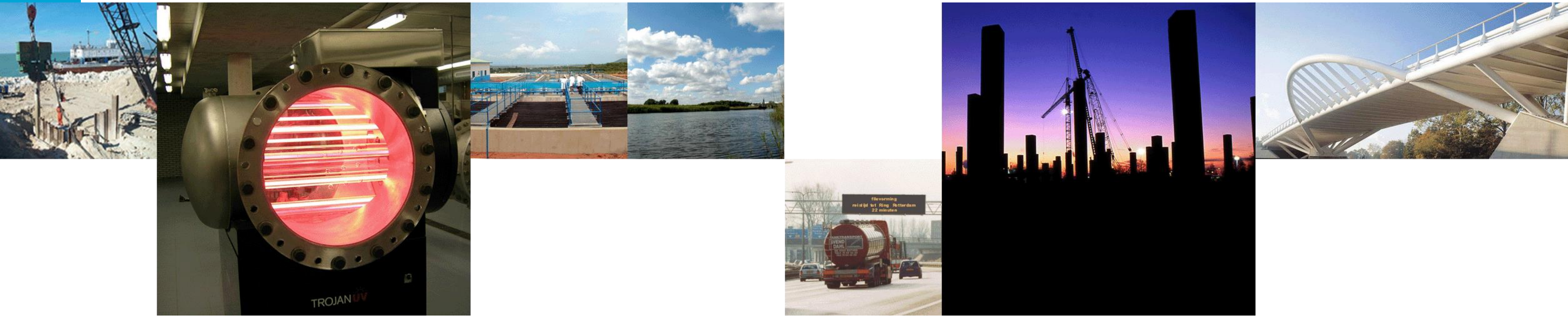
# Risk based design of hydraulic structures

## *Fault Tree Workshop*



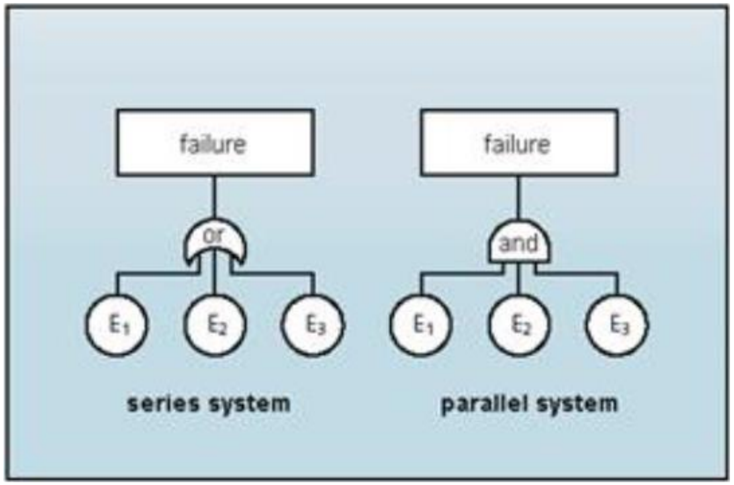
In cooperation with

Witteveen + Bos

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

# System reliability – Fault trees

- Graphical method for evaluating system failure probability
- CIE4130 Lecture notes Chapter 9



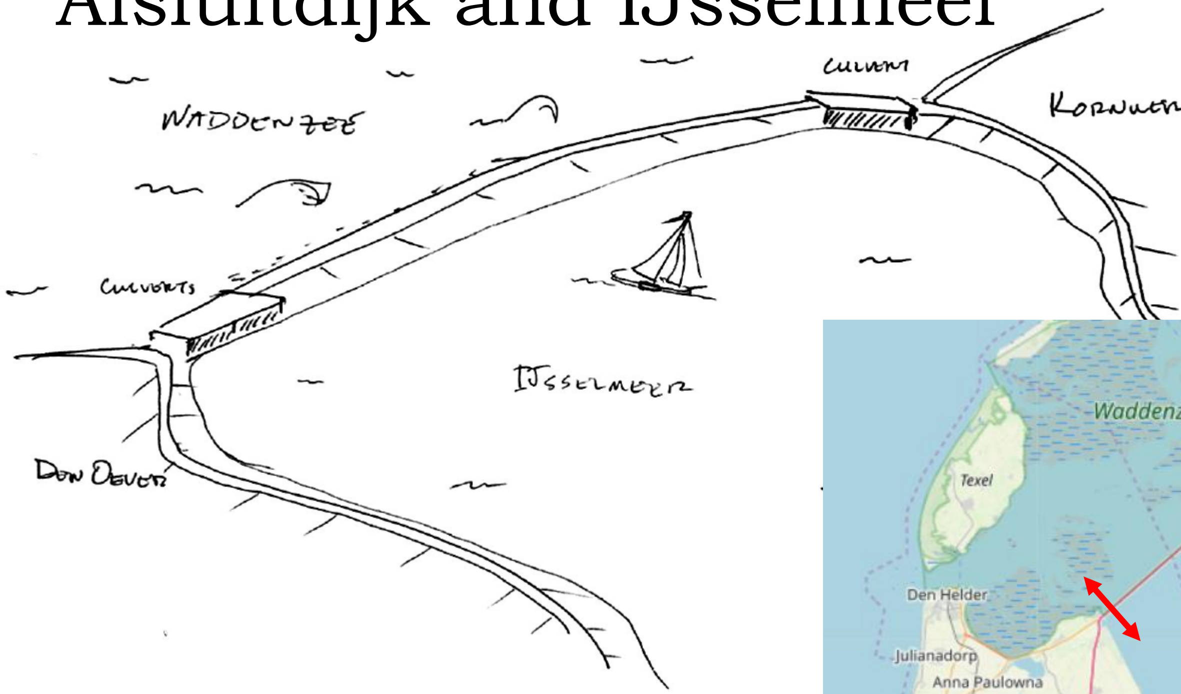

$P_{f,system}$ (with $n$ components):

| 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
- Work on assignment in groups of 4-5
- Presentation by groups and discussion
- Wrap-up and conclusions

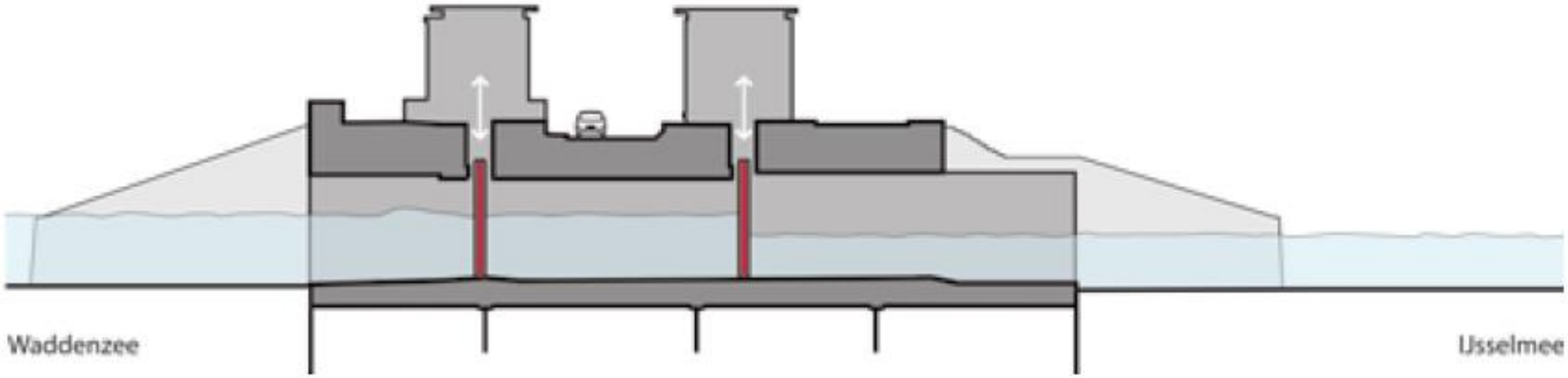
# Afsluitdijk and IJsselmeer





# 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

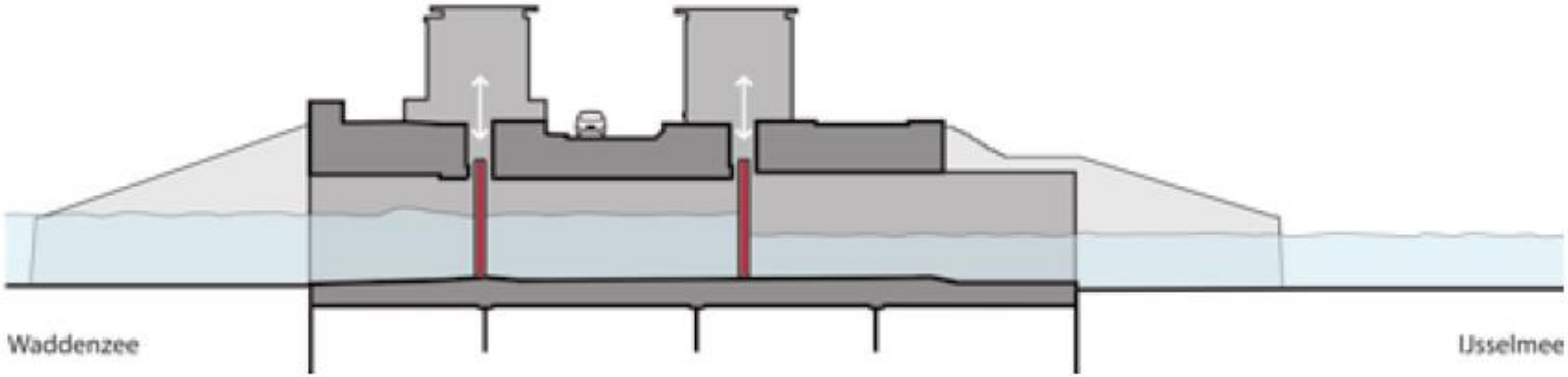
$$P_{f,system} = P(nc) \cdot P(Q > Q_{max} | nc)$$

# 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)



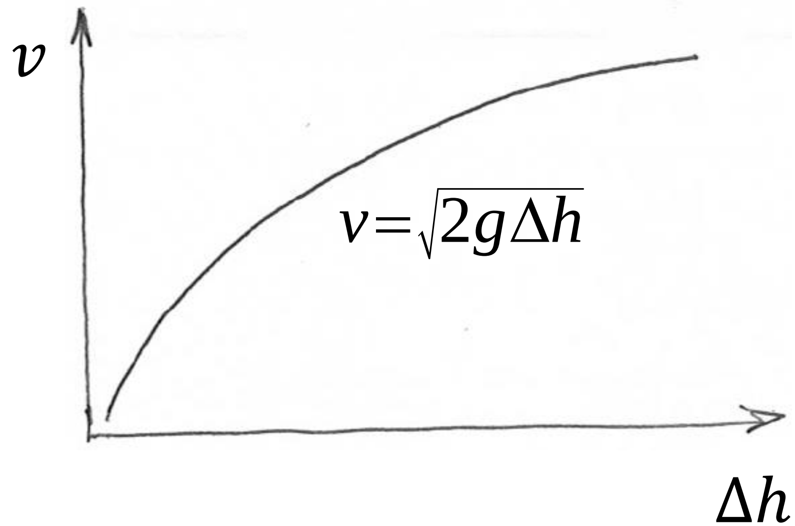

Governed by:

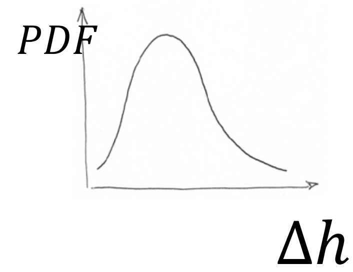
1. Critical hydraulic conditions in Ijsselmeer and Waddenzee

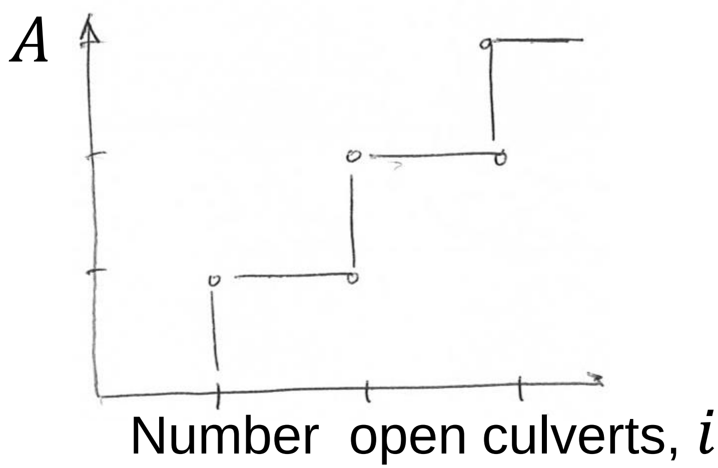
2. Number of open culverts, *i* (non-closure, *nc*)

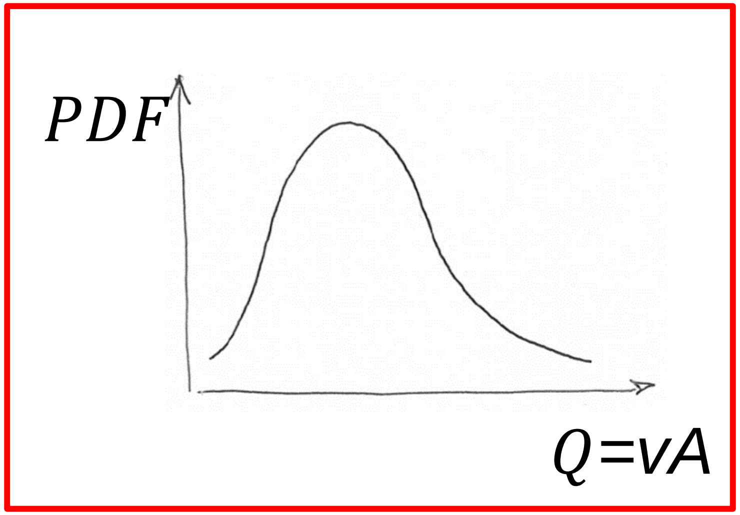
[illegible]

# 1. Critical hydraulic conditions



# 1. Critical hydraulic conditions

- 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 |

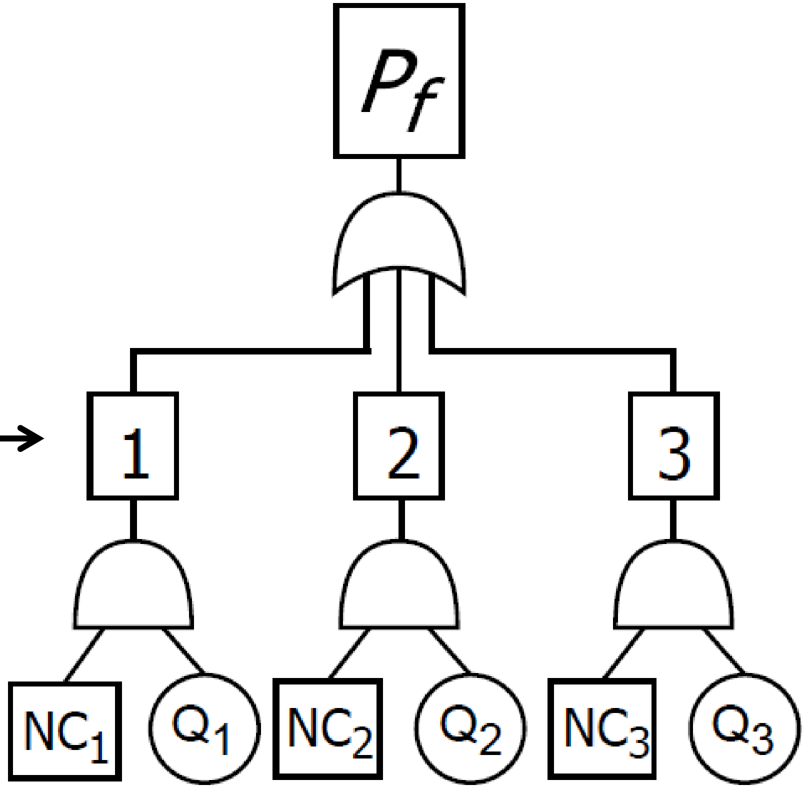
$$P_{f,system} = \sum_{i=1,2,3} P_{nc,i} \cdot P(Q < Q_{\max,i}) < 1.3e^{-5}$$

# 1. Critical hydraulic conditions

Hint: top level of fault tree

Flooding through culverts (3 cases)

Non-closure of 1, 2 or 3 culverts

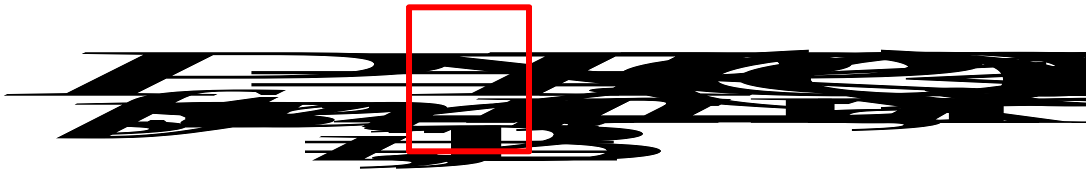


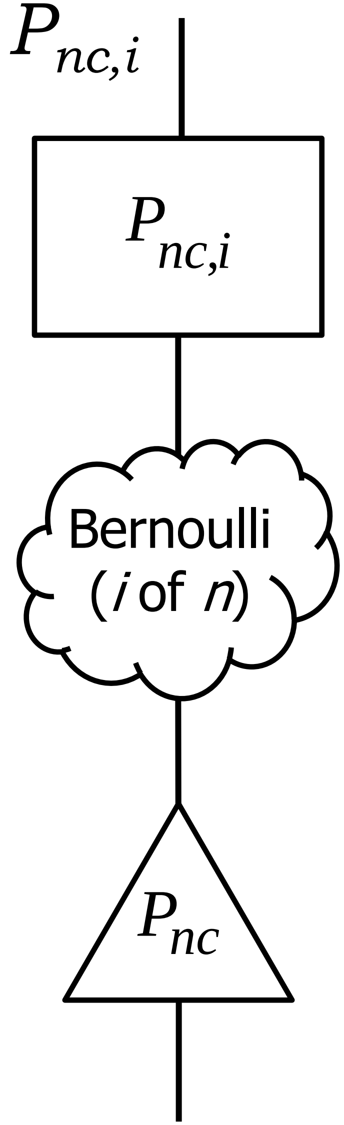

$$P_{f,system} = \sum_{i=1,2,3} P_{nc,i} \cdot P(Q < Q_{\max,i}) < 1.3e^{-5}$$

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

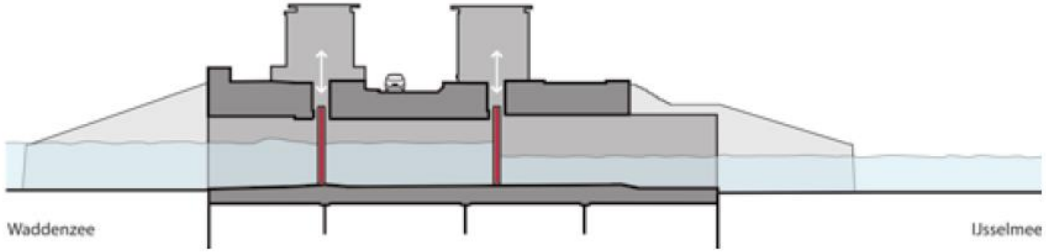
- All 3 culverts are always asked to close together ($n$=3)
- Bernoulli: probability of $i$ failures in $n$ trials
- Need probability of single culvert non-closure, $P_{nc}$

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





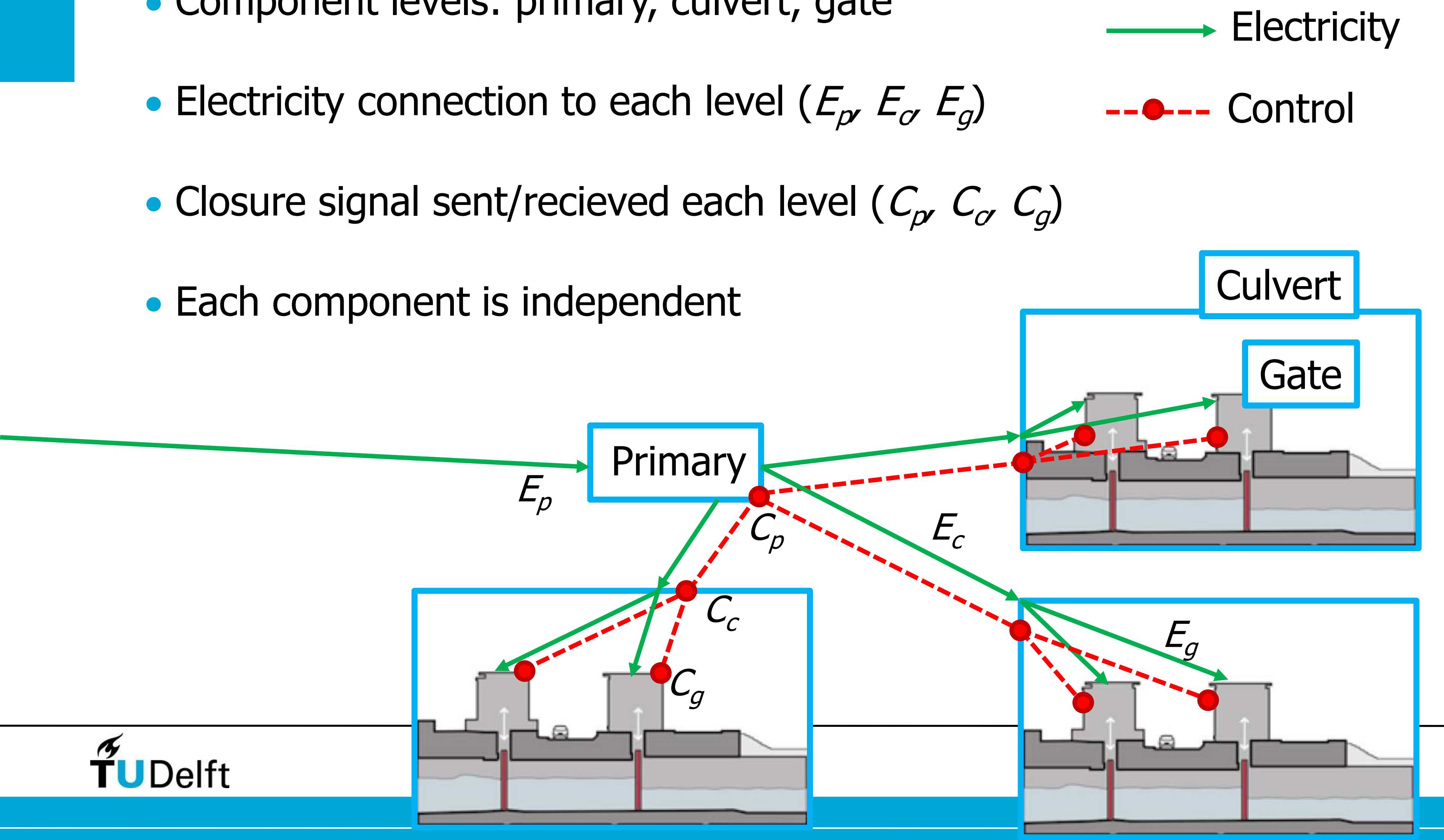
# Single culvert non-closure, $P_{nc}$




- 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

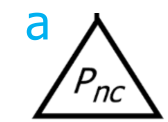
- Component levels: primary, culvert, gate
- Electricity connection to each level ($E_p$, $E_c$, $E_g$)
- Closure signal sent/recieved each level ($C_p$, $C_c$, $C_g$)
- Each component is independent



# 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 |

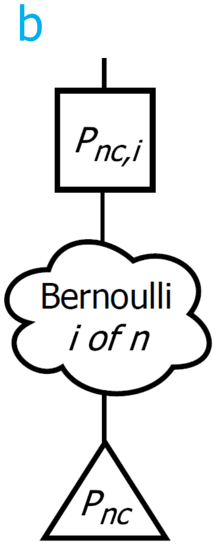
# Assignment – 1. System failure

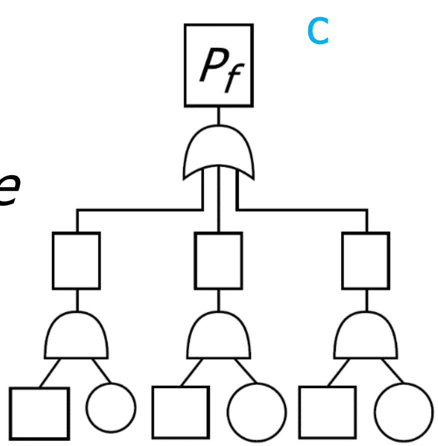



1. Find probability of culvert system failure $P_{f,system}$
   a. Fault tree for single culvert non-closure, $P_{nc}$
   b. Evaluate $P_{nc,i}$ for $i$ non-closure cases using Bernoulli
   c. Fault tree for $P_{f,system}$ that includes 3 non-closure cases

Evaluate: does the system meet the requirement?

*Remember to use all events from the table*



# 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
- Keep the numbers of culvert at 3

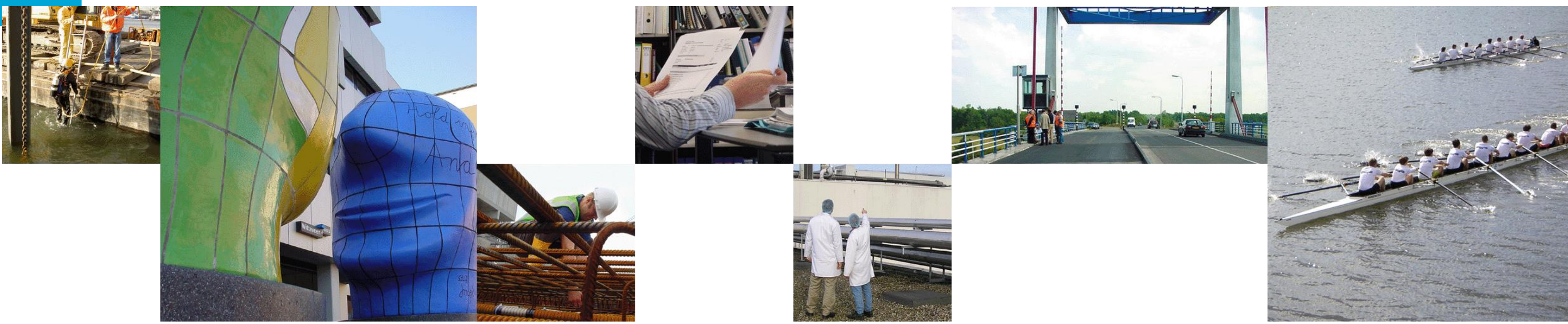
# Assignment

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 (see course website Workshop 4):

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

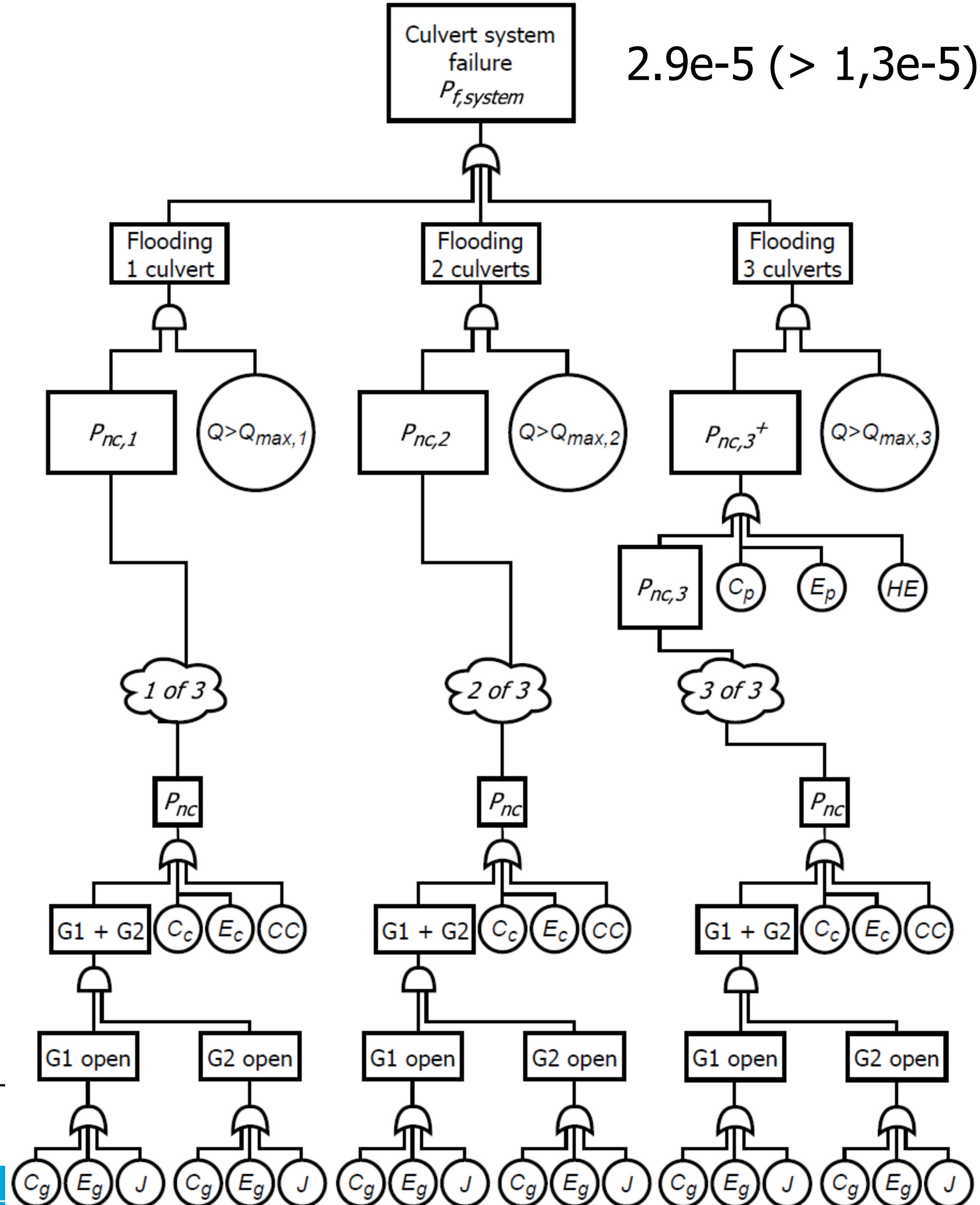


# Case study results

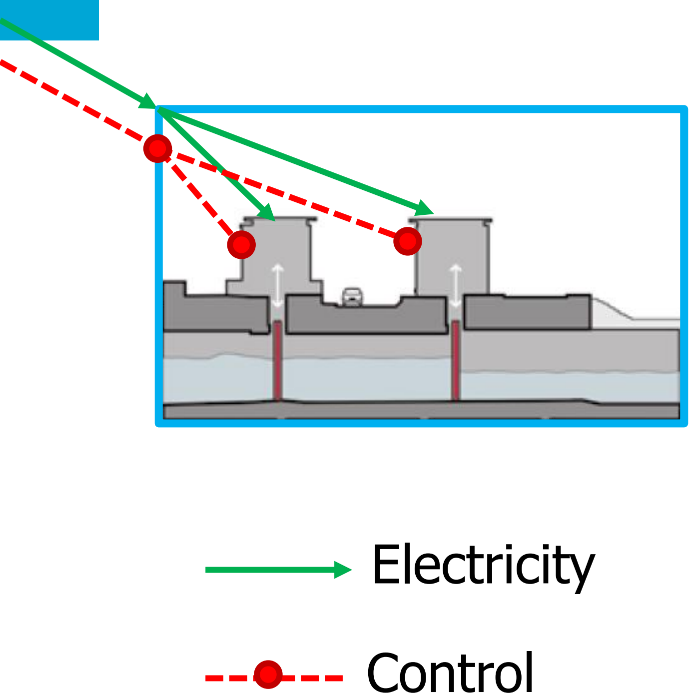
$P_{f,system}$ (with $n$ components):

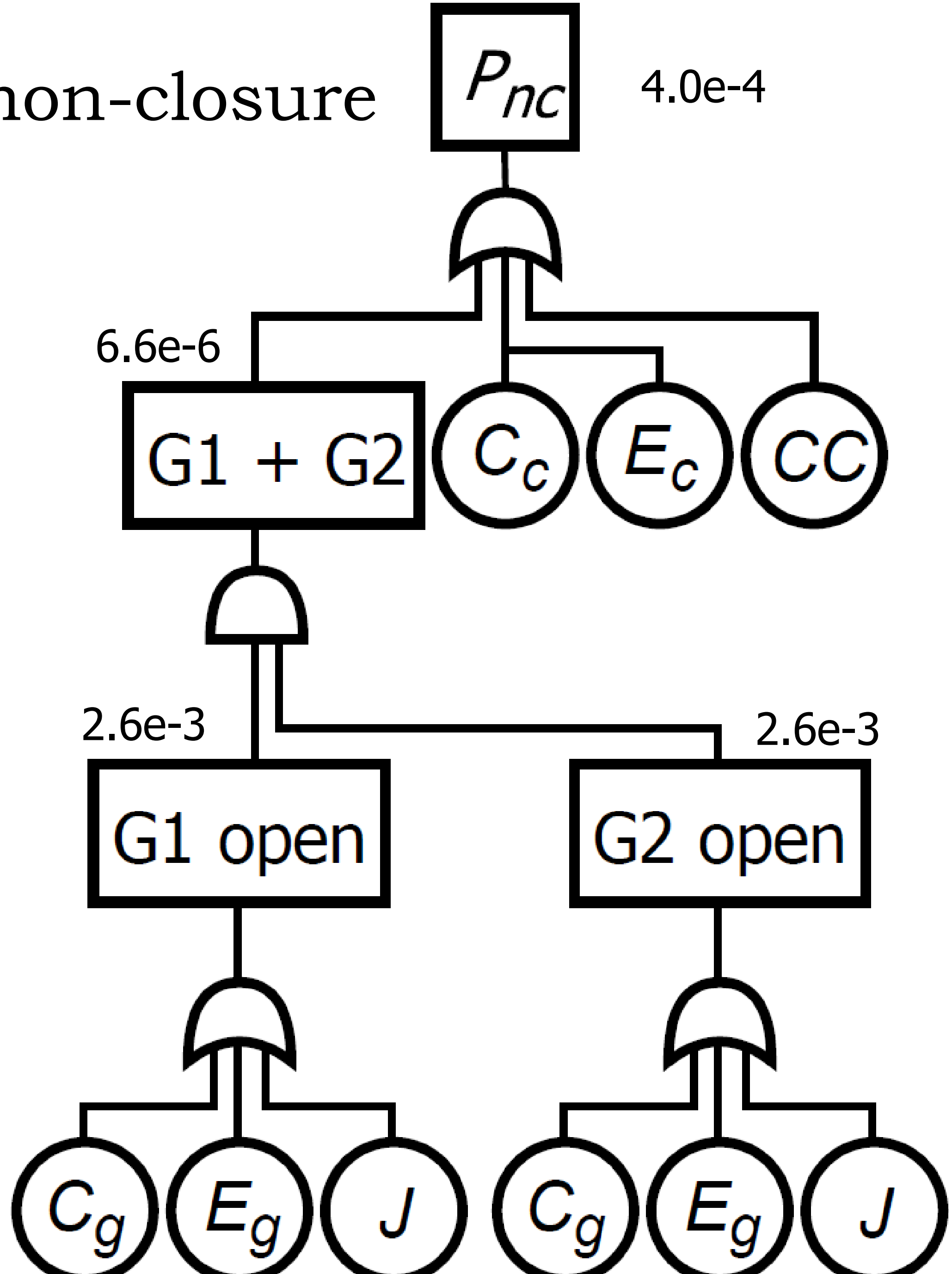
| system | gate | operator | components | | |
|---|---|---|---|---|---|
| | | | mutually exclusive | independent | fully dependent |
| series | OR | $\bigcup$ | $\sum_{i=1}^{n} P_i$ (upper bound) | $1-\prod_{i=1}^{n}(1-P_i)$ | $\max\{P_i\}$ (lower bound) |
| parallel | AND | $\bigcap$ | $0$ (lower bound)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

2.9e-5 (> 1,3e-5)


Culvert system failure
P f,system
Flooding 1 culvert
Flooding 2 culverts
Flooding 3 culverts
P nc,1
Q>Q max,1
P nc,2
Q>Q max,2
P nc,3 +
Q>Q max,3
P nc,3
C p
E p
HE
1 of 3
2 of 3
3 of 3
P nc
G1 + G2
C c
E c
CC
G1 open
G2 open
C g
E g
J

# 1a. Single culvert non-closure

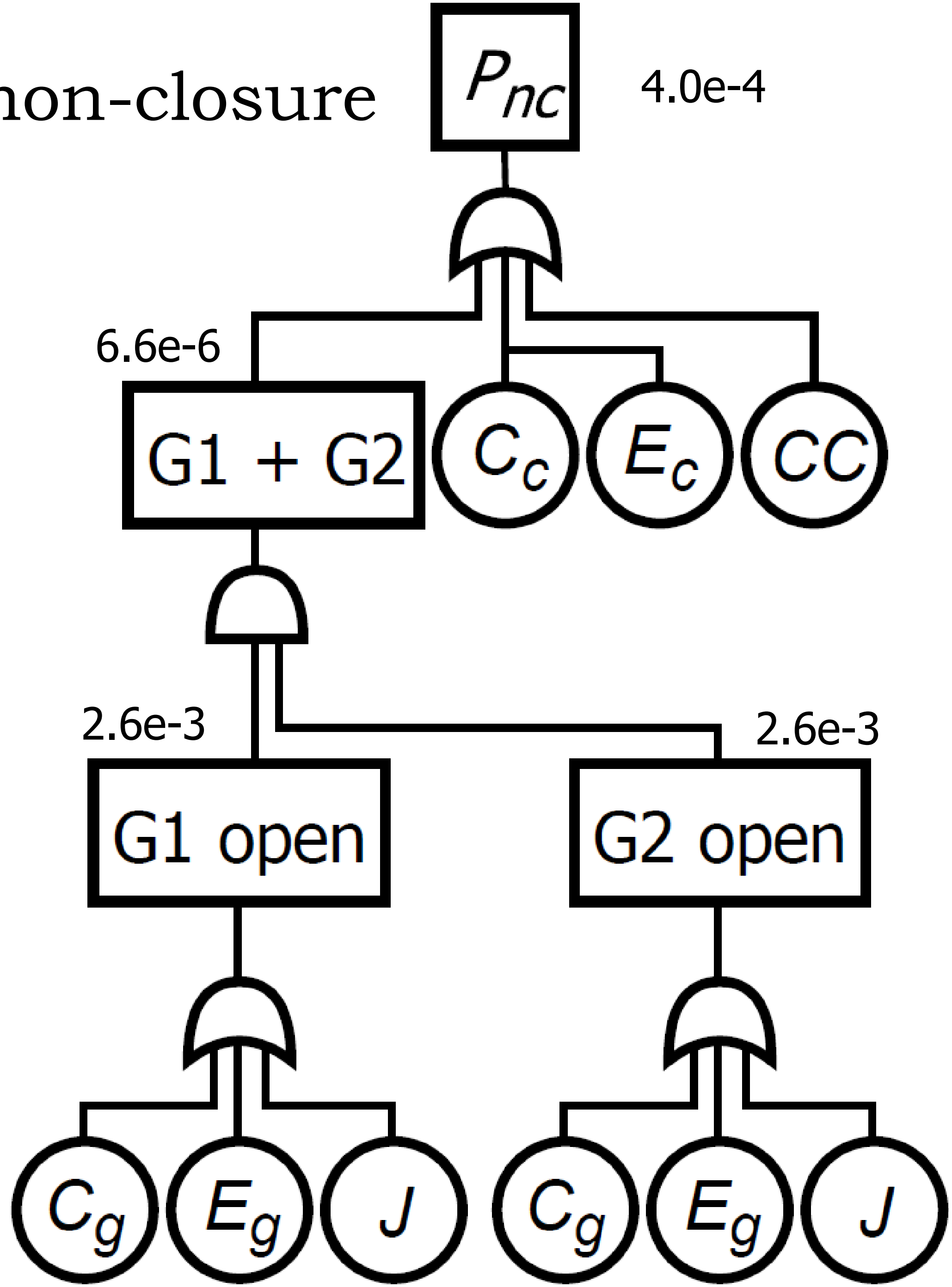


# 1a. Single culvert non-closure

| | |
|---|---|
| $C_c$ | 3.8E-04 |
| $E_c$ | 9.6E-06 |
| $CC$ | 2.0E-09 |

| | |
|---|---|
| $C_g$ | 8.7E-06 |
| $E_g$ | 1.5E-04 |
| $J$ | 2.4E-03 |

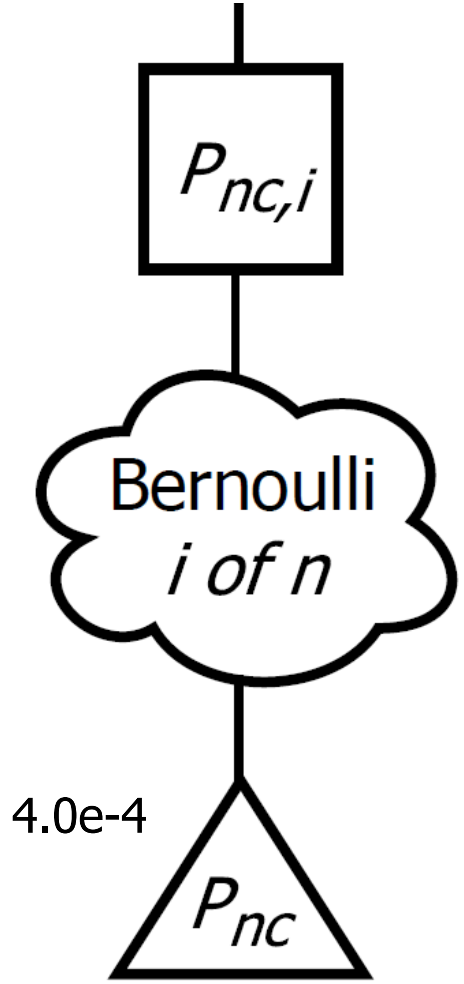


# 1b. Bernoulli

*i* non-closures out of *n* trials

| $i$ | $P_{nc,i}$ |
|---|---|
| 1 | 1.2E-03 |
| 2 | 4.7E-07 |
| 3 | 6.2E-11 |

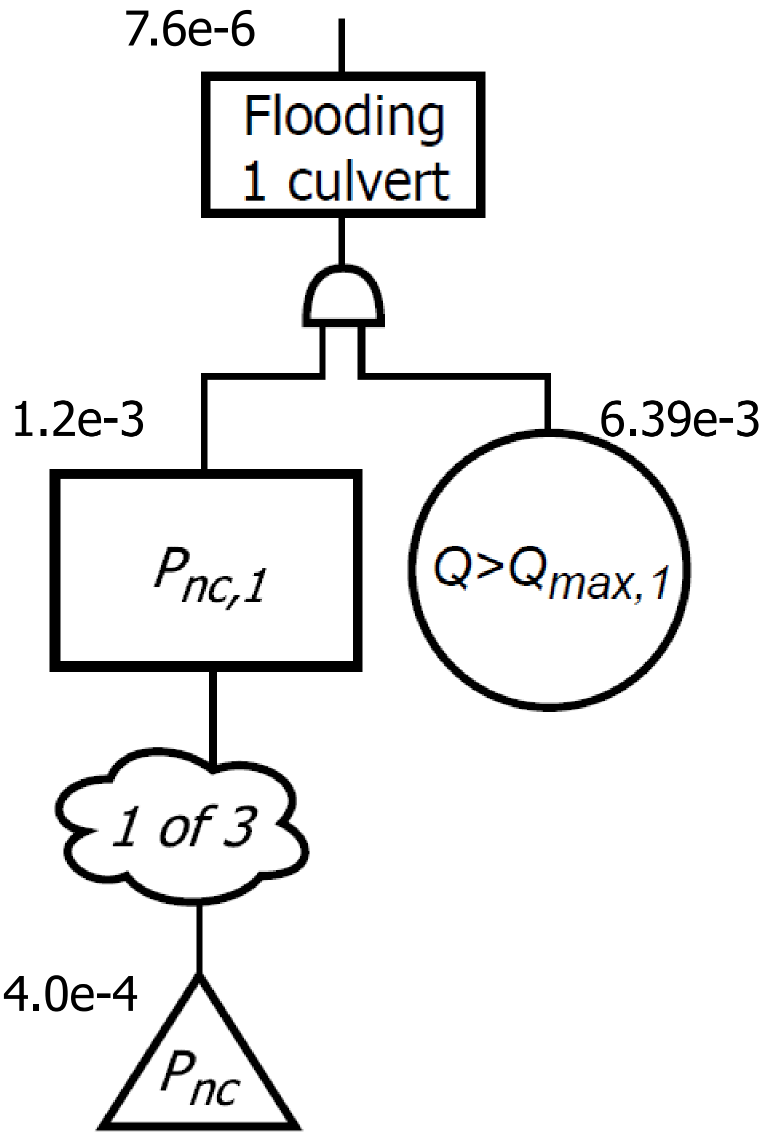
$$P_i = \frac{n!}{i!(n-i)!} * p^i * (1-p)^{(n-i)}$$



# 1c. System failure

1 non-closure out of 3 trials

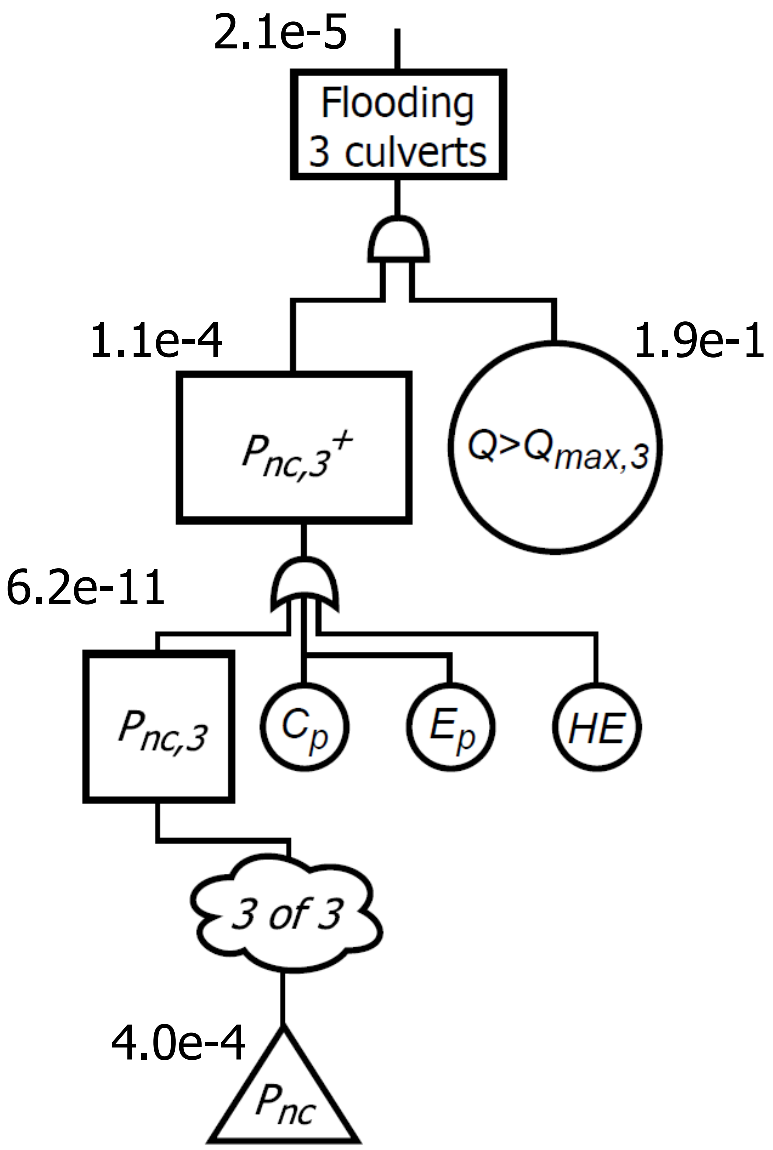
| $i$ | $P(Q>Q_{max})$ |
|---|---|
| 1 | 6.39E-03 |
| 2 | 3.7E-02 |
| 3 | 1.89E-01 |



# 1c. System failure

3 non-closures out of 3 trials

| | |
|---|---|
| $C_p$ | 3.5E-05 |
| $E_p$ | 7.3E-05 |
| *HE* | 2.5E-06 |
| | Σ = 1.1E-04 |

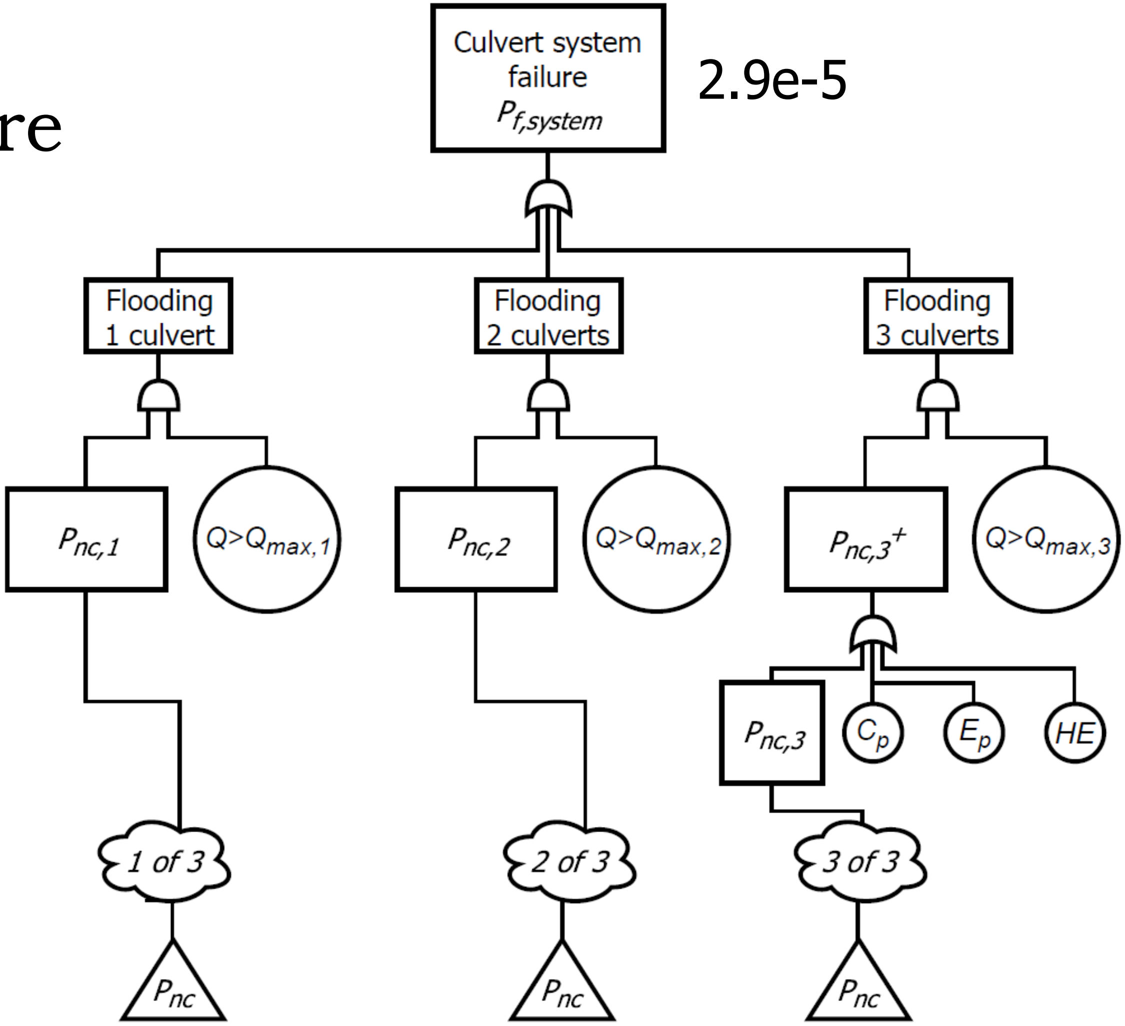


# 1c. System failure

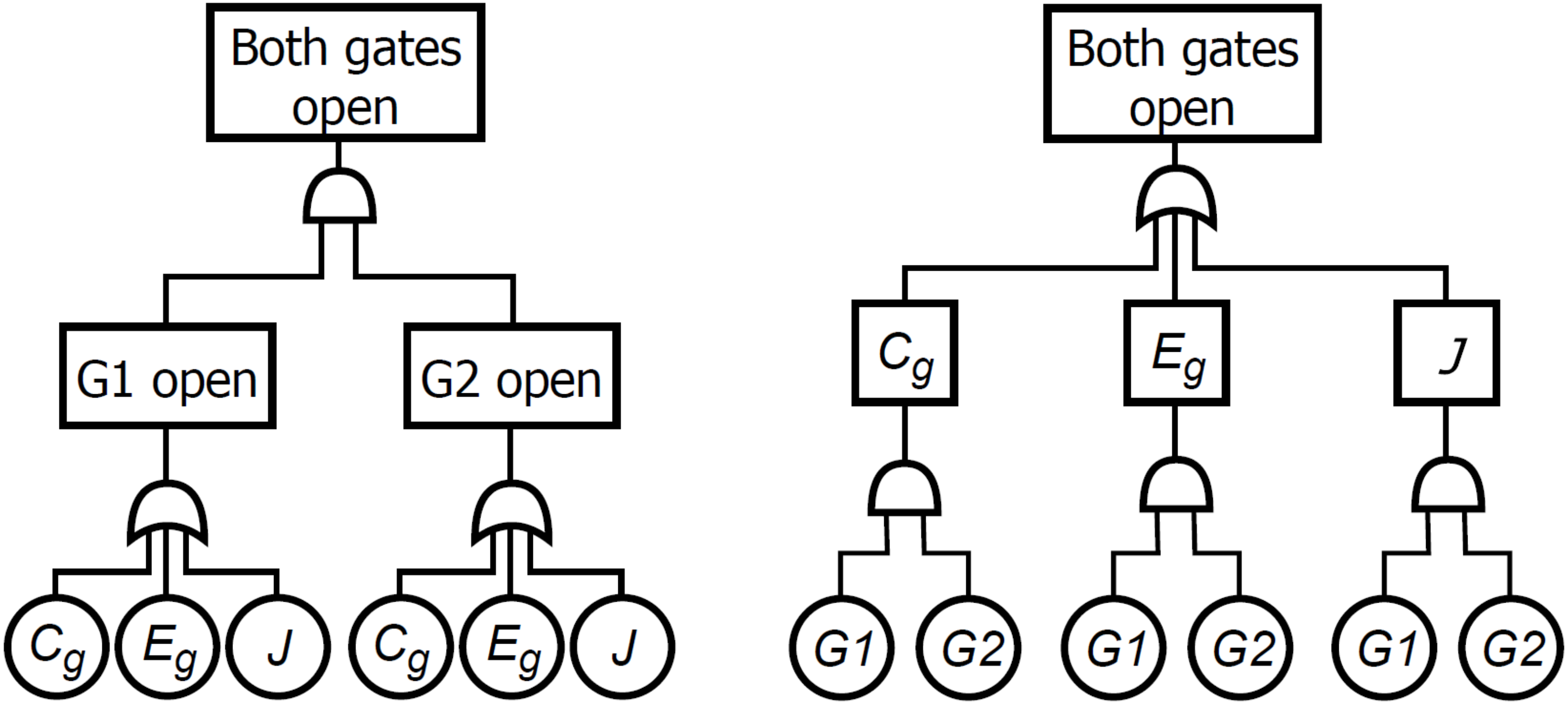
All 3 non-closures

| $i$ | $P_{nc,i}$ | $P(Q>Q_{max,i})$ | $P_f(\text{flood}\|i)$ |
|---|---|---|---|
| 1 | 1.2e-3 | 6.4e-3 | 7.6e-6 |
| 2 | 4.7e-7 | 3.3e-2 | 1.5e-8 |
| 3 | 1.1e-4 * | 1.9e-1 | 2.1e-5 |
| | | | Σ = 2.9e-5 |

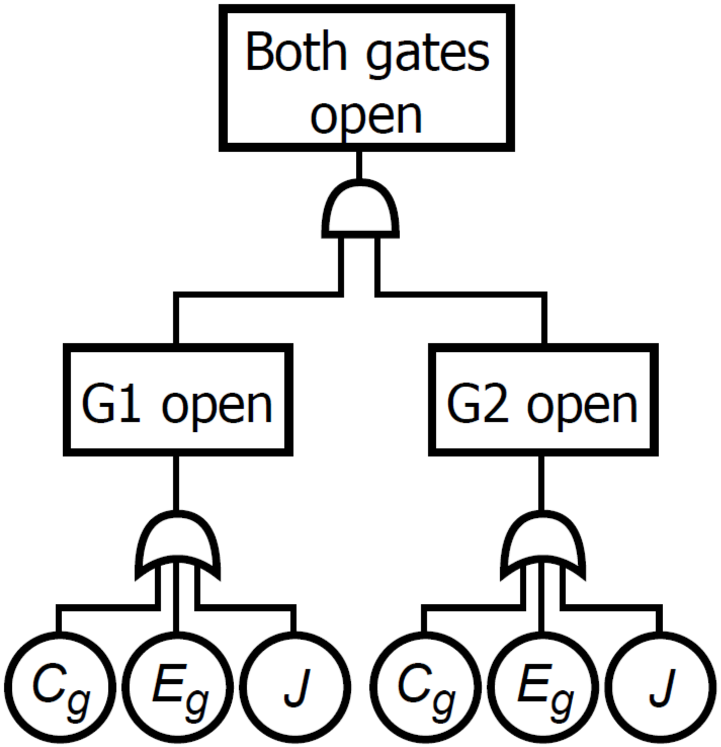
*includes other failure modes for $i$ =3

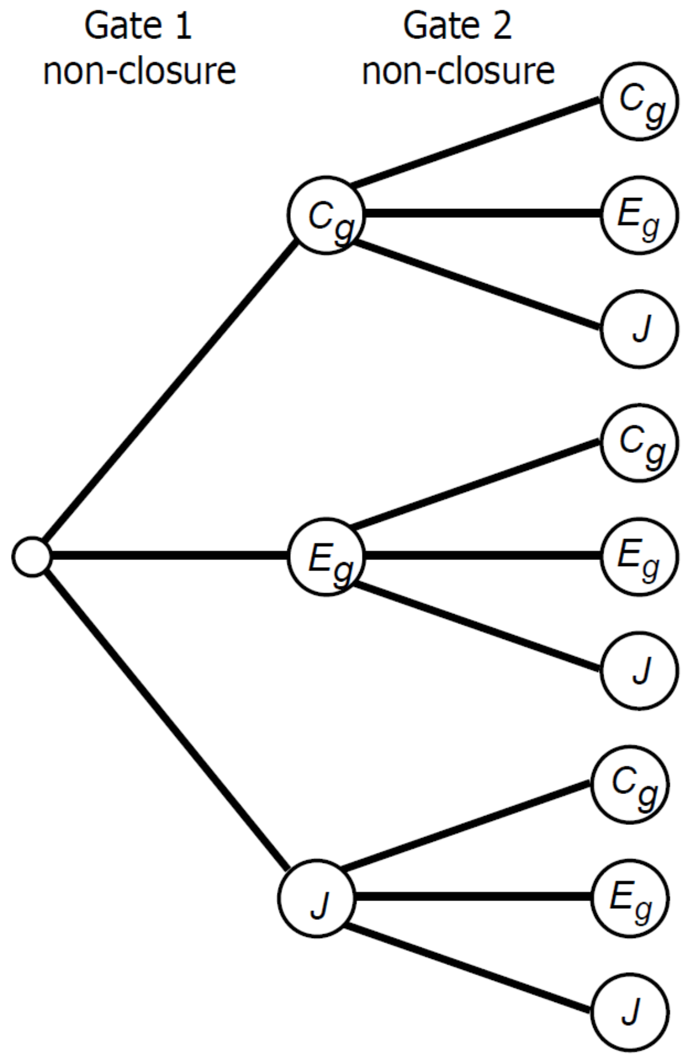


# 1a. Single non-closure – 2 approaches



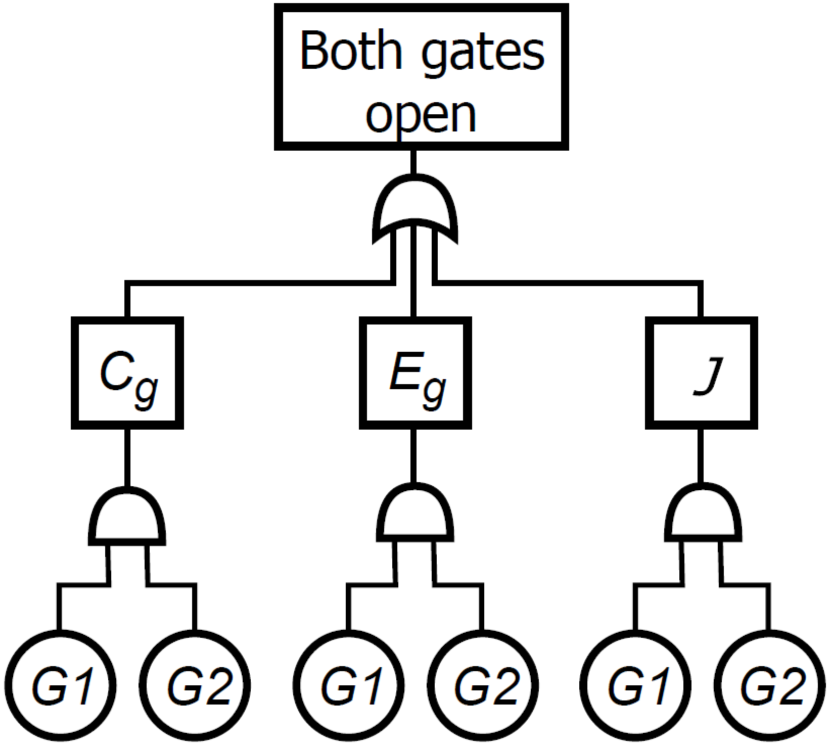
# 1a. Single non-closure – approach 1

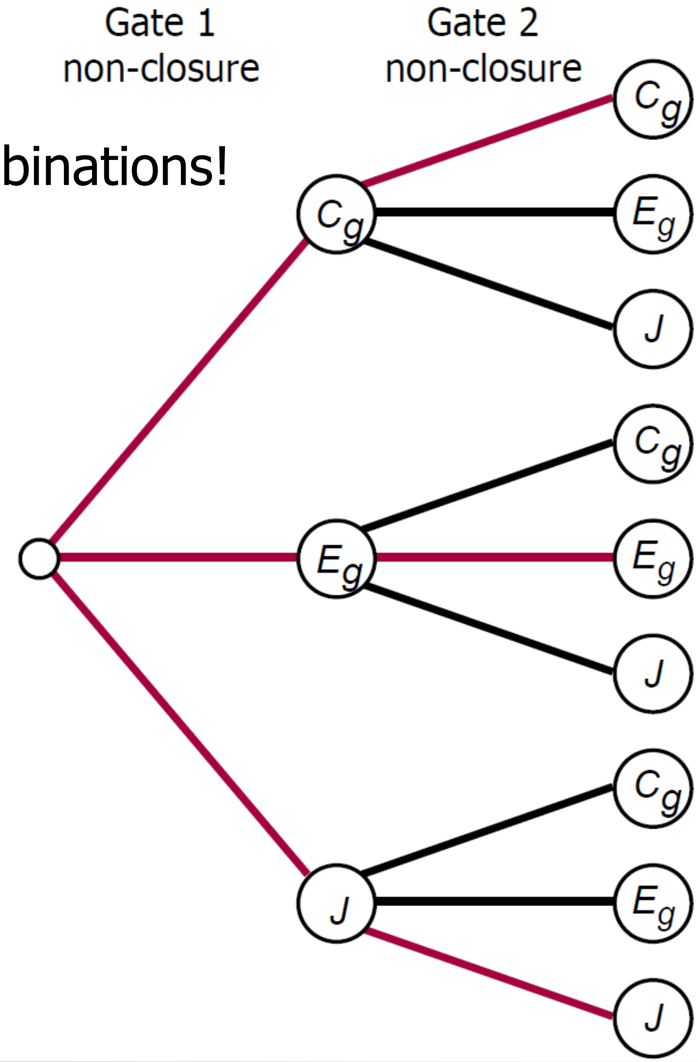


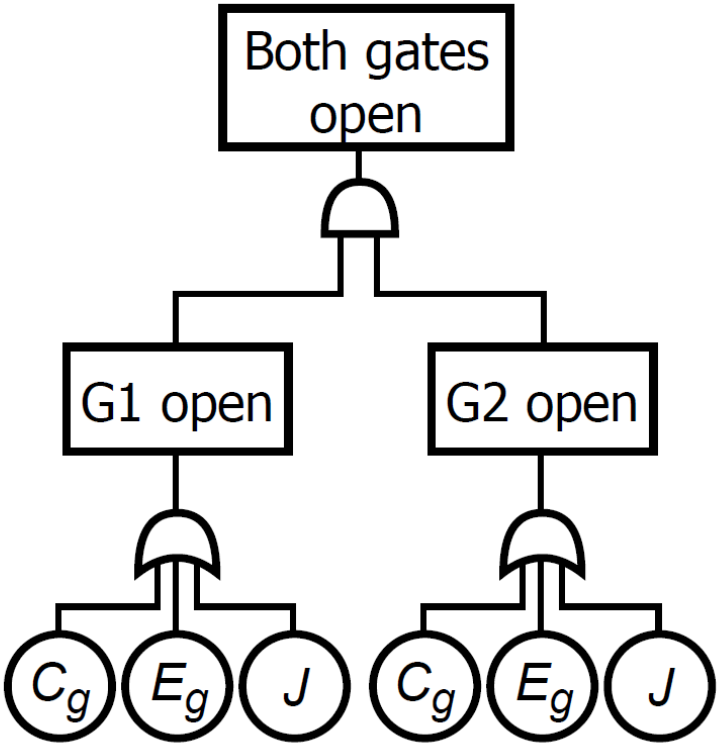
# 1a. Single non-closure – approach 2

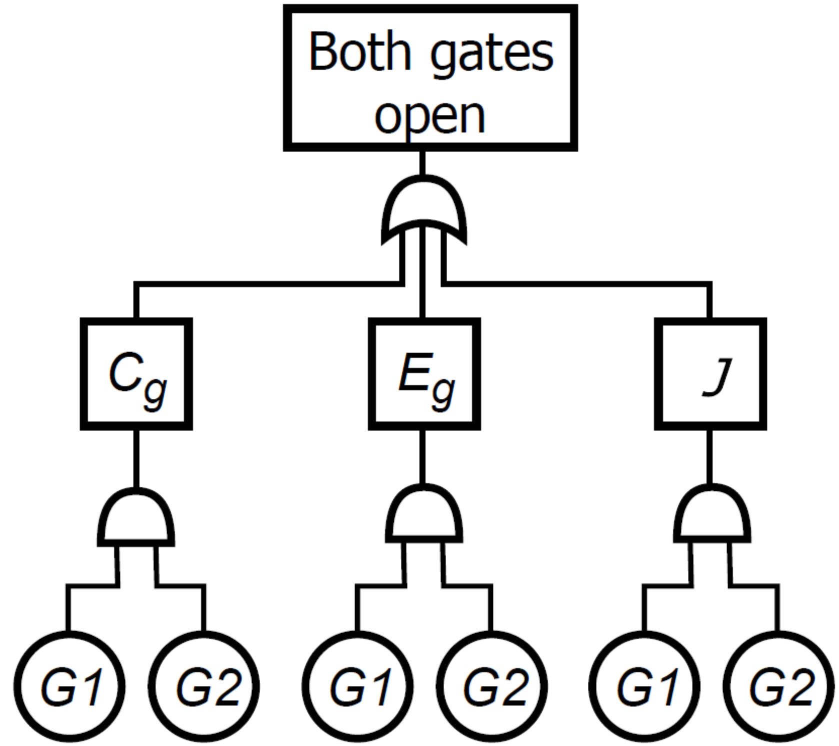
2nd alternative does not consider all combinations!



# 1a. Single non-closure – 2 approaches




$P = (P_1+P_2+P_3)^2$

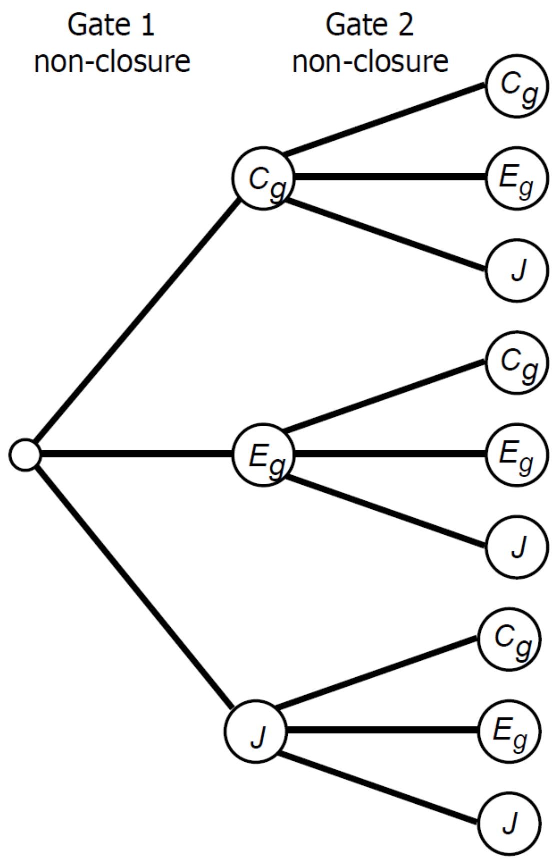
$P = P_1{}^2+P_2{}^2+P_3{}^2+2(P_1+P_2+P_3)$

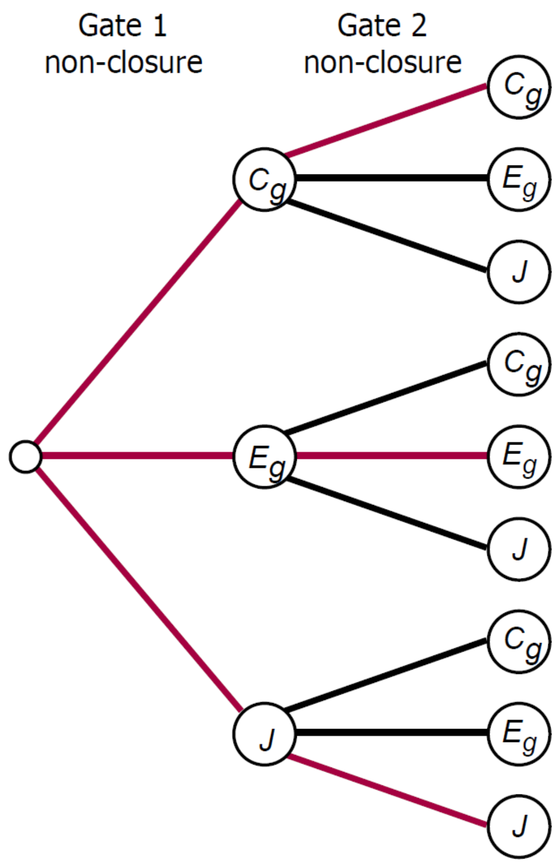
P = 6.6e-06

$P = P_1{}^2+P_2{}^2+P_3{}^2$

P = 5.8e-6

# 1a. Single non-closure – 2 approaches



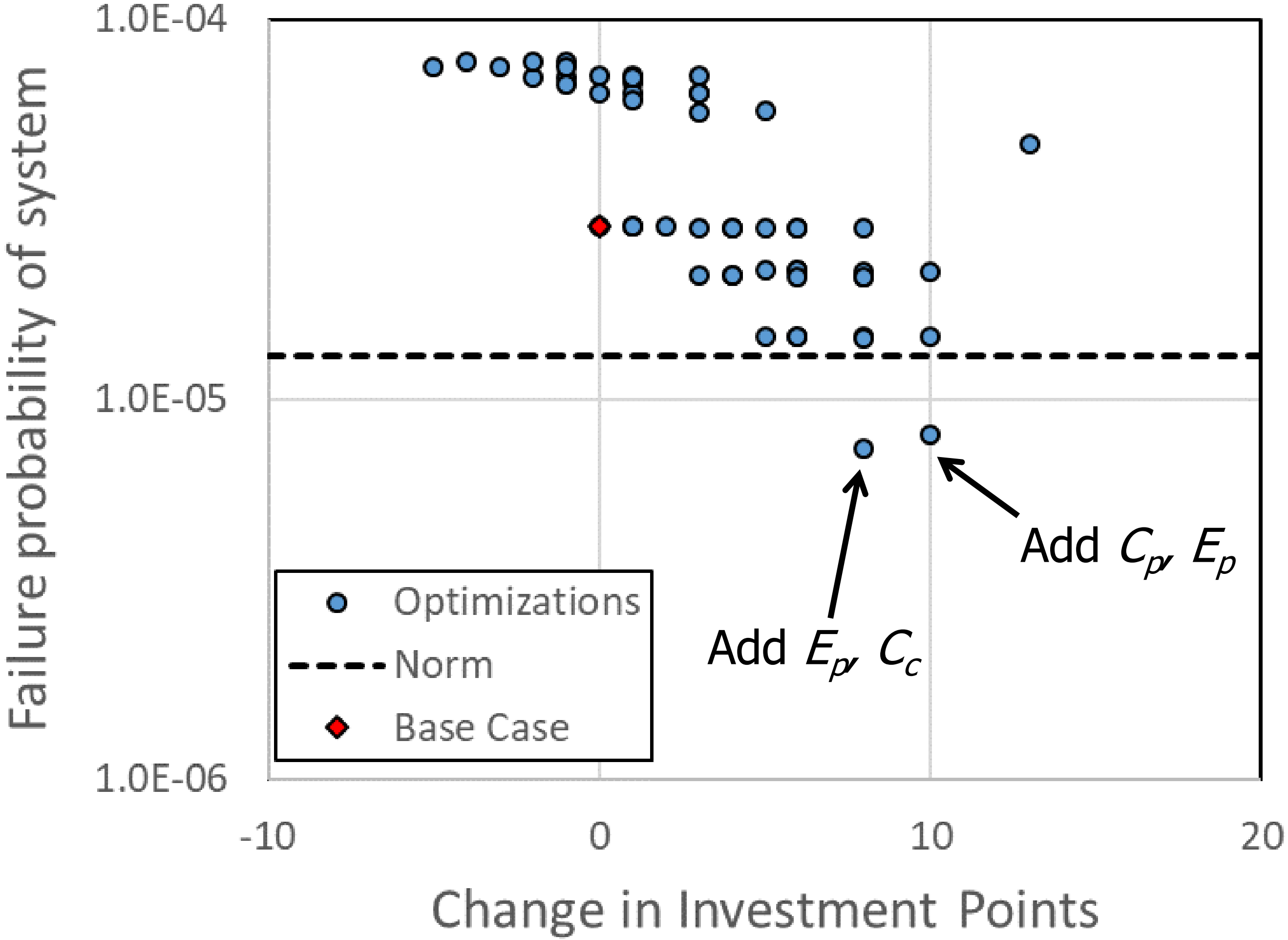

$$P = P_1 (P_1+P_2+P_3)+ P_2 (P_1+P_2+P_3)+ P_3 (P_1+P_2+P_3)$$

$$P = 6.6e\text{-}06$$

$$P = P_1^2+P_2^2+P_3^2$$

$$P = 5.8e\text{-}6$$

# Design optimizations



# Project in reality

Influence 1 or 2 gates on:

- **safety**;
- initial and life time costs;
- maintenance ease;
- safety during maintenance;
- monumental significance of the Afsluitdijk.

# Project in reality – optimize safety

Possible steps

- Start small (like we did)
- Scale up to the reality (15 culverts)
- Check out sensitivity (see screenshot for 3 culverts)
- Check conservatism in POF sensitive components
- For (in)sensitive components find alternatives (cheaper/safer) or add/remove redundancy (light weight cost optimization)

```
increasing Cp with factor 2 increases pof with 23 %
increasing Ep with factor 2 increases pof with 48 %
increasing Cc with factor 2 increases pof with 26 %
increasing Ec with factor 2 increases pof with 1 %
increasing Cg with factor 2 increases pof with 0 %
increasing Eg with factor 2 increases pof with 0 %
increasing CC with factor 2 increases pof with 0 %
increasing HE with factor 2 increases pof with 2 %
increasing J with factor 2 increases pof with 1 %
```