CIEM42X0 Probabilistic Design – Fault tree workshop handout – June 9, 2023

Assignment

1. Find probability of culvert system failure $P_{f,system}$
    a. Create a fault tree for single culvert non-closure, P_{nc}
    b. Find probability non-closure of *i* culverts ($P_{nc,i}$) using Bernoulli
    c. Create a fault tree for $P_{f,system}$ that includes 3 non-closure cases

Evaluate the system reliability: does the current system satisfy the norm of $1.3 \cdot 10^{-5}$? What part of the fault tree influences reliability the most?

2. Optimize system: get $P_{f,system}$ as close to norm as possible, while reducing overall costs

Hint: it will be easier to adjust your fault tree and optimize it if you use Excel or Python. Make sure your fault tree clearly indicates all failure mechanisms in the table, 3 culvert scenarios and Bernoulli.

Exercise Details – Afsluitdijk culvert system

- There are 3 culverts that must close to limit water flow into the IJsselmeer and prevent flooding in adjacent polders. System failure occurs when too much water enters the IJsselmeer. This happens when: a) 1 or more culverts do not close when asked, $P_{nc,i}$, b) flow through open culverts exceeds critical value: $P(Q < Q_{\max,i})$
- All 3 culverts are always asked to close together, not individually
- The probability $P(Q < Q_{\max,i})$ is dependent on the hydraulic boundary conditions and the number of open culverts (table below). Three different culvert non-closure scenarios need to be taken into account in your fault tree.
- Failure mechanisms that can cause gates, culverts or system to fail are given below, and must be incorporated into the fault tree. Consider all components statistically independent
- For the optimization only use components defined herein (can add or reduce redundancy at the different system levels), with costs represented by investment points (table below). While it is possible to change the number of culverts, be mindful of how this affects Bernoulli

Where

P_{nc}	Failure probability of a single culvert not closing
$P_{nc,i}$	probability of *i* out of *n* culverts not closing
$P_{f,system}$	failure of the entire system
$P(Q < Q_{\max,i})$	probability of excessive flow with *i* out of *n* culverts open

Hint: P_{nc} should be the same for all three culverts. Note that for $P_{nc,i}$ the subscript *i* indicates the number of unclosed culverts, and is *not* the culvert identifier.

A Bernoulli trial gives the probability of *i* failures out of *n* trials (each trial has probability *p*):

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

Failure probability of the system should not exceed the norm:

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

Failure modes to be included in fault tree:

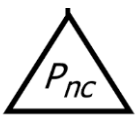
Symbol	Component	Consequence	Probability
C_p	Primary control system	All culverts open	3.5E-05
E_p	Primary electrical supply	All culverts open	7.3E-05
C_c	Culvert control system	Culvert open	3.8E-04
E_c	Culvert electrical supply	Culvert open	9.6E-06
C_g	Gate control system	Gate open	8.7E-06
E_g	Gate electrical 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

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

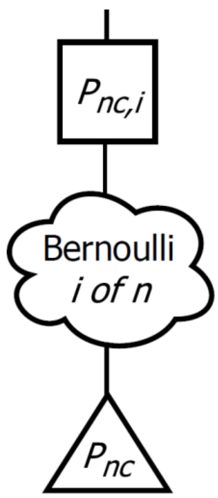
Design option	Investment Points
At gate level	1
At culvert level	3
At primary level	5
Extra gate construction	5
Removing second gate	-5

You can use the following symbols in your fault trees for assignment parts a, b and c:

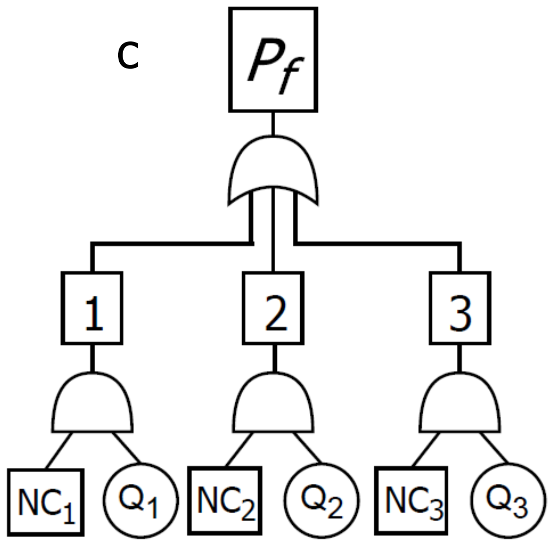
a



b



c



Note: not all failure modes illustrated!