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Reliability Meeting
Thursday 9 June
Durham

Dynamic and Dependent Tree Theory for Event Trees

Silvia Tolo

University of Nottingham
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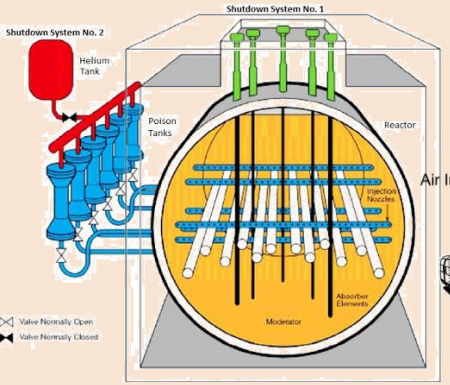
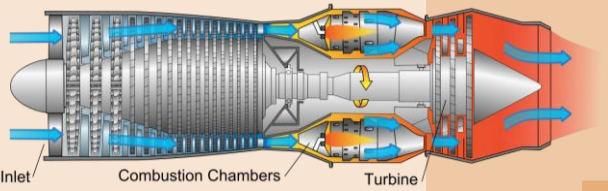
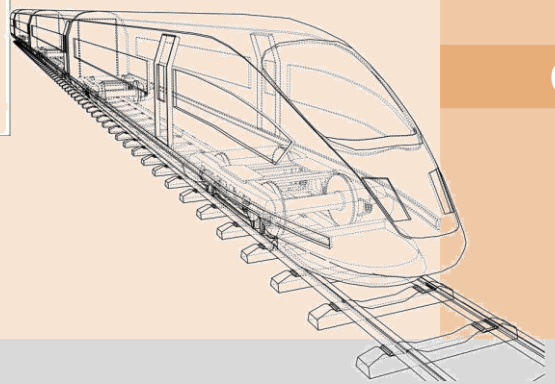
Aims and Objectives

FAMILIAR MODELLING LANGUAGE







REALISTIC RISK MODELLING

- Dependencies
- Non-Constant Failure Rates
- Complex Maintenance Strategies

ANALYSIS ACCURACY

- System Safety Metrics
- Failure Probability
- Failure Frequency
- Component Importance

COMPUTATIONAL FEASIBILITY

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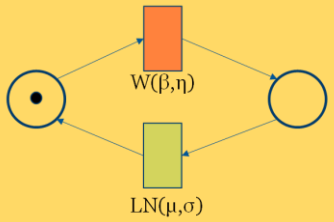
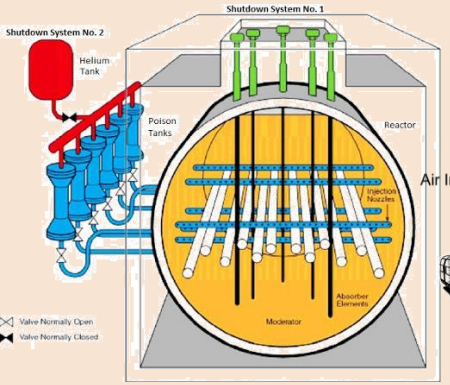
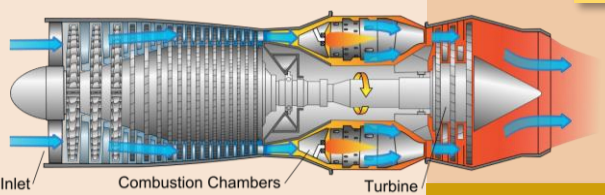
Methodology Overview…

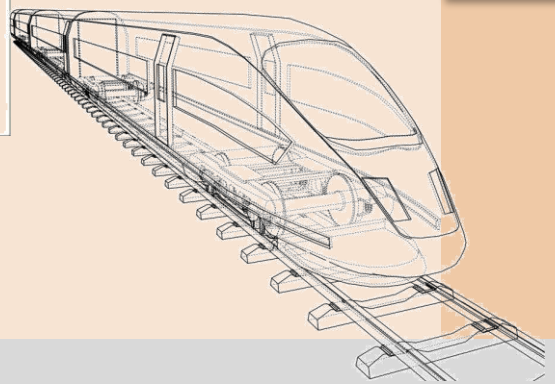
Non-Constant Failure Rates

PETRI NETS







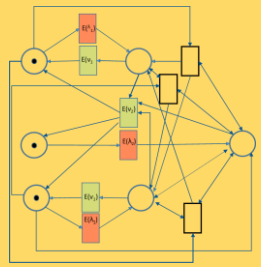


FT Modelling

BDD

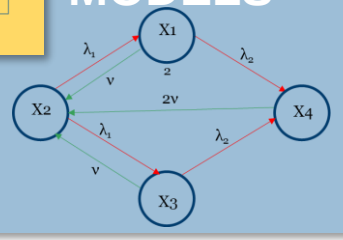
- System Safety Metrics
- Failure Probability
- Failure Frequency
- Component Importance

PETRI NETS



Dependencies

MARKOV MODELS



Complex Maintenance Strategies

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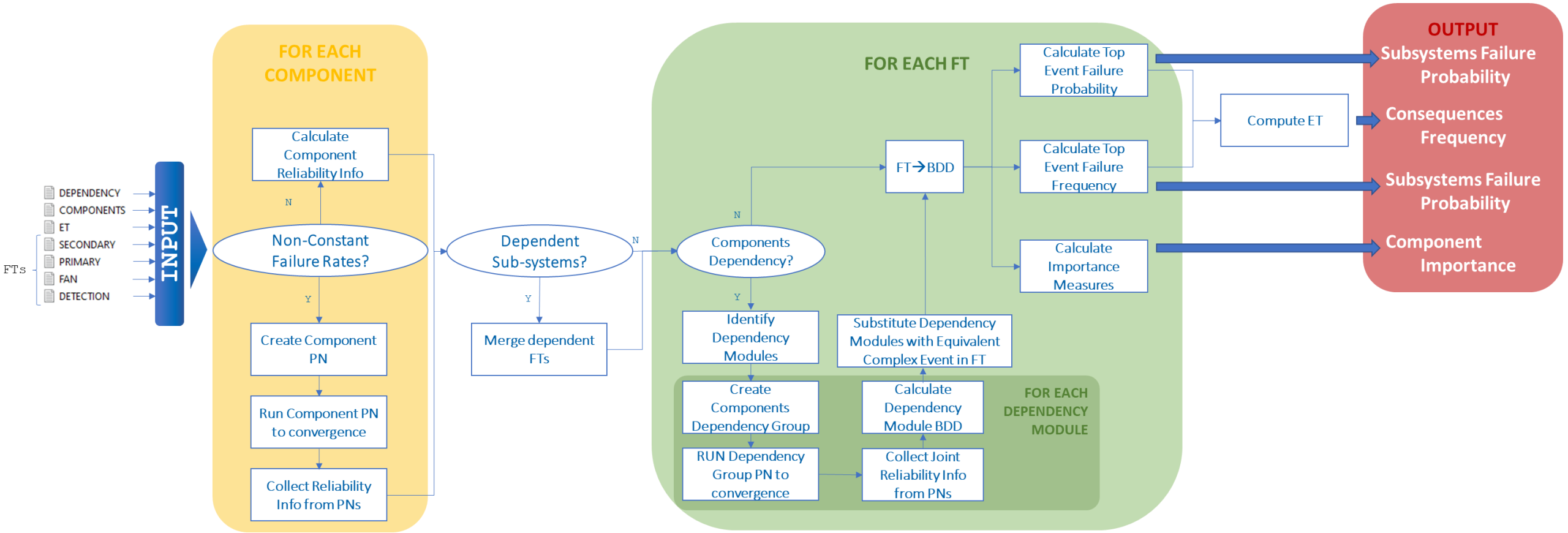
…in 5 Steps



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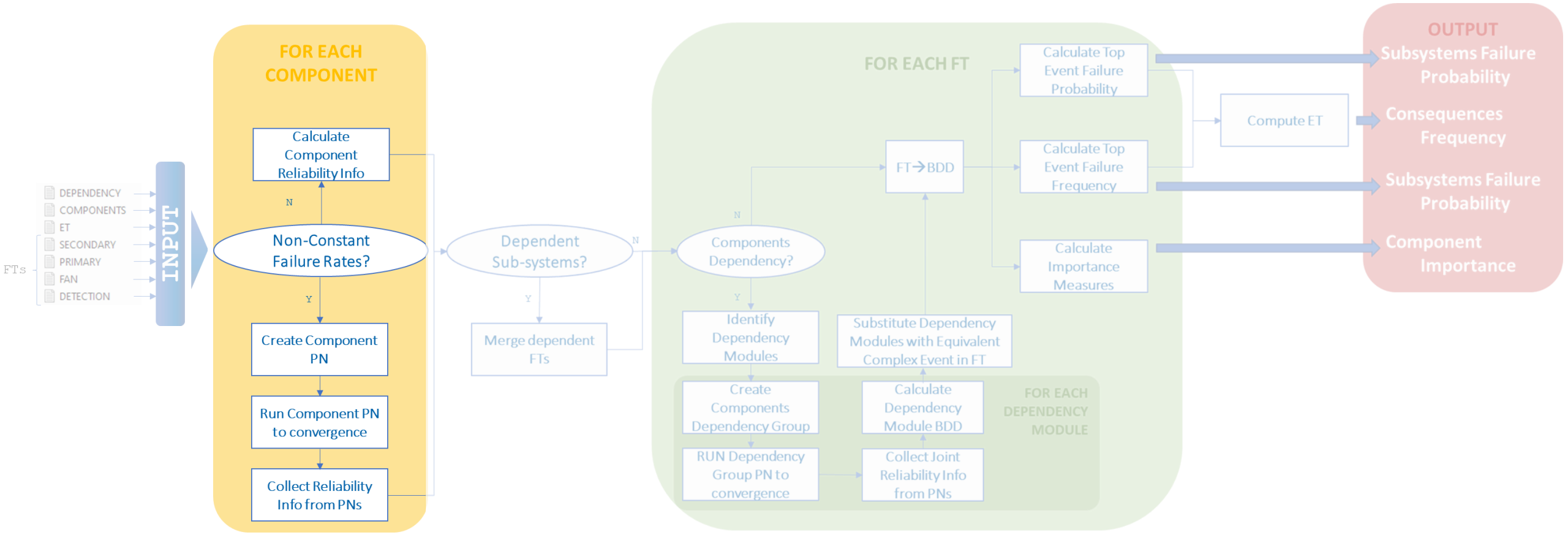
Step 1: Component Reliability



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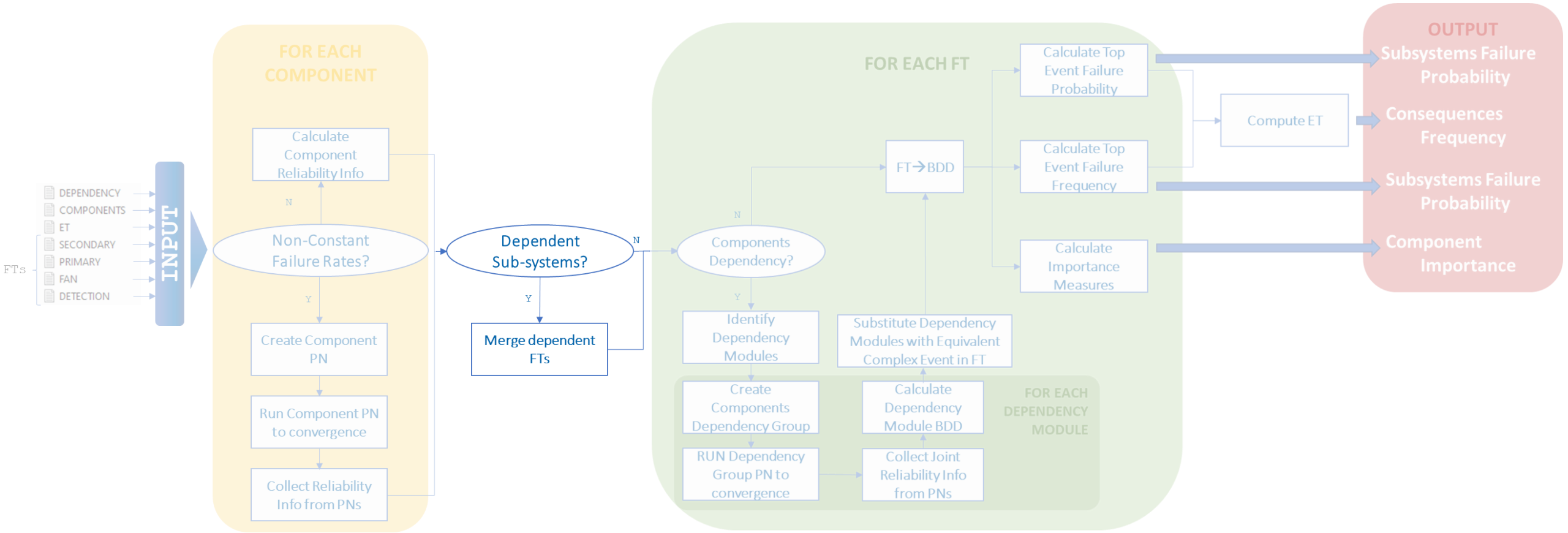
Step 2: Independent FTs Definition



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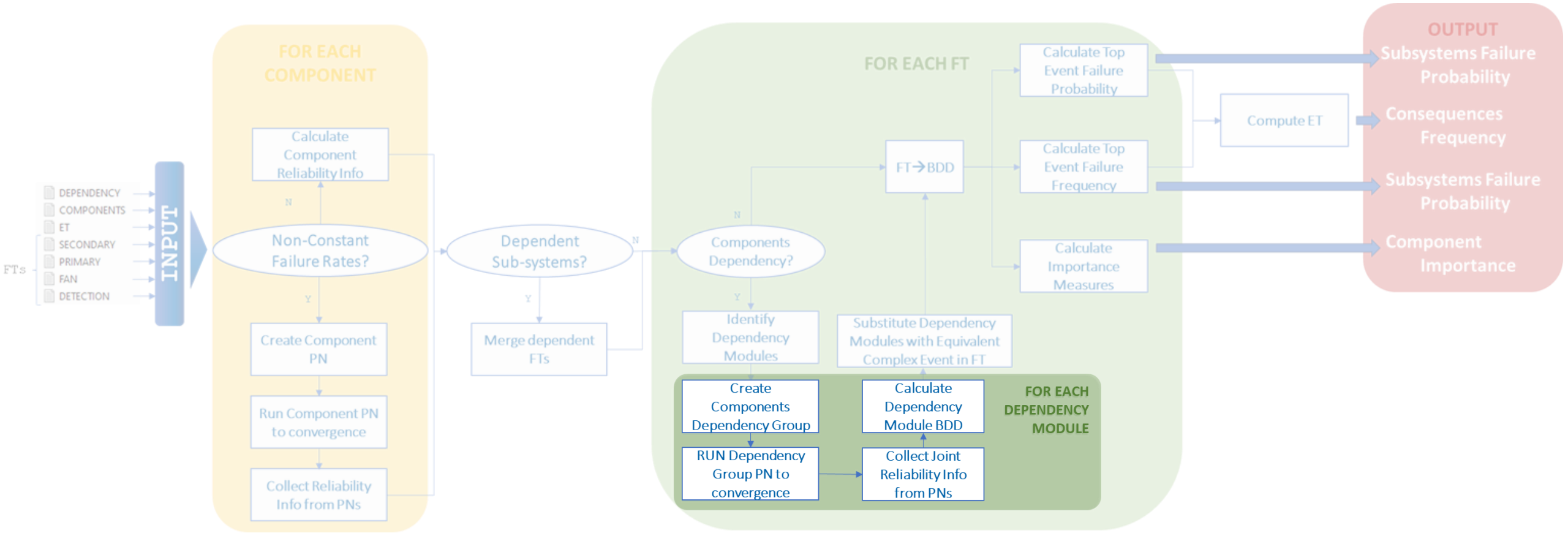
Step 3: Dependency Groups Computation



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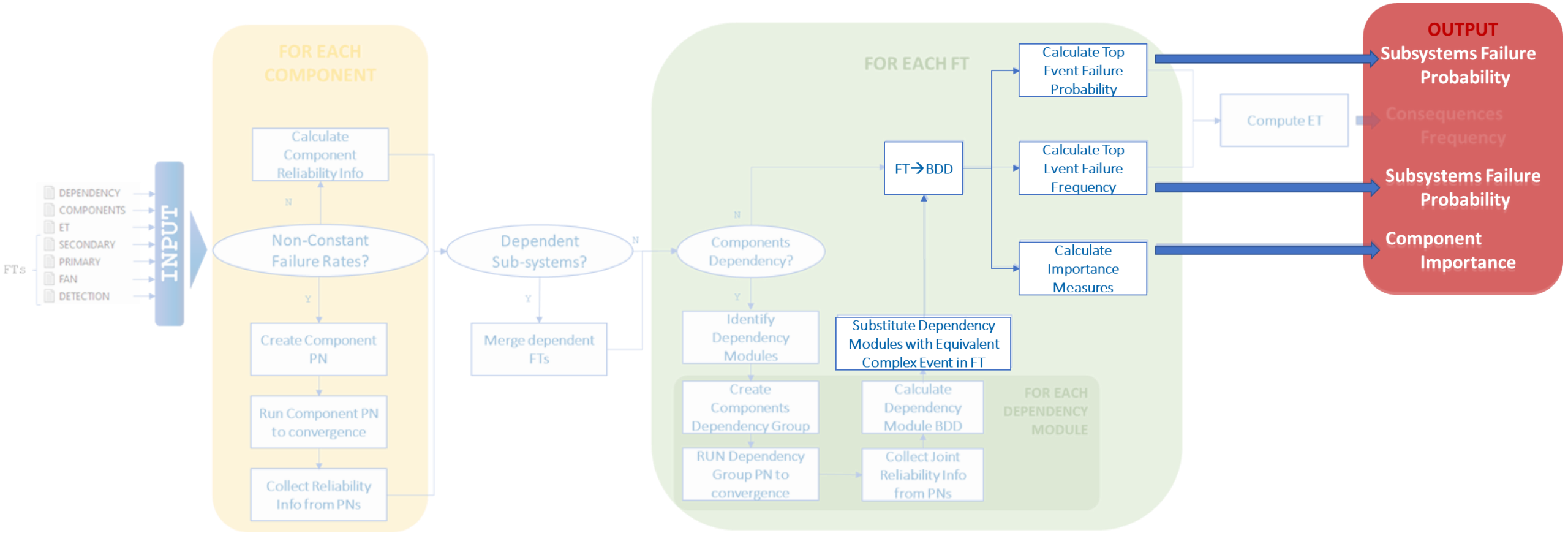
Step 4: FTs Computation



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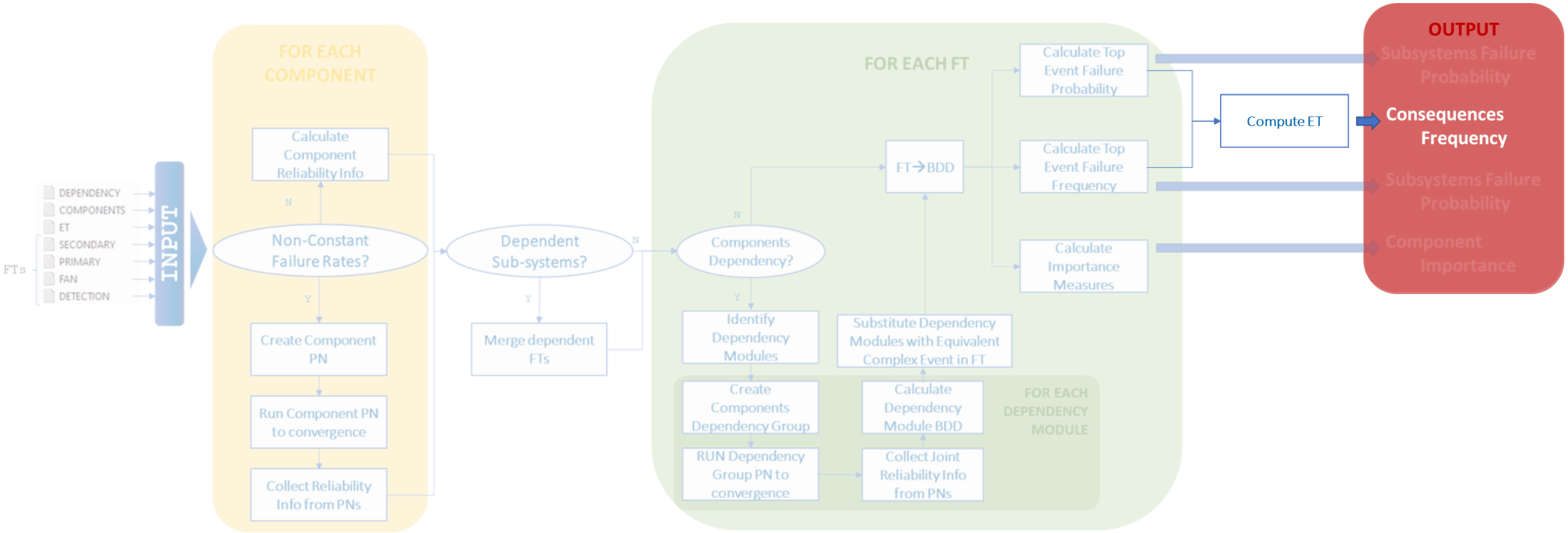
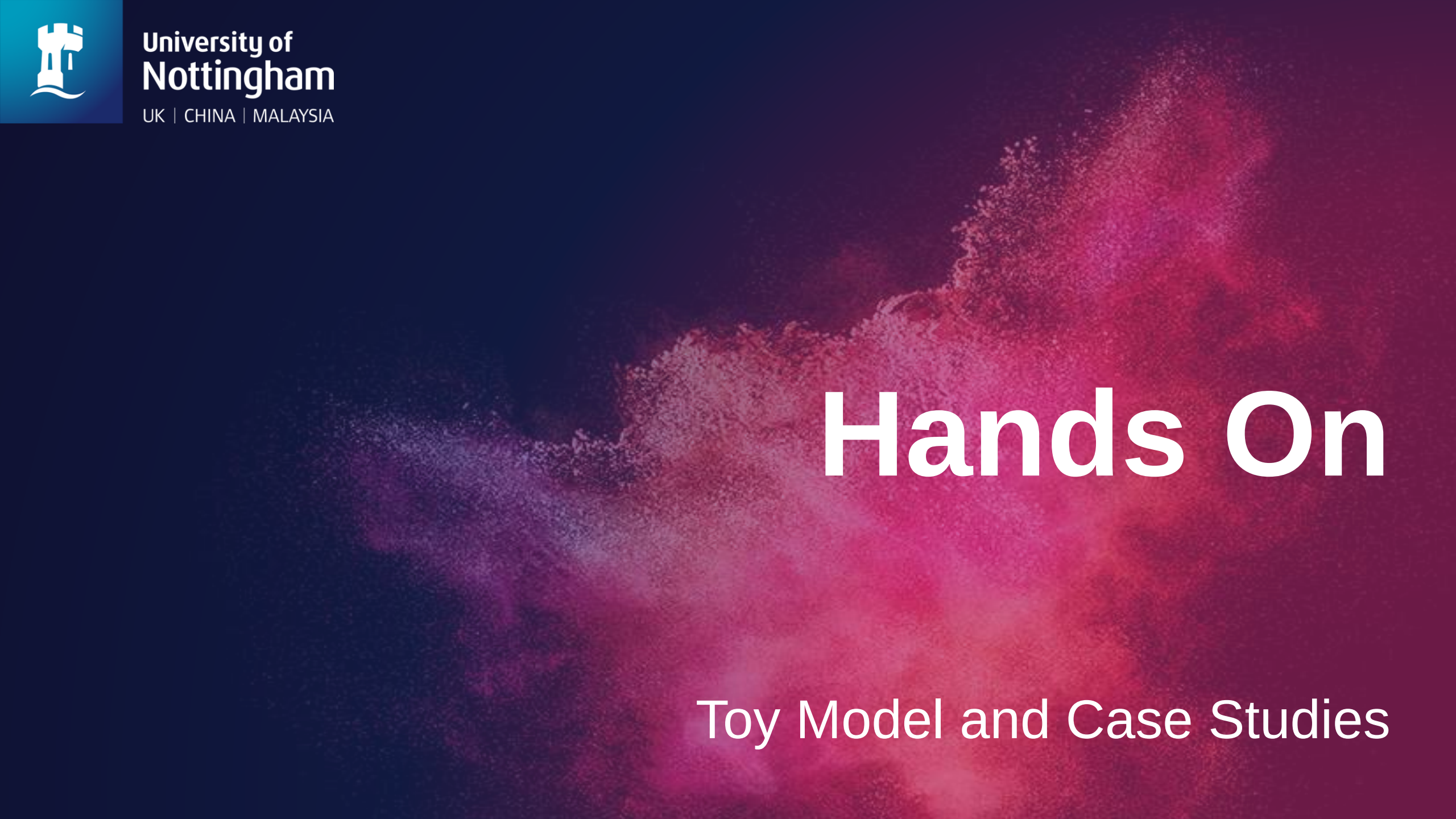
Step 5: ET Computation

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Hands On
Toy Model and Case Studies

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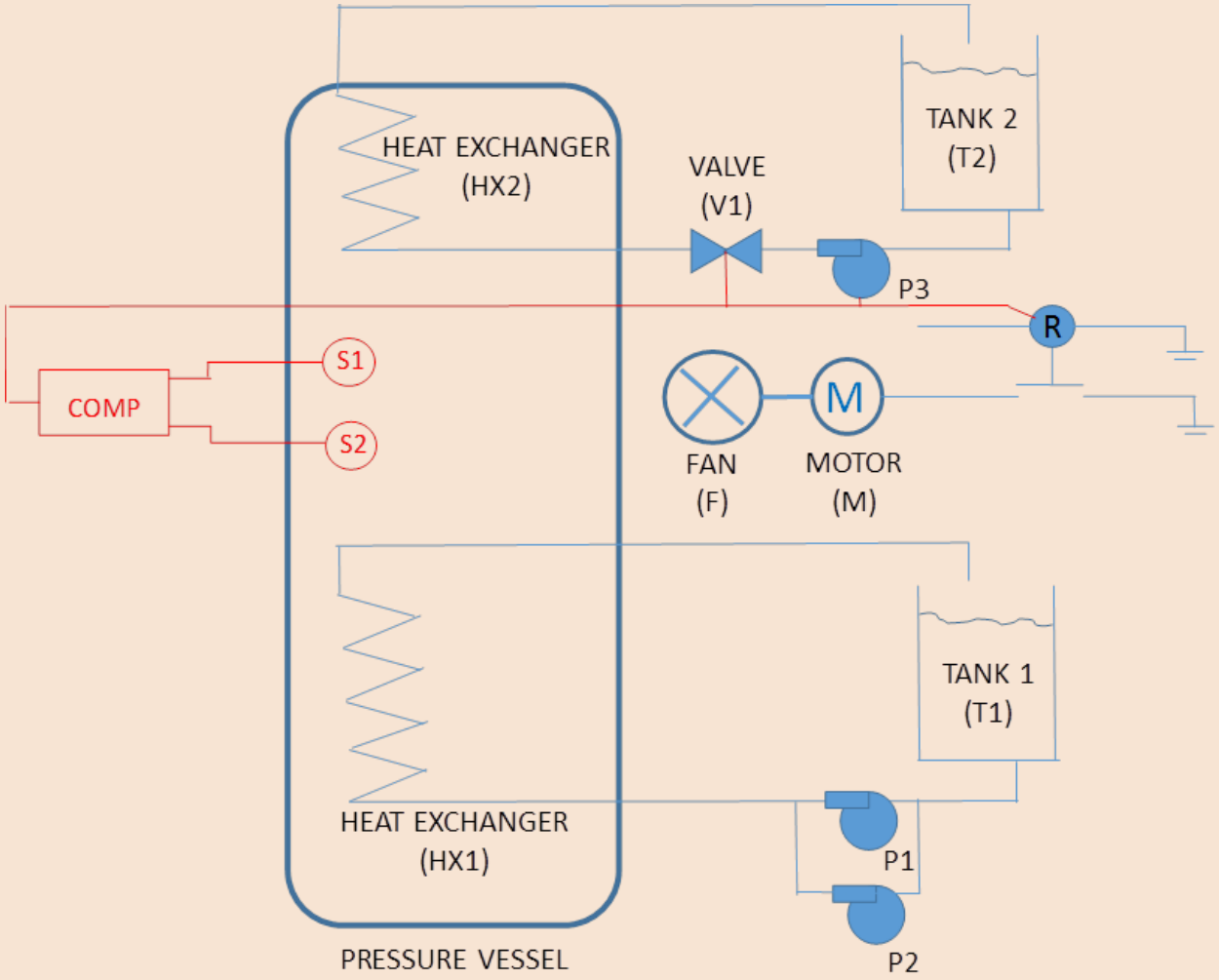
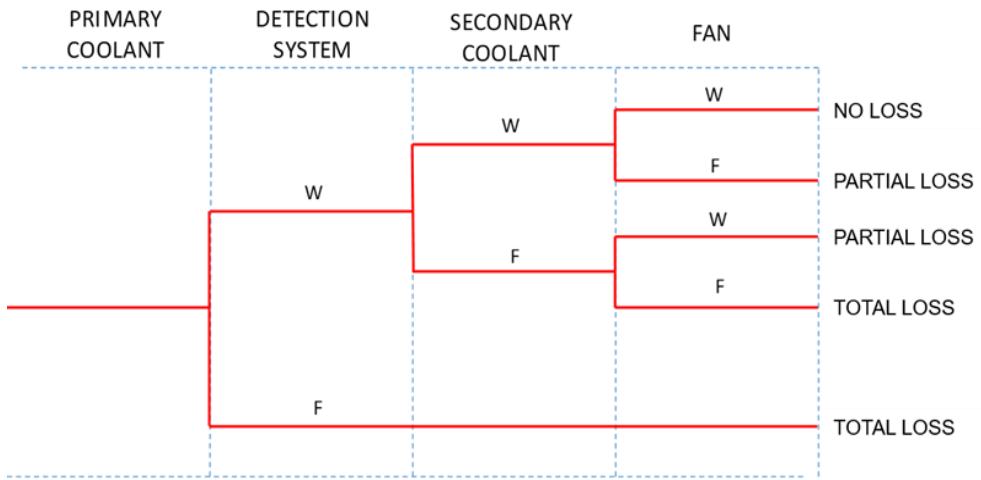
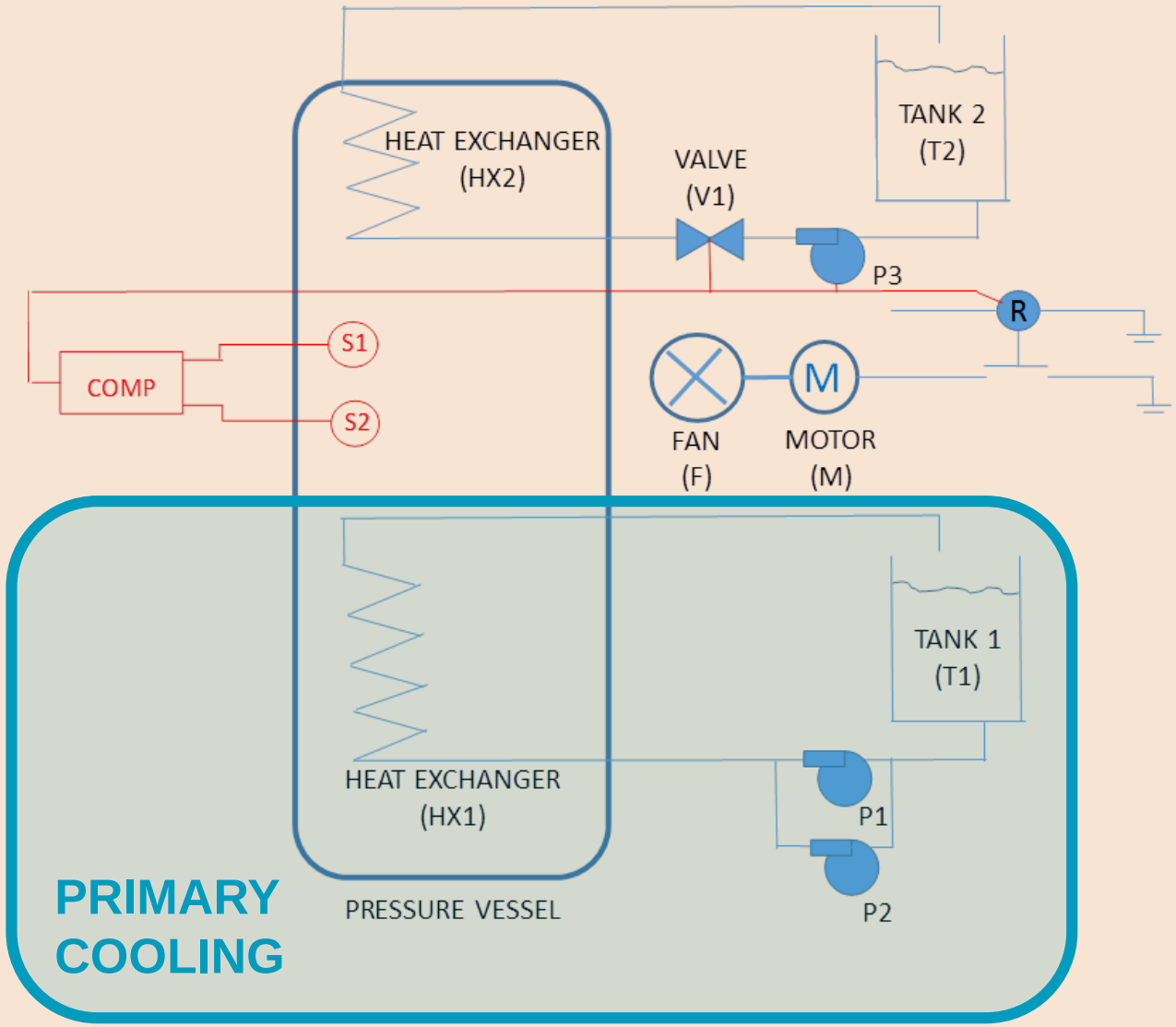
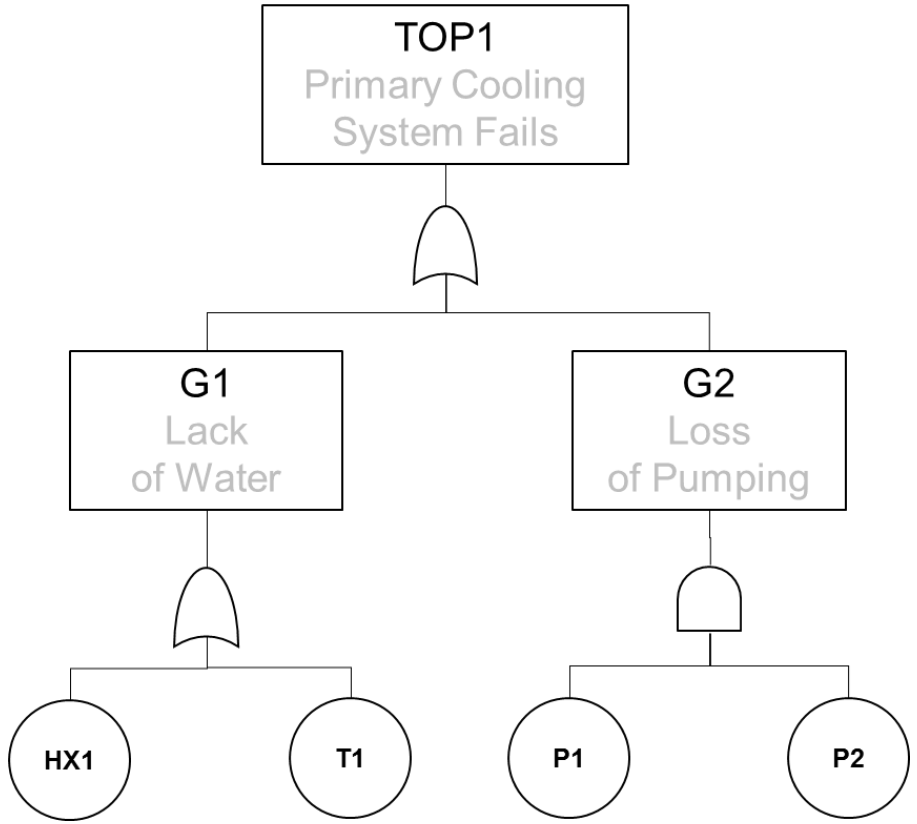
System Overview





System Overview





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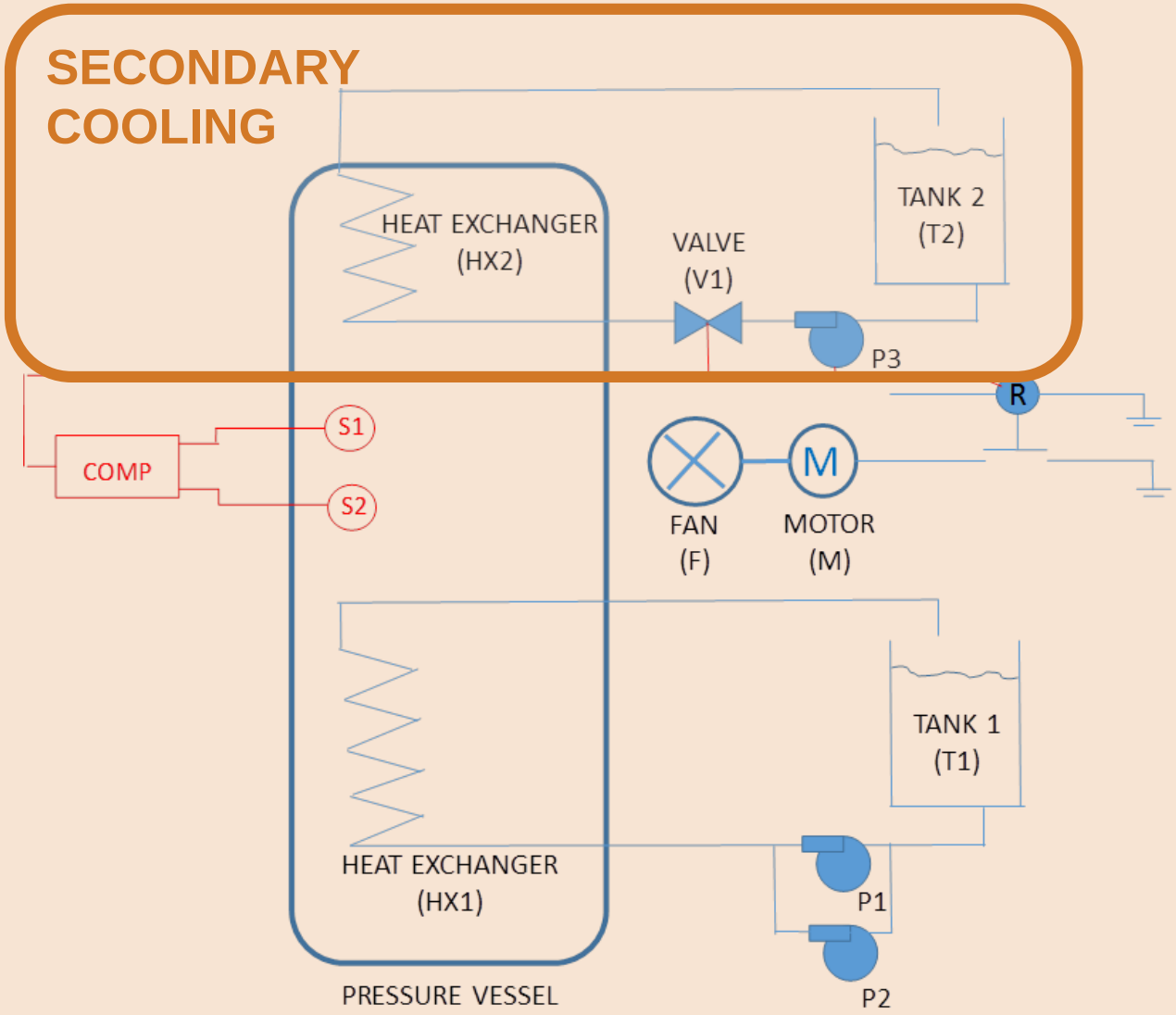
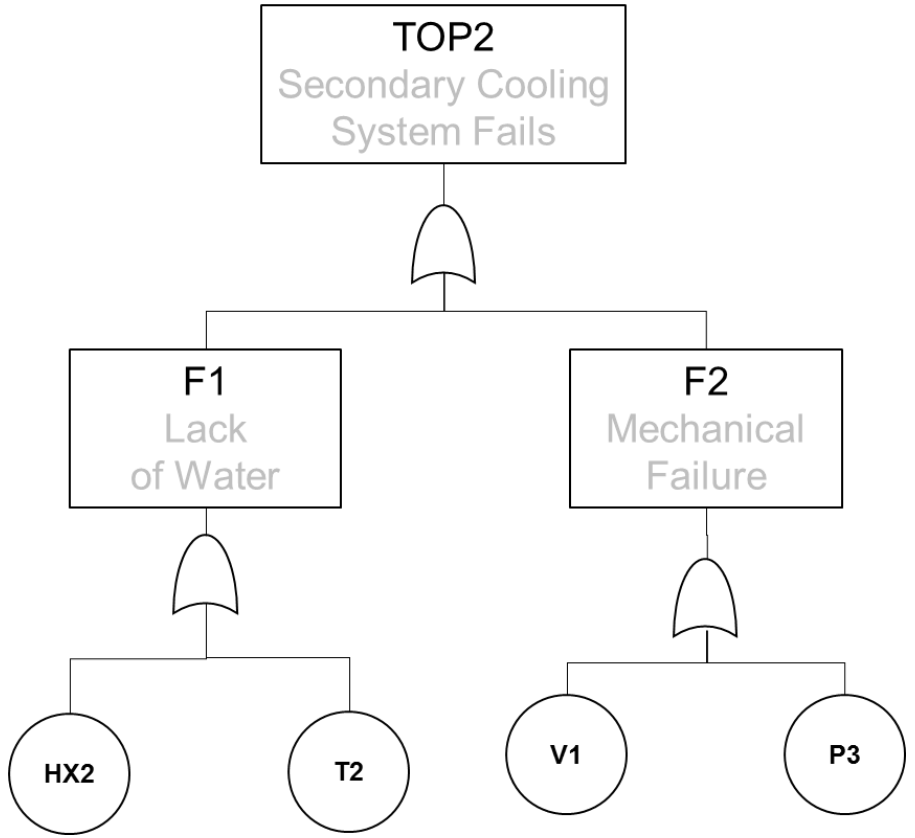
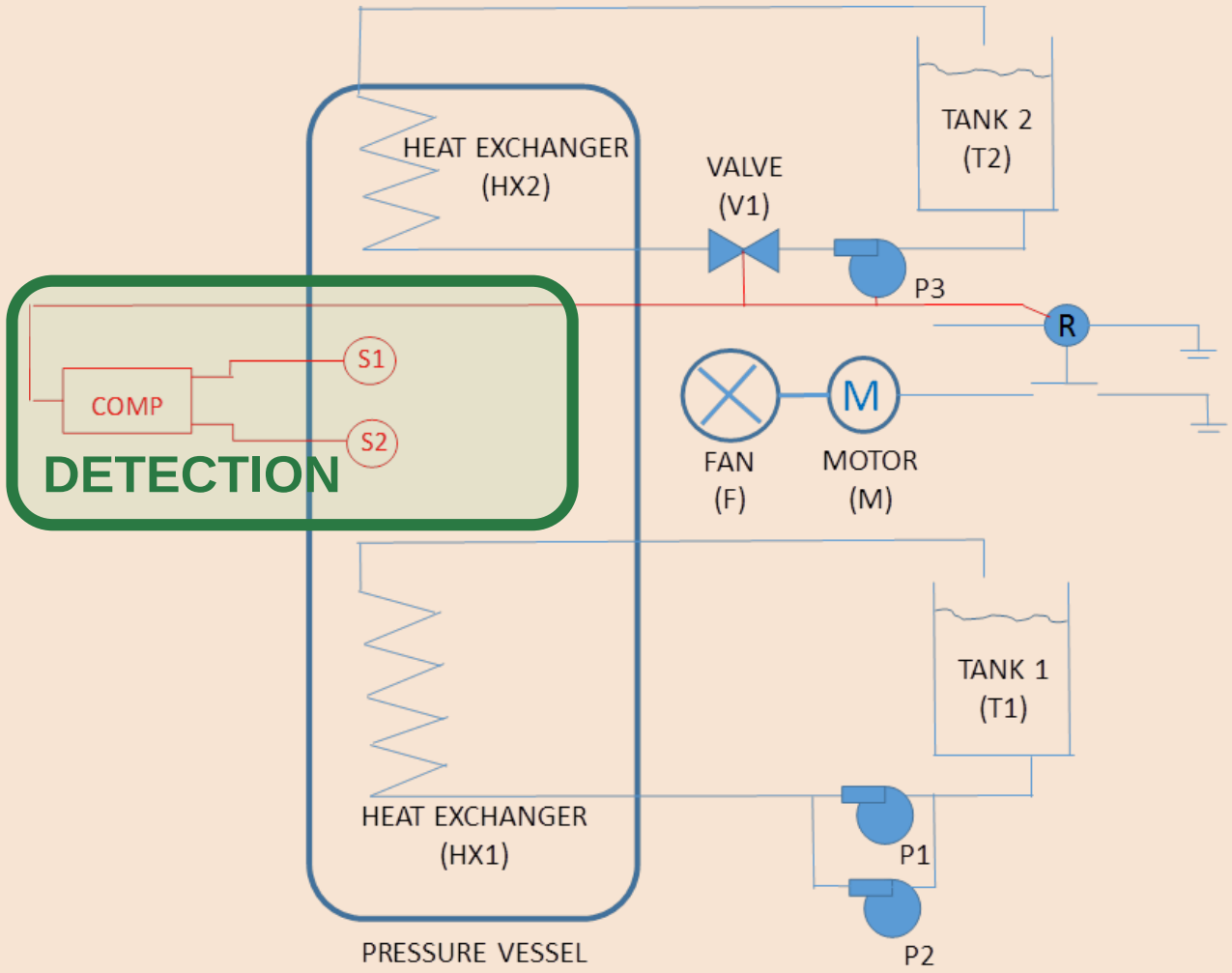
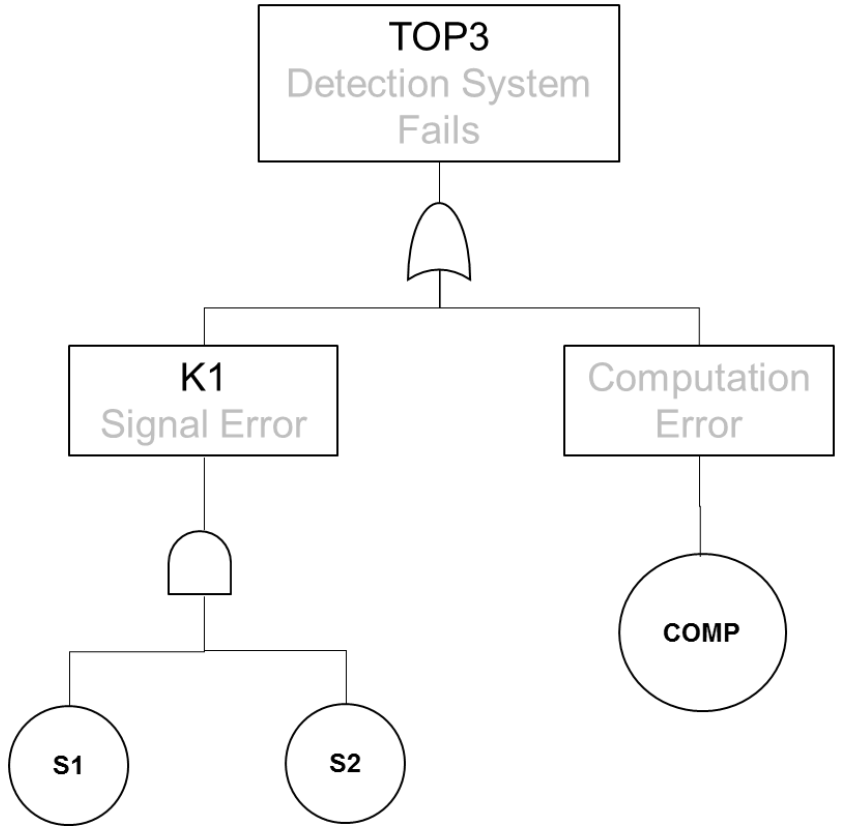
System Overview



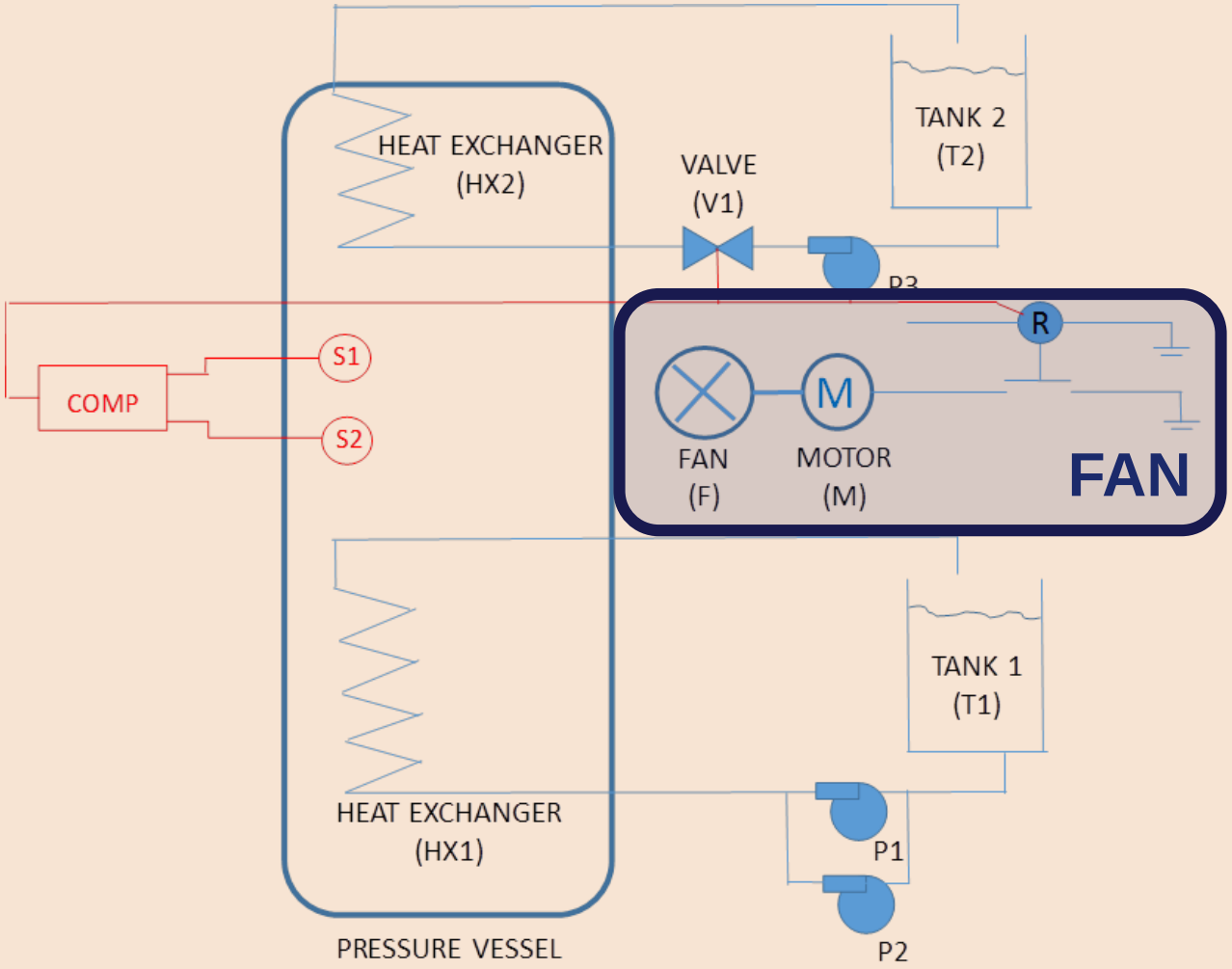


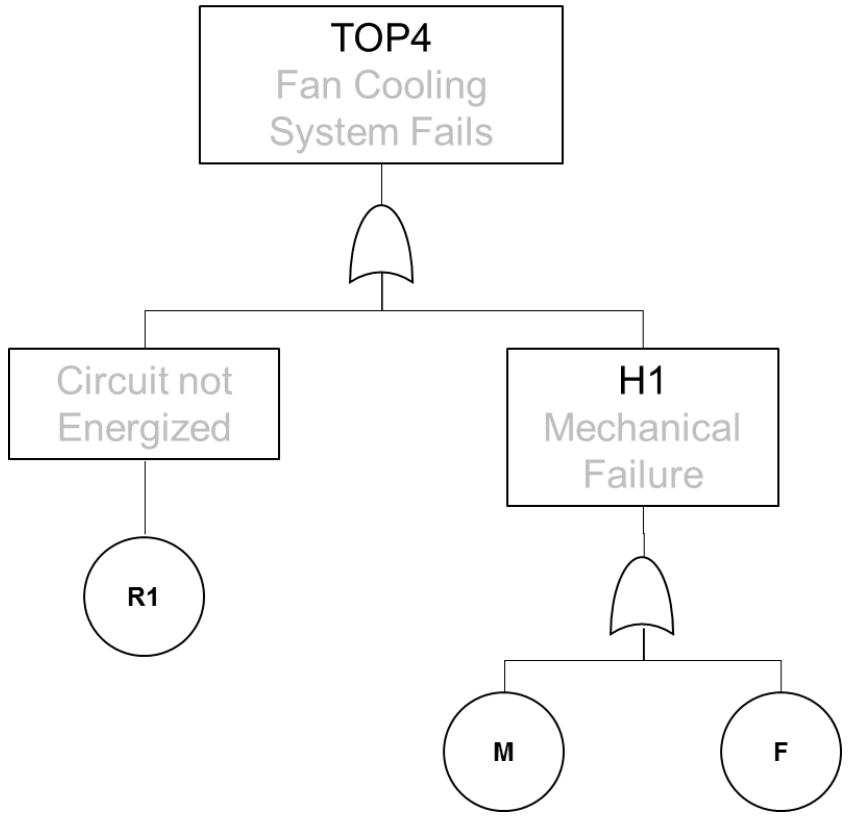
System Overview





System Overview





Case Studies

4 Case-studies:

a) Non-constant failure rates
(full independence)

b) Hard dependency
(component shared between subsystems)

c) Soft dependency
(stochastic, between components due to secondary processes)

d) Complex dependency
(soft+hard dependencies)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Case Study A
Non-Constant Failure/Repair Rates

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Non-constant Failure/Repair Rates

COMPONENTS - Notepad

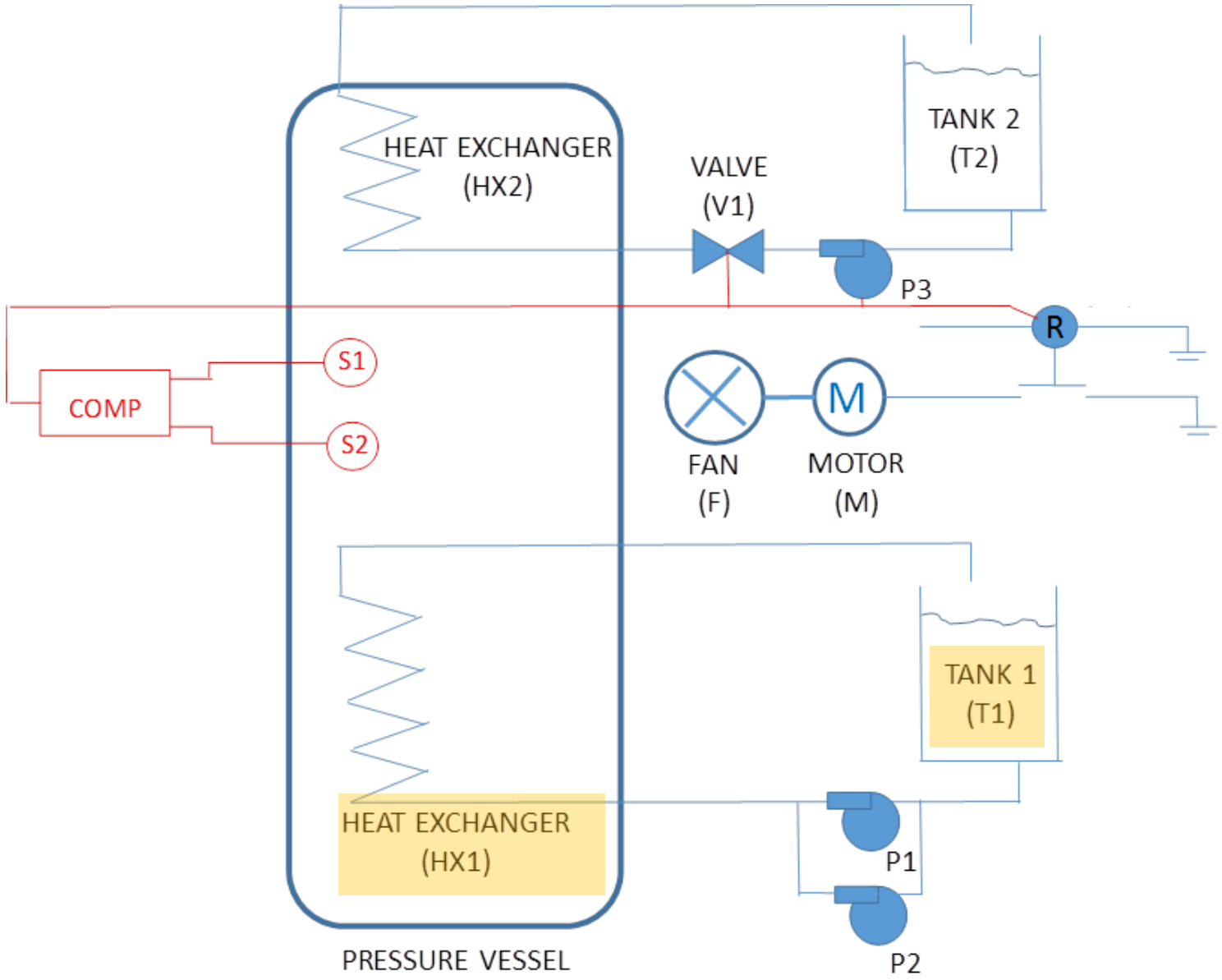
File Edit Format View Help

```
HX1
FAIL
weibull,3,6.6227e+03
REPAIR
0.0417

T1
FAIL
weibull,2,4.1792e+05
REPAIR
lognormal,8,4.125

P1
FAIL
8.0e-4
REPAIR
0.1250

P2
FAIL
8.0e-4
REPAIR
0.1250
```



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Step 1: Component Reliability

COMPONENTS - Notepad

File Edit Format View Help

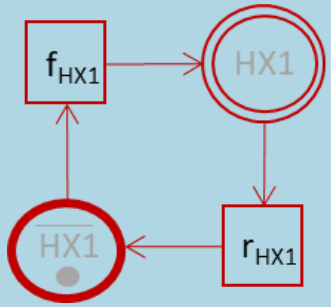
```
HX1
FAIL
weibull,3,6.6227e+03
REPAIR
0.0417

T1
FAIL
weibull,2,4.1792e+05
REPAIR
lognormal,8,4.125

P1
FAIL
8.0e-4
REPAIR
0.1250

P2
FAIL
8.0e-4
REPAIR
0.1250
```

Exponentially Distributed?

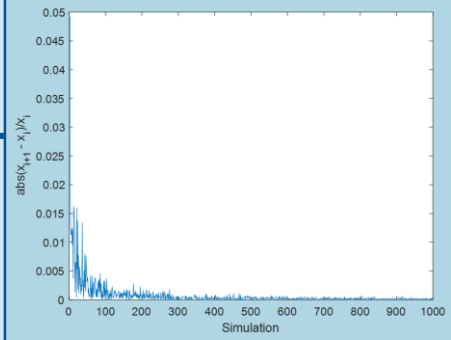
N

NON-CONSTANT FAILURE/REPAIR RATES

GENERATE PN



RUN TO CONVERGENCE



STORE OUTPUT

HX1	
Unavailability	$3.92e^{-3}$
Failure Frequency [h^{-1}]	$1.63e^{-4}$

Y

CONSTANT FAILURE/REPAIR RATES

IDENTIFY MODEL

- Non-Repairable
- **Corrective Maintenance**
- Scheduled Maintenance

COMPUTE RELIABILITY

$$q(P1) = \frac{\lambda}{\lambda + \nu}$$

$$f(P1) = \lambda * (1 - q(P1))$$

[λ= failure rate, ν = repair rate]

STORE OUTPUT

P1	
Unavailability	$6.40e^{-03}$
Failure Frequency [h^{-1}]	$7.95e^{-04}$

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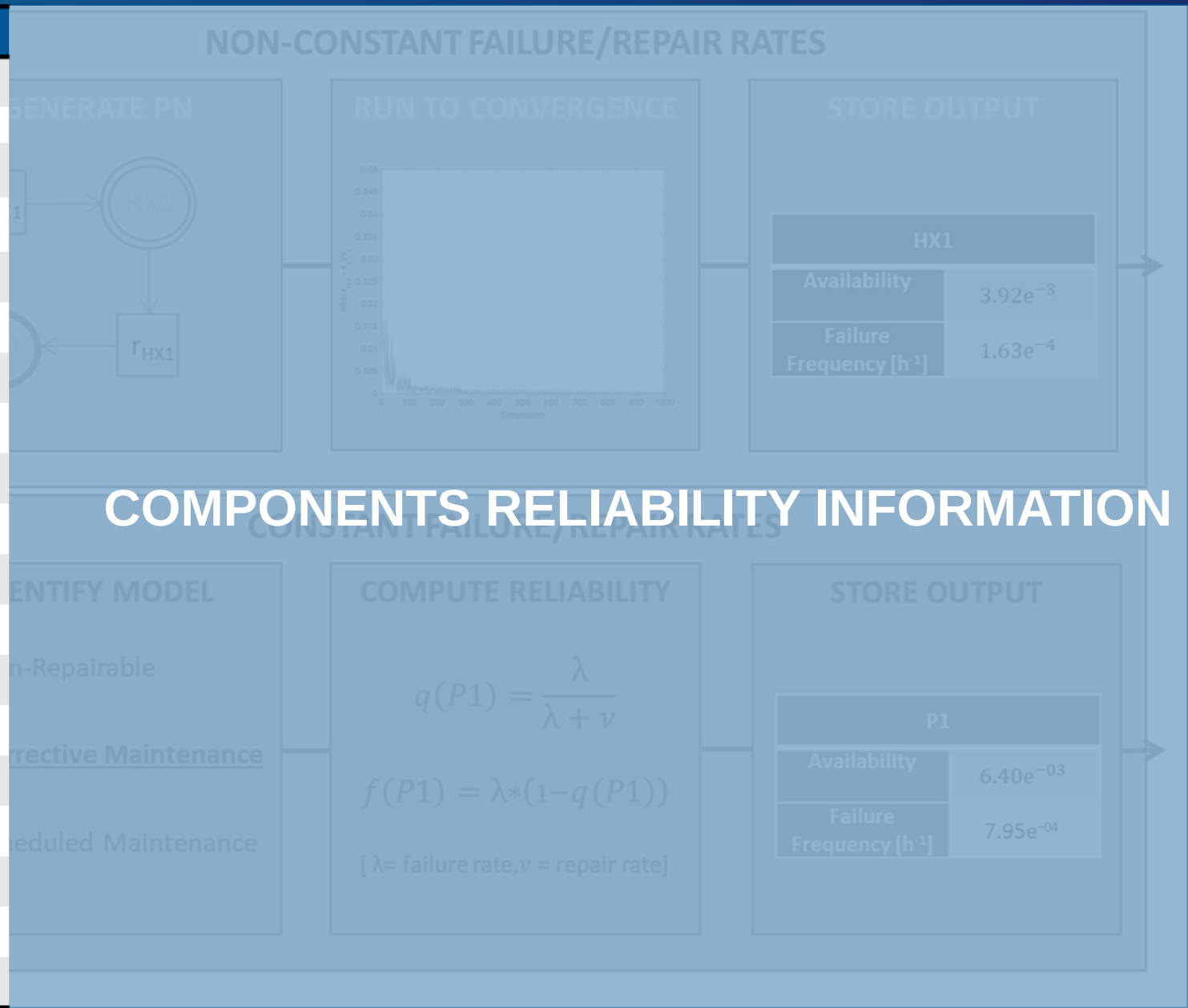
Step 1: Component Reliability

COMPONENT	UNAVAILABILITY	FAILURE FREQUENCY [h^{-1}]
P1	$6.40e^{-03}$	$7.95e^{-04}$
P2	$6.40e^{-03}$	$7.95e^{-04}$
HX1	$3.92e^{-03}$	$1.63e^{-04}$
T1	$5.29e^{-03}$	$4.87e^{-07}$
HX2	$2.38e^{-05}$	$1.70e^{-06}$
T2	$2.16e^{-07}$	$2.70e^{-08}$
V1	$1.35e^{-06}$	$2.70e^{-07}$
P3	$6.40\ e^{-03}$	$7.95e^{-04}$
TC	$2.13e^{-06}$	$7.10e^{-07}$
PGA	$9.4e^{-03}$	$3.1e^{-03}$
ADC	$6.90e^{-05}$	$2.30e^{-05}$
DF	$3.50e^{-03}$	$1.2e^{-03}$
RTD	$6.80e^{-06}$	$1.70e^{-06}$
FT	$3.60e^{-06}$	$1.20e^{-06}$
CMP	$4.80e^{-06}$	$1.20e^{-06}$
PLC	$3.67e^{-05}$	$3.06e^{-06}$
R1	$1.02e^{-06}$	$3.40e^{-07}$
M	$1.2e^{-03}$	$7.99e^{-06}$
F	$1.42e^{-04}$	$3.50e^{-06}$



COMPONENTS RELIABILITY INFORMATION

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Step 2: Independent FTs Definition

INPUT FTs

PRIMARY - Notepad

File Edit Format View Help

```
PRIMARY,1,G1,G2
G2,0,P1,P2
G1,1,HX1,T1
```

SECONDARY - Notepad

File Edit Format View Help

```
SECONDARY,1,F2,F1
F2,1,V1,P3
F1,1,HX2,T2
```

DETECTION_FT - Notepad

File Edit Format View Help

```
DETECTION,1,K1,COMP
K1,0,S1,S2
```

FAN - Notepad

File Edit Format View Help

```
FAN,1,R1,H1
H1,1,M,F
```

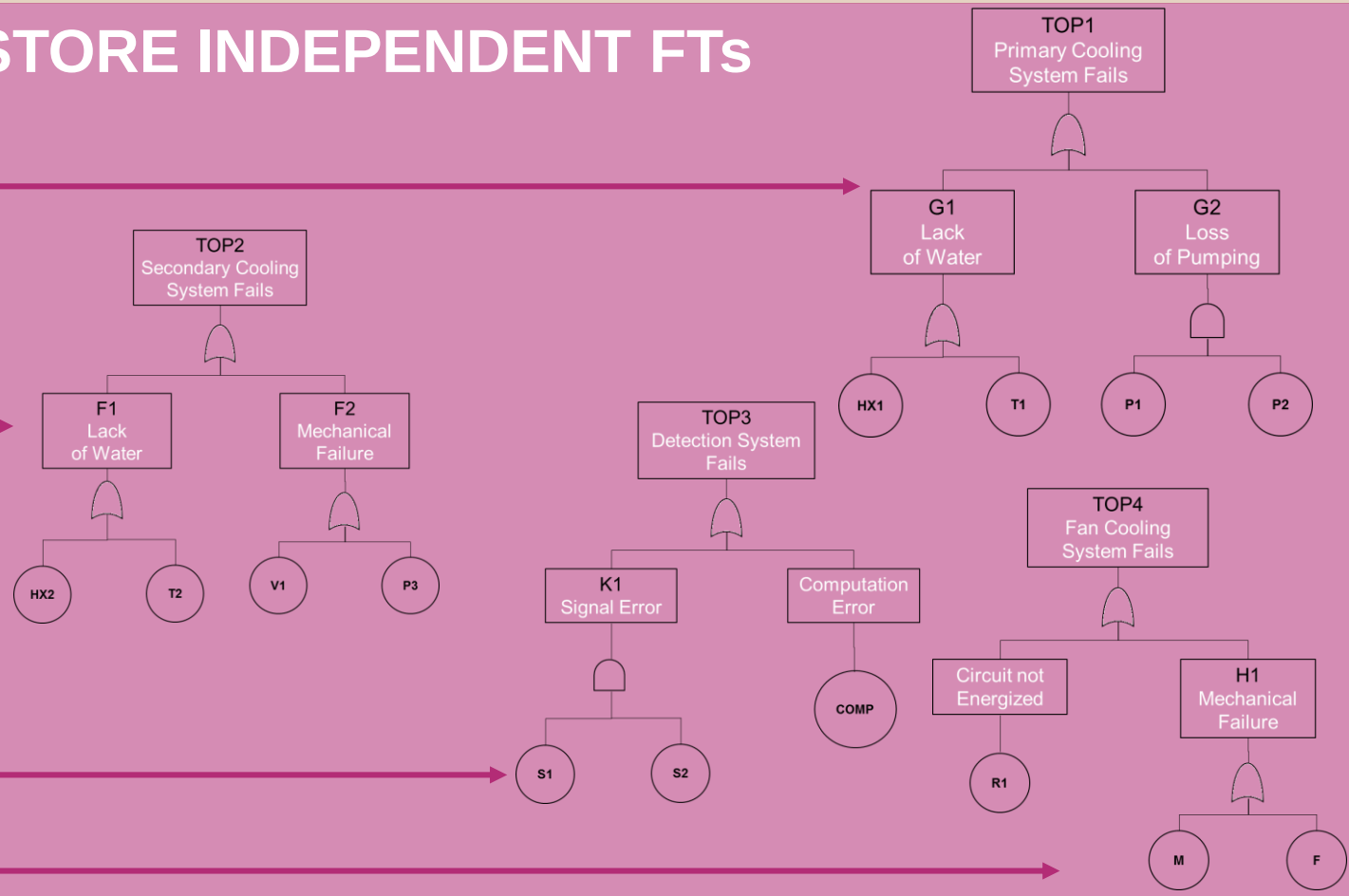
INDEPENDENT ?

DEPENDENCIES - Notepad

File Edit Format View Help

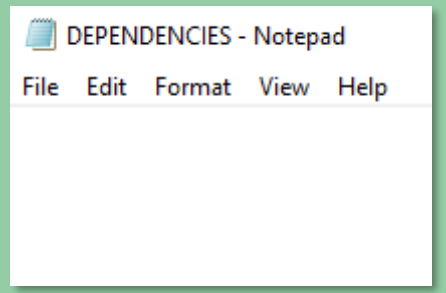
MERGE DEPENDENT FTs

STORE INDEPENDENT FTs



Step 3: Dependency Groups Computation

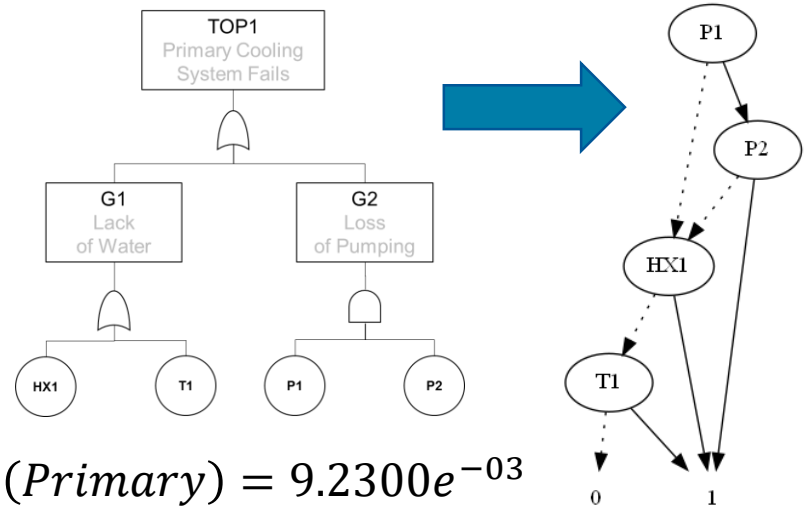
INDEPENDENT!



Since Case A assumes full independence, there are no dependency groups

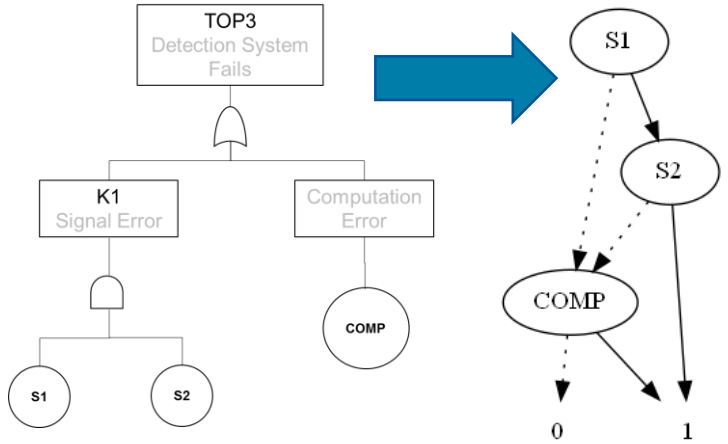
→ SKIP!

Step 4: FTs Computation

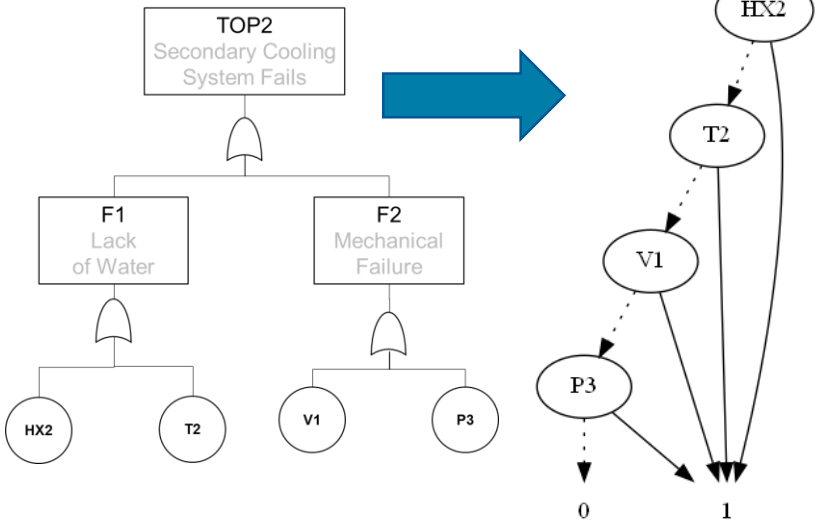


$$q(Primary) = 9.2300e^{-03}$$

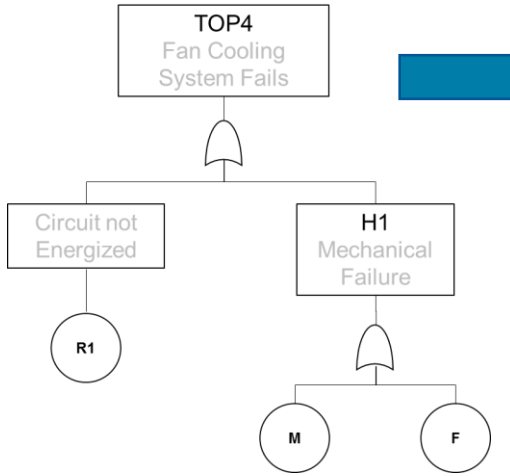
$$f(Primary) = 1.2257e^{-05}h^{-1}$$

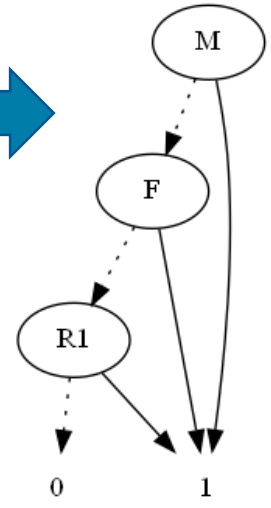


$$q(Detection) = 6.7154e^{-03}$$



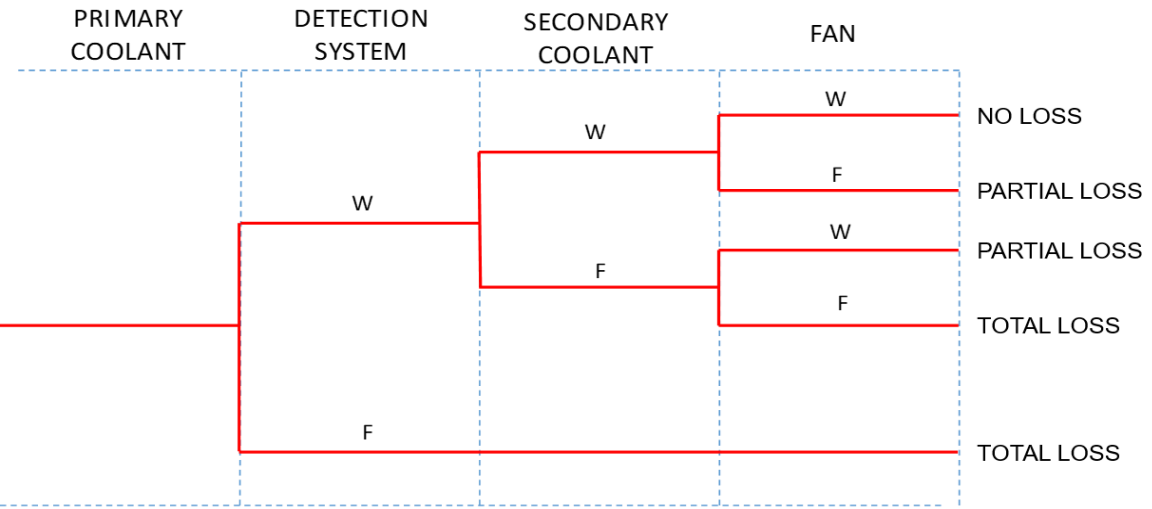
$$q(Secondary) = 5.4615e^{-03}$$





$$q(Fan) = 1.2747e^{-02}$$

Step 5: ET Computation



CONSEQUENCE FREQUENCIES

$$F_{NoLoss} = 1.1954e^{-05}h^{-1}$$

$$F_{PartialLoss} = f_{PartialLoss1} + f_{PartialLoss2} = 2.1999e^{-07}\,h^{-1}$$

$$FTotalLo_{ss} = f_{TotalLoss1}{}_{+} f_{TotalLoss1}{}_{=} 8.3158\,e^{-08}\,h^{-1}$$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Case Study B
Hard Dependency

Case Study C: Hard Dependency

DEPENDENCY -...

File Edit Format View Help

```
COMMON COMPONENTS
P2:PRIMARY,SECONDARY
```

PRIMARY_FT - ...

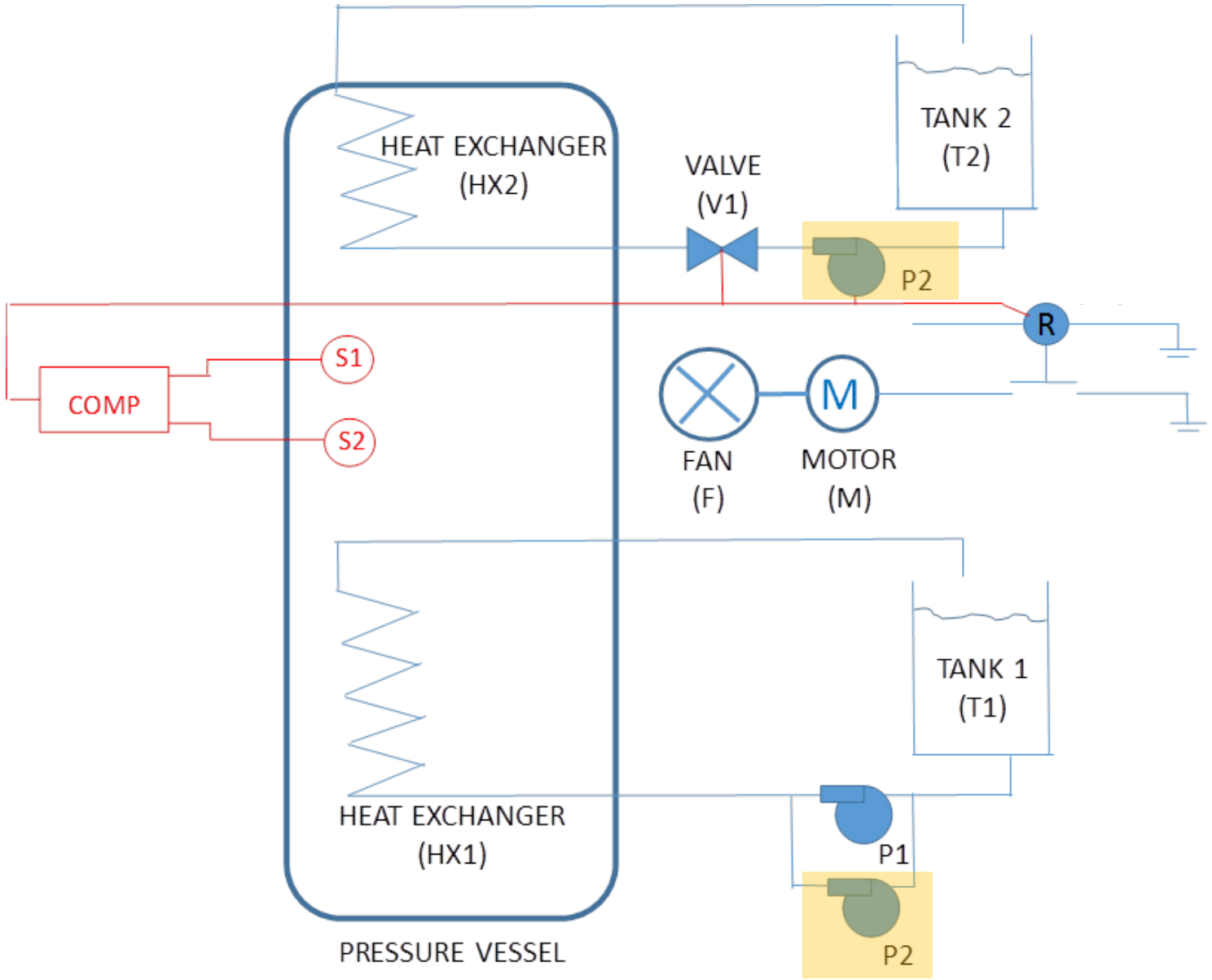
File Edit Format View Help

```
PRIMARY,1,G1,G2
G2,0,P1,P2
G1,1,HX1,T1
```

SECONDARY_F...

File Edit Format View Help

```
SECONDARY,1,F2,F1
F2,1,V1,P2
F1,1,HX2,T2
```



Step 1: Component Reliability

COMPONENTS ...

File Edit Format View Help

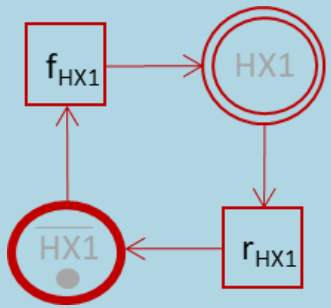
```
HX1
FAIL
1.7e-6
REPAIR
0.0417

T1
FAIL
2.7e-8
REPAIR
0.1250

P1
FAIL
8.0e-4
REPAIR
0.1250

P2
FAIL
8.0e-4
REPAIR
0.1250

HX2
FAIL
1.7e-6
REPAIR
0.0714
INSPECTION
4380
```

Exponentially Distributed?

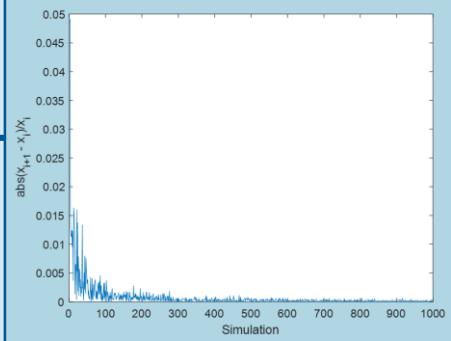
N

NON-CONSTANT FAILURE/REPAIR RATES

GENERATE PN



RUN TO CONVERGENCE



STORE OUTPUT

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[λ= failure rate, ν = repair rate]

STORE OUTPUT

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Failure Frequency [h^{-1}]	$7.95e^{-04}$

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Step 2: Independent FTs Definition

INPUT FTs

PRIMARY - Notepad

File Edit Format View Help

```
PRIMARY,1,G1,G2
G2,0,P1,P2
G1,1,HX1,T1
```

SECONDARY_FT - Notepad

File Edit Format View Help

```
SECONDARY,1,F2,F1
F2,1,V1,P2
F1,1,HX2,T2
```

DETECTION_FT - Notepad

File Edit Format View Help

```
DETECTION,1,K1,COMP
K1,0,S1,S2
```

FAN - Notepad

File Edit Format View Help

```
FAN,1,R1,H1
H1,1,M,F
```

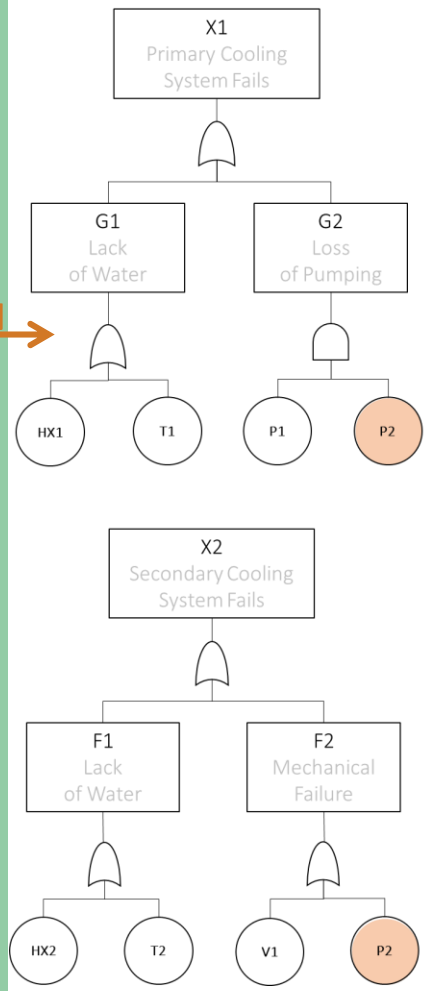
INDEPENDENT ?

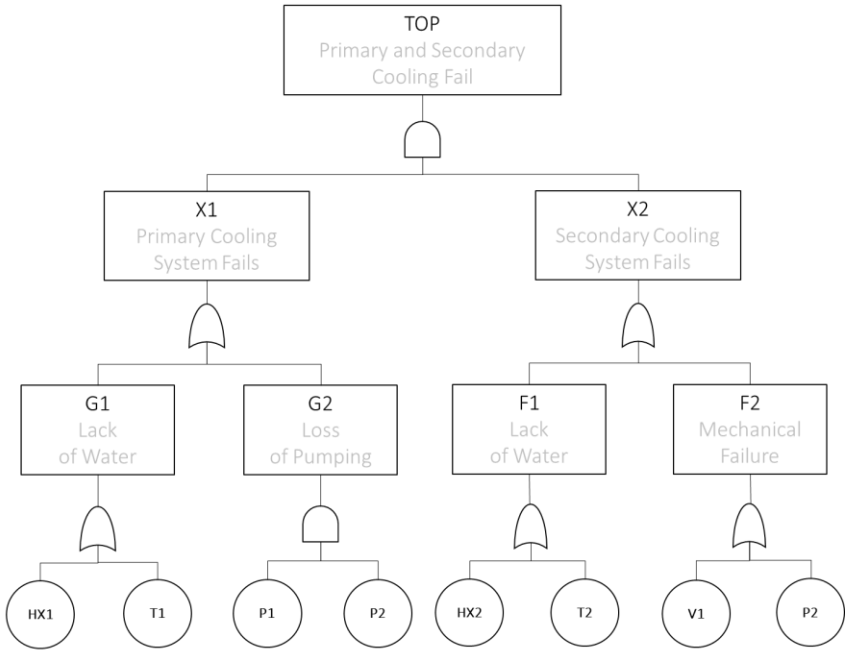
DEPENDENCY -...

File Edit Format View Help

```
COMMON COMPONENTS
P2:PRIMARY,SECONDARY
```

N





Step 2: Independent FTs Definition

INPUT FTs

PRIMARY - Notepad

File Edit Format View Help

```
PRIMARY,1,G1,G2
G2,0,P1,P2
G1,1,HX1,T1
```

SECONDARY_FT - Notepad

File Edit Format View Help

```
SECONDARY,1,F2,F1
F2,1,V1,P2
F1,1,HX2,T2
```

DETECTION_FT - Notepad

File Edit Format View Help

```
DETECTION,1,K1,COMP
K1,0,S1,S2
```

FAN - Notepad

File Edit Format View Help

```
FAN,1,R1,H1
H1,1,M,F
```

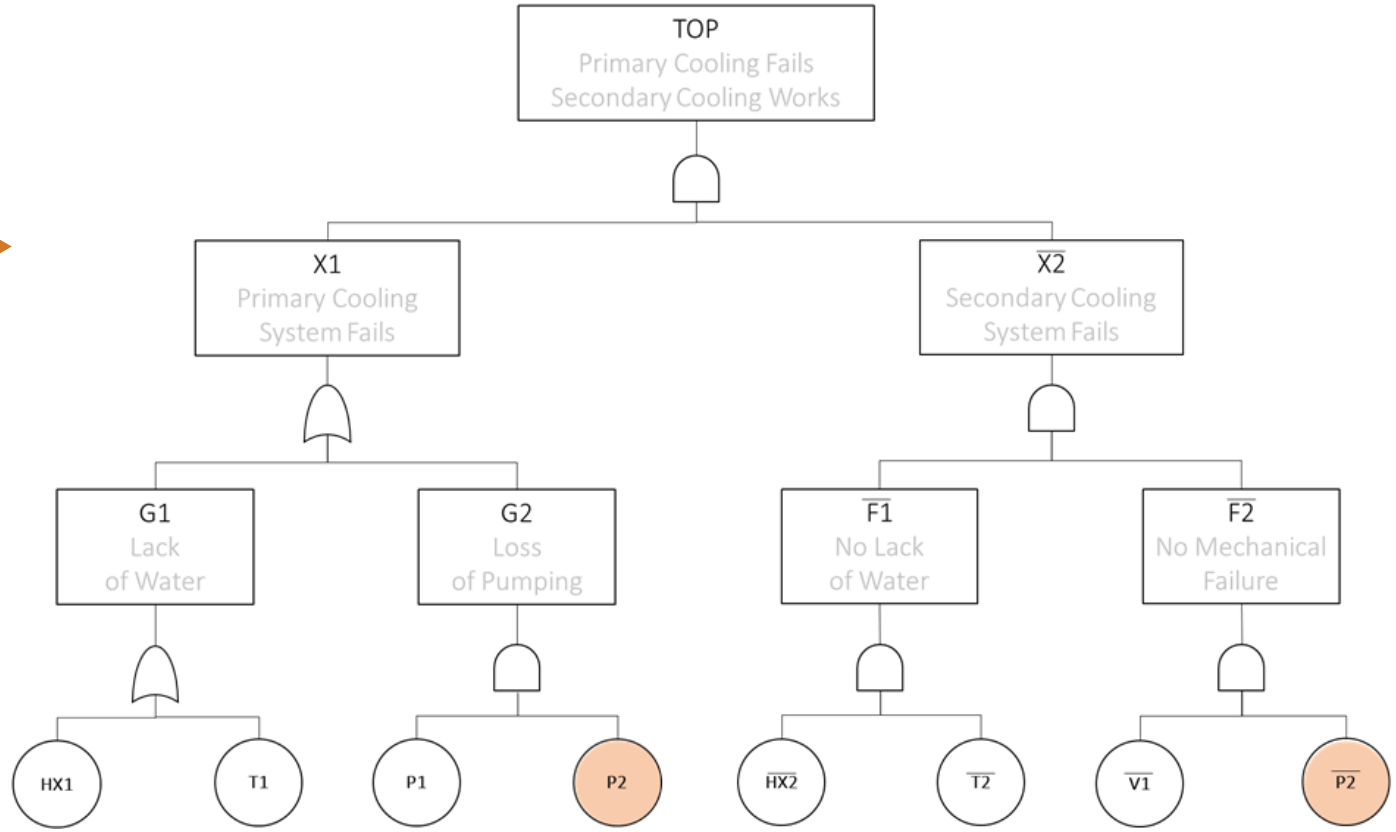
INDEPENDENT ?

DEPENDENCY -...

File Edit Format View Help

```
COMMON COMPONENTS
P2:PRIMARY,SECONDARY
```

N



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Step 2: Independent FTs Definition

INPUT FTs

PRIMARY - Notepad

File Edit Format View Help

```
PRIMARY,1,G1,G2
G2,0,P1,P2
G1,1,HX1,T1
```

SECONDARY_FT - Notepad

File Edit Format View Help

```
SECONDARY,1,F2,F1
F2,1,V1,P2
F1,1,HX2,T2
```

DETECTION_FT - Notepad

File Edit Format View Help

```
DETECTION,1,K1,COMP
K1,0,S1,S2
```

FAN - Notepad

File Edit Format View Help

```
FAN,1,R1,H1
H1,1,M,F
```

INDEPENDENT ?

DEPENDENCY -...

File Edit Format View Help

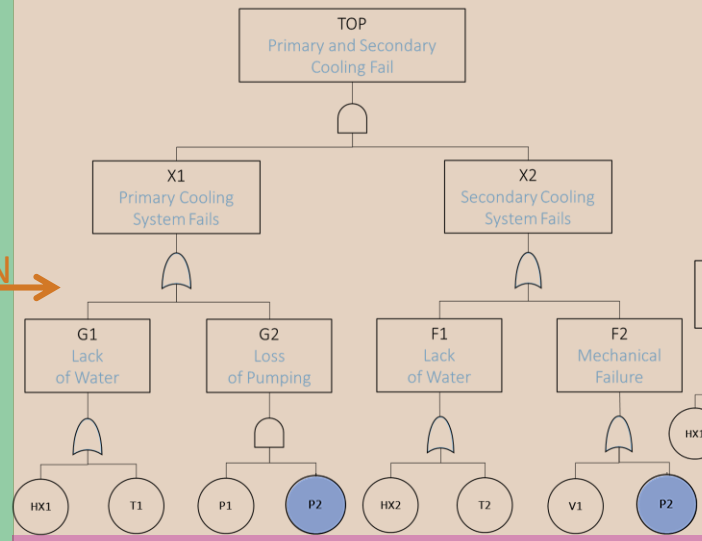
```
COMMON COMPONENTS
P2:PRIMARY,SECONDARY
```

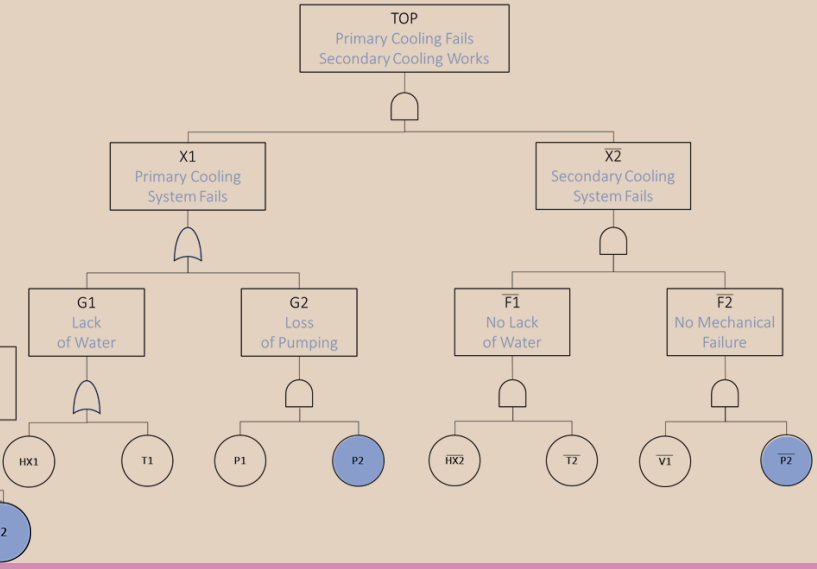
N

Y

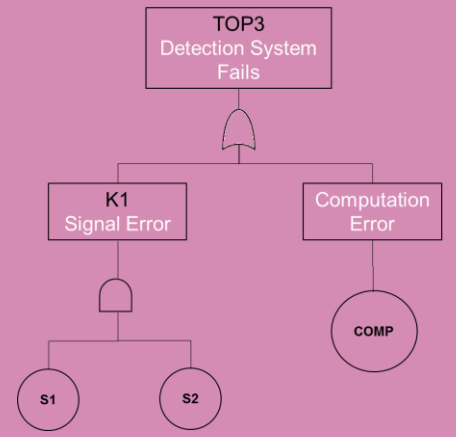
Y

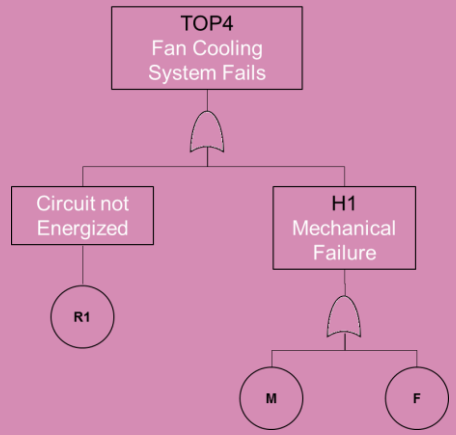
MERGE DEPENDENT FTs





STORE INDEPENDENT FTs





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Step 2: Independent FTs Definition

INPUT FTs

PRIMARY - Notepad

File Edit Format View Help

```
PRIMARY,1,G1,G2
G2,0,P1,P2
G1,1,HX1,T1
```

SECONDARY_FT - Notepad

File Edit Format View Help

```
SECONDARY,1,F2,F1
F2,1,V1,P2
F1,1,HX2,T2
```

DETECTION_FT - Notepad

File Edit Format View Help

```
DETECTION,1,K1,COMP
K1,0,S1,S2
```

FAN - Notepad

File Edit Format View Help

```
FAN,1,R1,H1
H1,1,M,F
```

INDEPENDENT ?

DEPENDENCY -...

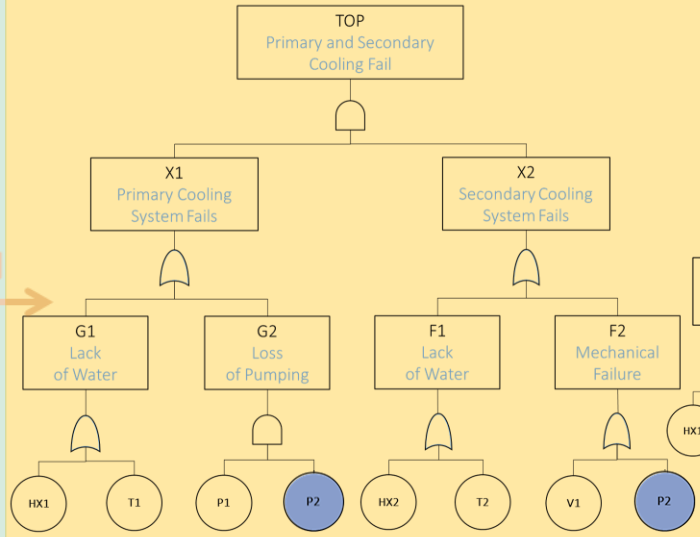
File Edit Format View Help

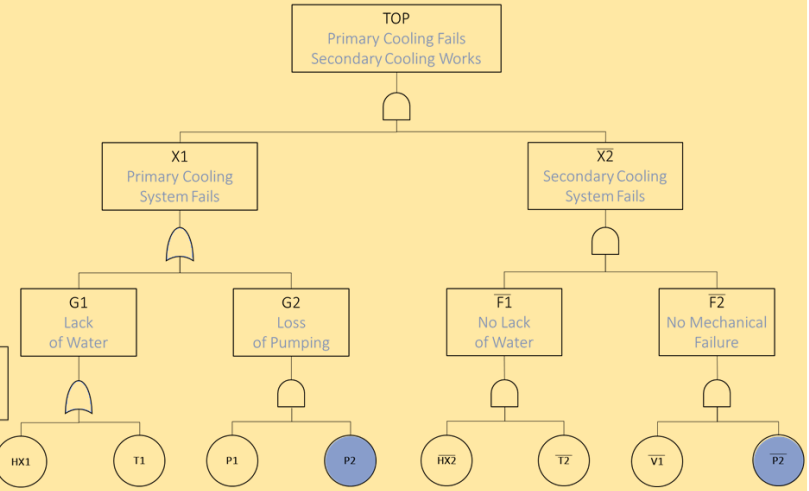
```
COMMON COMPONENTS
P2:PRIMARY,SECONDARY
```

N

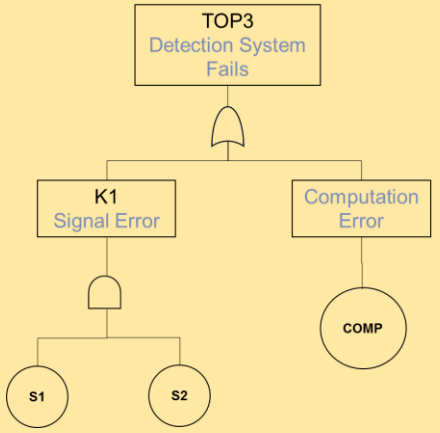
Y

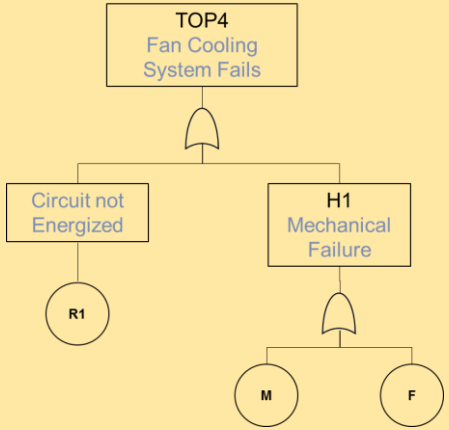
Y





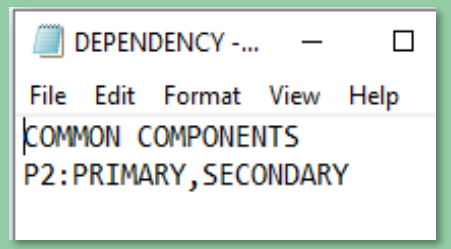
INDEPENDENT FTs





Step 3: Dependency Groups Computation

INDEPENDENT !

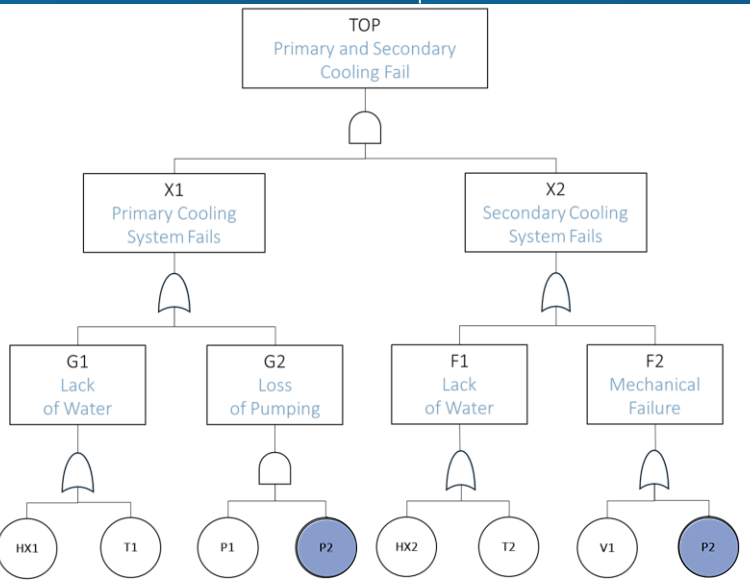


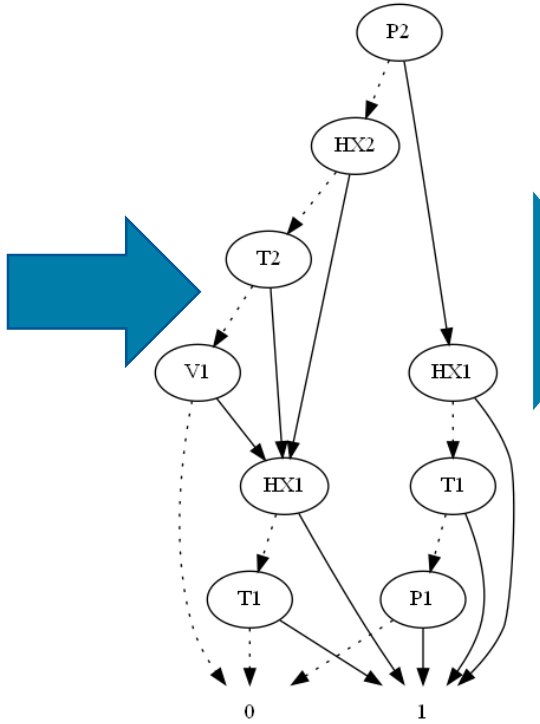
The only dependency associated with the case study is between FTs

Since Case B assumes full independence among components, there are no dependency groups to be computed

→ SKIP!

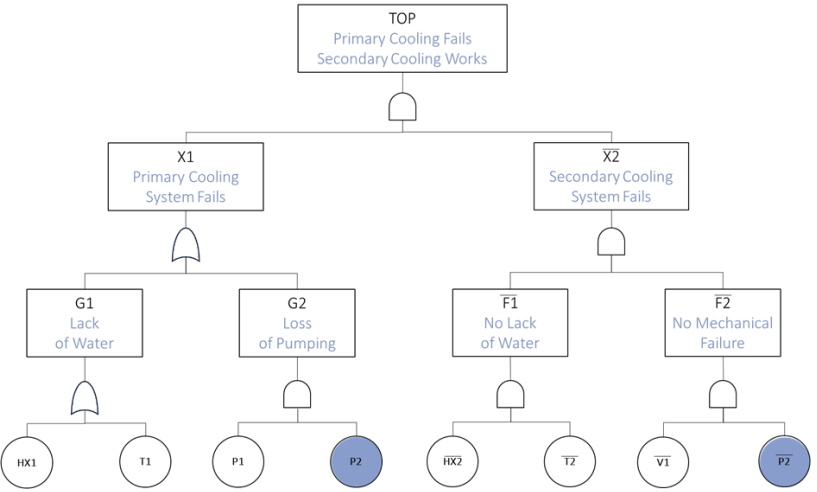
Step 4: FTs Computation

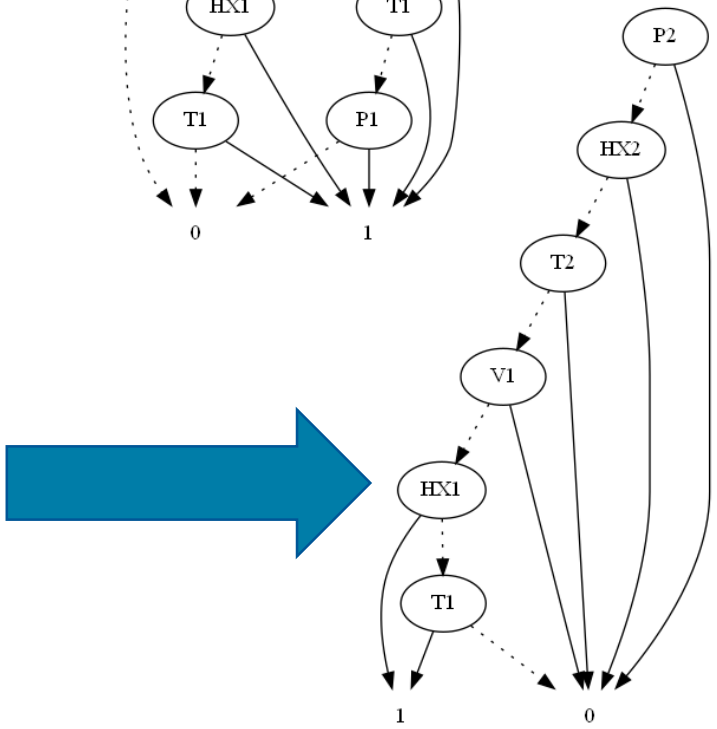




$$q(Primary, Secondary) = 4.1399ee^{-05}$$

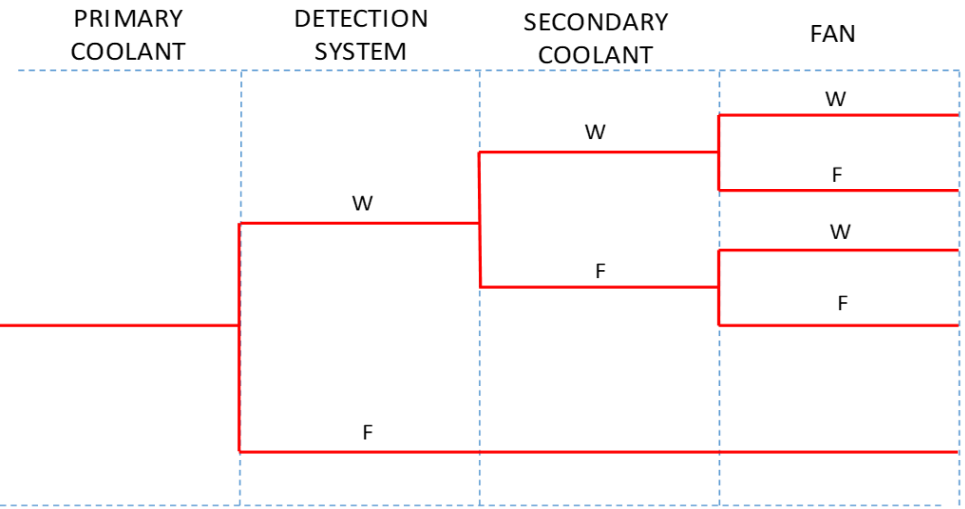
$$[f(Primary) = 1.2257e^{-05}h^{-1}]$$





$$q\left(Primary, \overline{Secondary}\right) = 8.1942e^{-05}$$

Step 5: ET Computation



NO LOSS

PARTIAL LOSS

PARTIAL LOSS

TOTAL LOSS

TOTAL LOSS

$$f_{NoLoss} = f_{primary} \cdot q(\overline{Secondary}|Primary) \cdot q(\overline{Detection}) \cdot q(\overline{Fan})$$

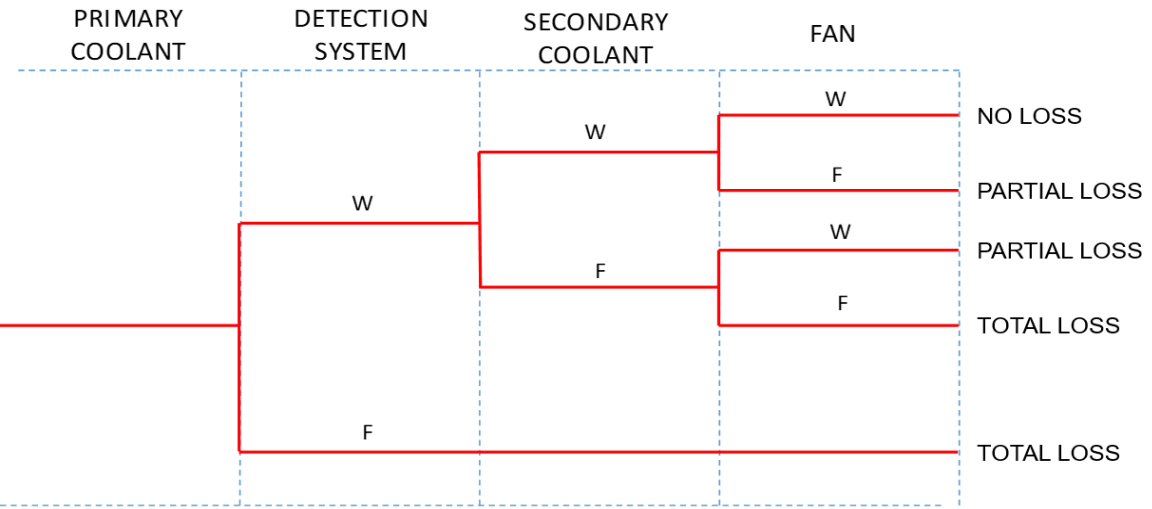
$$f_{PartialLoss1} = f_{primary} \cdot q(\overline{Secondary}|Primary) \cdot q(\overline{Detection}) \cdot q(Fan)$$

$$f_{PartialLoss2} = f_{primary} \cdot q(Secondary|Primary) \cdot q(\overline{Detection}) \cdot q(\overline{Fan})$$

$$f_{TotalLoss1} = f_{primary} \cdot q(Secondary|Primary) \cdot q(\overline{Detection}) \cdot q(Fan)$$

$$f_{TotalLoss2} = f_{primary} \cdot Q(Detection)$$

Step 5: ET Computation



TRIGGER RELIABILITY INFO

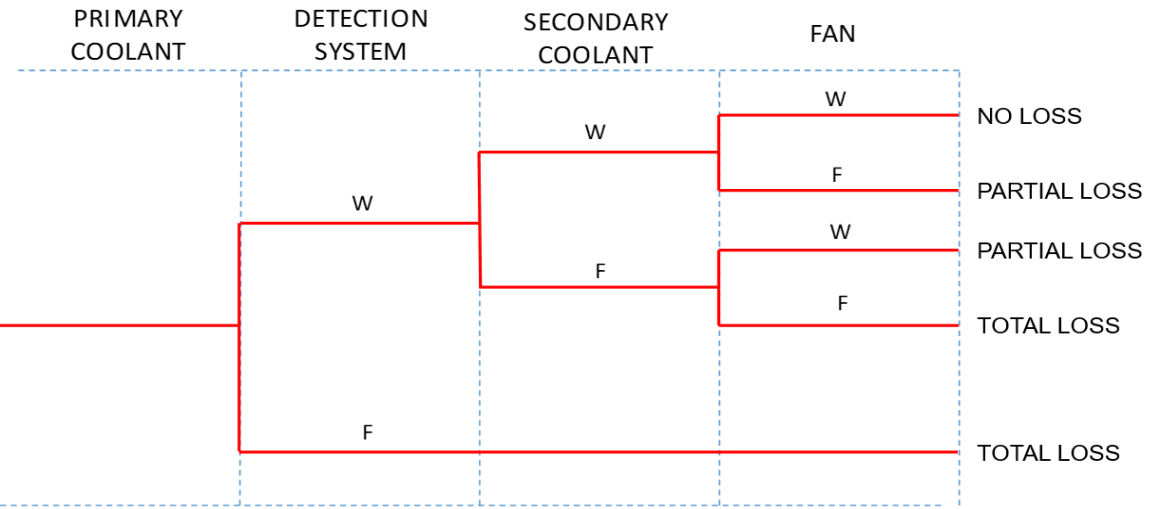
→ $Q(\text{Primary})$

$= Q(\text{Primary}, \text{Secondary}) + Q\left(\text{Primary}, \overline{\text{Secondary}}\right)$

→ $Q(\text{Secondary}|\text{Primary}) = \frac{Q(\text{Primary},\text{Secondary})}{Q(\text{Primary})}$

→ $Q\left(\overline{\text{Secondary}}|\text{Primary}\right) = \frac{Q\left(\text{Primary},\overline{\text{Secondary}}\right)}{Q(\text{Primary})}$

Step 5: ET Computation



CONSEQUENCE FREQUENCIES

$$F_{NoLoss} = 1.4415e^{-05}h^{-1}$$

$$F_{PartialLoss} = f_{PartialLoss1} + f_{PartialLoss2} = 7.4687\ e^{-06}\ h^{-1}$$

$$FTota_{lLoss} = f_{TotalLoss1}{}_{+} f_{TotalLoss1}{}_{=} 2.4262\ e^{-07}\ h^{-1}$$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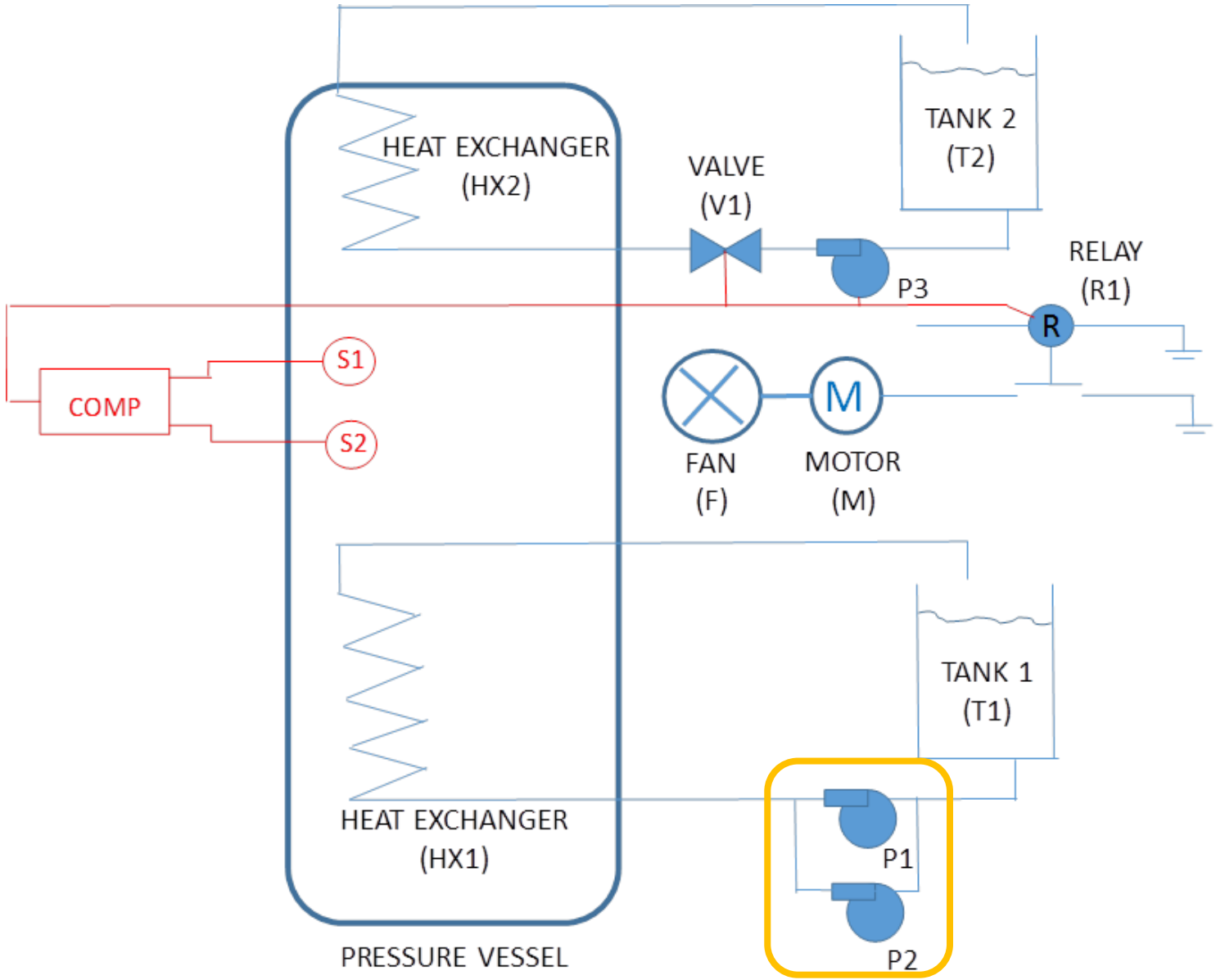
Case Study D
Soft Dependency

Case Study D: Soft Dependency

P1 and P2 stochastically dependent

The failure of P1 (P2) causes the increase of P2 (P1) failure probability due to the larger load processed by the working pump



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Case Study D: Soft Dependency

BUILT-IN GENERATION

DEPENDENCIES - Notepad

```
LOAD
P1|P2:exponential,14.0e-4
P2|P1:exponential,14.0e-4
```

COMPONENTS ...

```
HX1
FAIL
1.7e-6
REPAIR
0.0417

T1
FAIL
2.7e-8
REPAIR
0.1250

P1
FAIL
8.0e-4
REPAIR
0.1250

P2
FAIL
8.0e-4
REPAIR
0.1250
```

IMPORTED MM

COMPONENTS - Notepad

```
P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
```

DEPENDENCY - Notepad

```
MMS
P1P2_MM
```

P1P2_MM - Notepad

```
STATES
P1_W,P2_W
P1,P2_W
P1_W,P2
P1,P2

TRANSITION MATRIX
-1,0.5,0.5,0
12,-13,0,1
12,0,-13,1
6,0,0,-6
```

IMPORTED PN

COMPONENTS - Notepad

```
P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
```

DEPENDENCY - Notepad

```
PNS
P1P2_PN
```

P1P2_PN - Notepad

```
PLACES
P1requested,1
P1
P1_W
P2_W
P2

TRANSITIONS
P1requested->P1_W,P1:P1start,probability,0.981,0.019
P1_W->P1:P1fails,exponential,8.0e-4
P1->P1_W:P1repair,exponential,0.1250
P1->P1,P2_W,P2:P2start,probability,0.981,0.019
P2->P2_W:P2repair,exponential,0.1250
P2_W->P2:P2fails,exponential,8.0e-4
P1_W,P2_W->P1_W:P2toSleep,instant,0

INHIBITORS
P2->P2start
```

IMPORTED DATA

COMPONENTS - Notepad

```
P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
```

DEPENDENCY - Notepad

```
DATA
DG1_DATA
```

DG1_DATA - Notepad

```
PROBABILITY
P1_W,P2_W:9.8749e-01
P1,P2_W:6.1863e-03
P1_W,P2:6.1863e-03
P1,P2:1.3362e-04

FREQUENCY
P1_W,P2_W:1.5799e-03
P1,P2_W:7.8999e-04
P1_W,P2:7.8999e-04
P1,P2:3.3406e-05
```

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Case Study D: Soft Dependency

BUILT-IN GENERATION

DEPENDENCIES - Notepad

```
LOAD
P1|P2:exponential,14.0e-4
P2|P1:exponential,14.0e-4
```

COMPONENTS ...

```
HX1
FAIL
1.7e-6
REPAIR
0.0417

T1
FAIL
2.7e-8
REPAIR
0.1250

P1
FAIL
8.0e-4
REPAIR
0.1250

P2
FAIL
8.0e-4
REPAIR
0.1250
```

IMPORTED MM

COMPONENTS - Notepad

```
P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
```

DEPENDENCY - Notepad

```
MMS
P1P2_MM
```

P1P2_MM - Notepad

```
STATES
P1_W,P2_W
P1,P2_W
P1_W,P2
P1,P2

TRANSITION MATRIX
-1,0.5,0.5,0
12,-13,0,1
12,0,-13,1
6,0,0,-6
```

IMPORTED PN

COMPONENTS - Notepad

```
P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
```

DEPENDENCY - Notepad

```
PNS
P1P2_PN
```

P1P2_PN - Notepad

```
PLACES
P1requested,1
P1
P1_W
P2_W
P2

TRANSITIONS
P1requested->P1_W,P1:P1start,probability,0.981,0.019
P1_W->P1:P1fails,exponential,8.0e-4
P1->P1_W:P1repair,exponential,0.1250
P1->P1,P2_W,P2:P2start,probability,0.981,0.019
P2->P2_W:P2repair,exponential,0.1250
P2_W->P2:P2fails,exponential,8.0e-4
P1_W,P2_W->P1_W:P2toSleep,instant,0

INHIBITORS
P2->P2start
```

IMPORTED DATA

COMPONENTS - Notepad

```
P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
```

DEPENDENCY - Notepad

```
DATA
DG1_DATA
```

DG1_DATA - Notepad

```
PROBABILITY
P1_W,P2_W:9.8749e-01
P1,P2_W:6.1863e-03
P1_W,P2:6.1863e-03
P1,P2:1.3362e-04

FREQUENCY
P1_W,P2_W:1.5799e-03
P1,P2_W:7.8999e-04
P1_W,P2:7.8999e-04
P1,P2:3.3406e-05
```

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Step 1: Component Reliability

COMPONENTS - Notepad

File Edit Format View Help

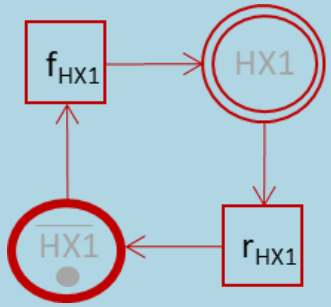
```
HX1
FAIL
1.7e-6
REPAIR
0.0417

T1
FAIL
2.7e-8
REPAIR
0.1250

P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
0.0714
INSPECTION
4380

T2
FAIL
2.7e-8
REPAIR
0.1250
INSPECTION
```

Exponentially Distributed?

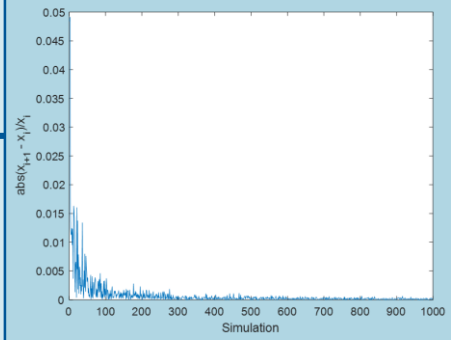
N

NON-CONSTANT FAILURE/REPAIR RATES

GENERATE PN



RUN TO CONVERGENCE



STORE OUTPUT

HX1	
Unavailability	$3.92e^{-3}$
Failure Frequency [h^{-1}]	$1.63e^{-4}$

Y

CONSTANT FAILURE/REPAIR RATES

IDENTIFY MODEL

- Non-Repairable
- **Corrective Maintenance**
- Scheduled Maintenance

COMPUTE RELIABILITY

$$q(P1) = \frac{\lambda}{\lambda + \nu}$$

$$f(P1) = \lambda * (1 - q(P1))$$

[λ= failure rate, ν = repair rate]

STORE OUTPUT

P1	
Unavailability	$6.40e^{-03}$
Failure Frequency [h^{-1}]	$7.95e^{-04}$

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Step 2: Independent FTs Definition

INPUT FTs

PRIMARY - Notepad

File Edit Format View Help

```
PRIMARY,1,G1,G2
G2,0,P1,P2
G1,1,HX1,T1
```

SECONDARY - Notepad

File Edit Format View Help

```
SECONDARY,1,F2,F1
F2,1,V1,P3
F1,1,HX2,T2
```

DETECTION_FT - Notepad

File Edit Format View Help

```
DETECTION,1,K1,COMP
K1,0,S1,S2
```

FAN - Notepad

File Edit Format View Help

```
FAN,1,R1,H1
H1,1,M,F
```

INDEPENDENT ?

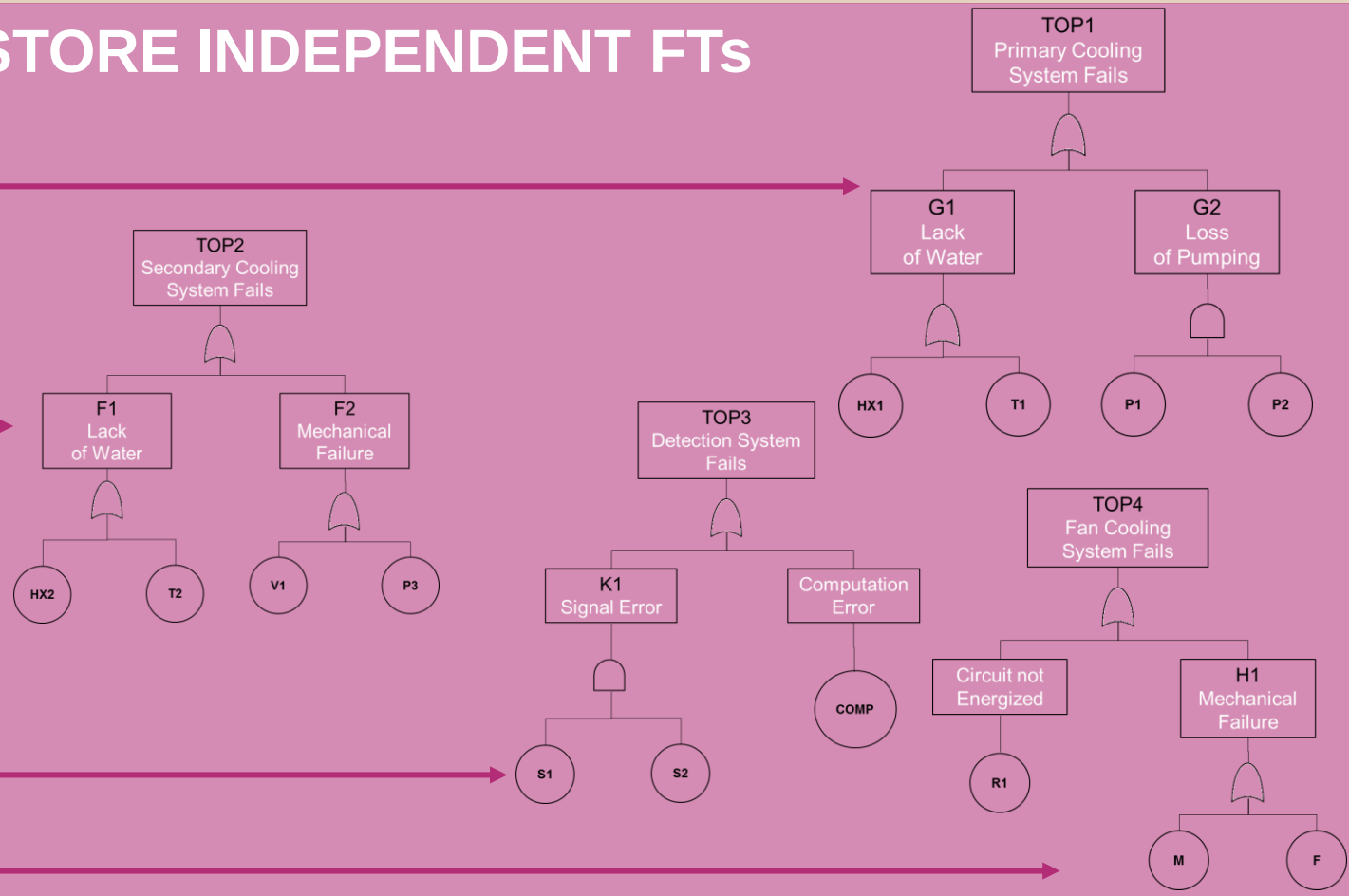
DEPENDENCY - Notepad

File Edit Format View Help

```
MMS
P1P2_MM
```

MERGE DEPENDENT FTs

STORE INDEPENDENT FTs



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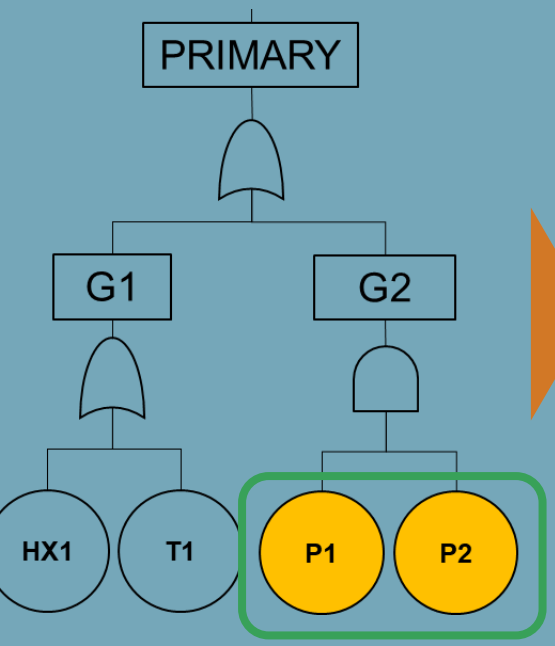
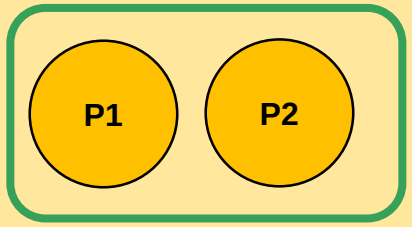
Step 3: Dependency Group Computation

FT 1



DEPENDENCY GROUPS



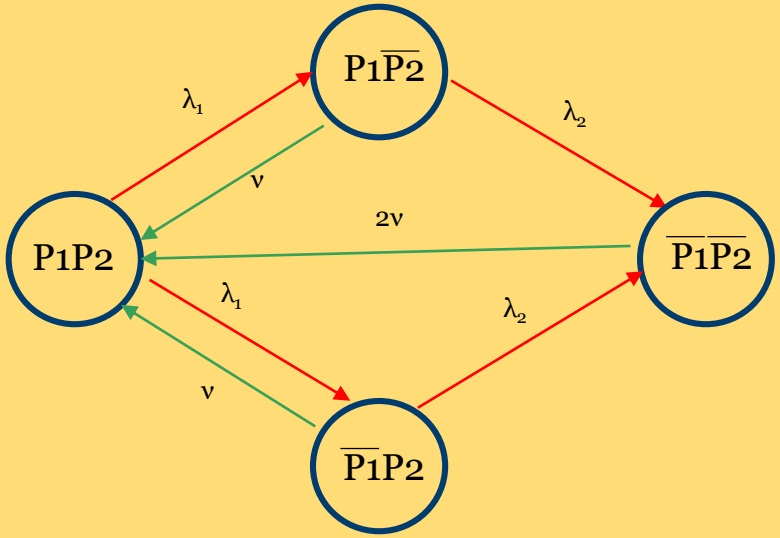
P1P2_MM - Notepad

File Edit Format View Help

```
STATES
P1_W,P2_W
P1,P2_W
P1_W,P2
P1,P2

TRANSITION MATRIX
-1,0.5,0.5,0
12,-13,0,1
12,0,-13,1
6,0,0,-6
```

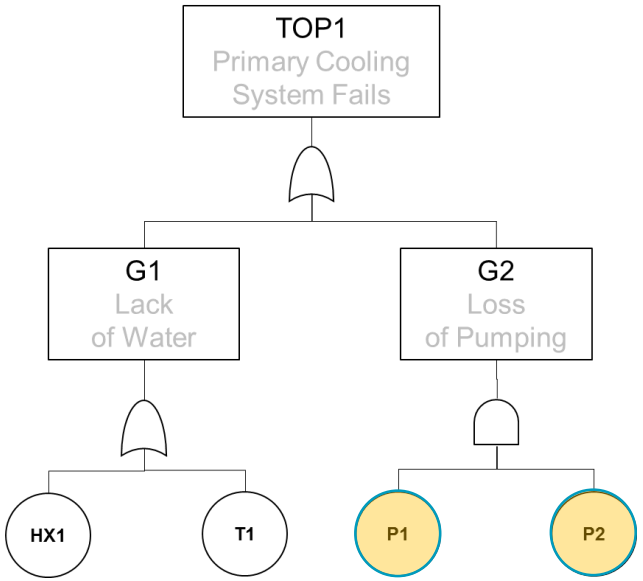
MM GENERATION

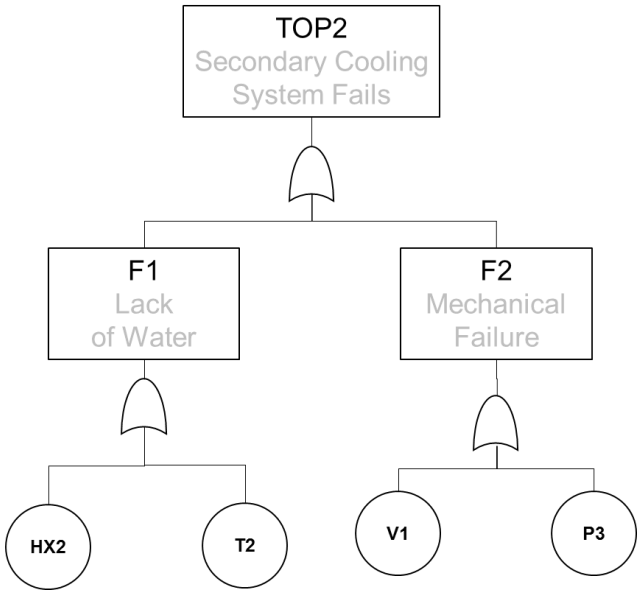


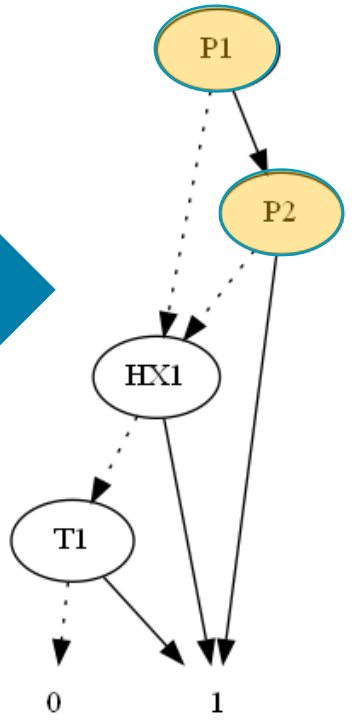
MM CALCULATION

STATE	PROBABILITY	FREQUENCY
$P1, P2$	$1.3362e^{-04}$	$3.3406e^{-05}$
$P1, \overline{P2}$	$6.1863e^{-03}$	$7.8999e^{-04}$
$\overline{P1}, P2$	$6.1863e^{-03}$	$7.8999e^{-04}$
$\overline{P1}, \overline{P2}$	$9.8749e^{-01}$	$1.5799e^{-03}$

Step 4: FTs Computation

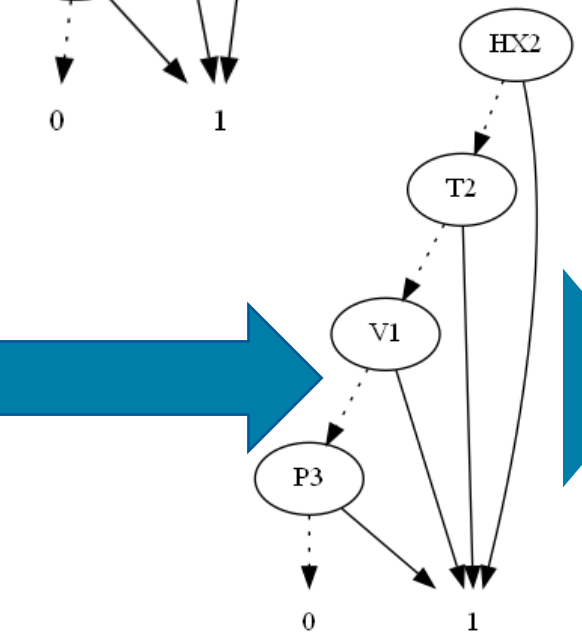






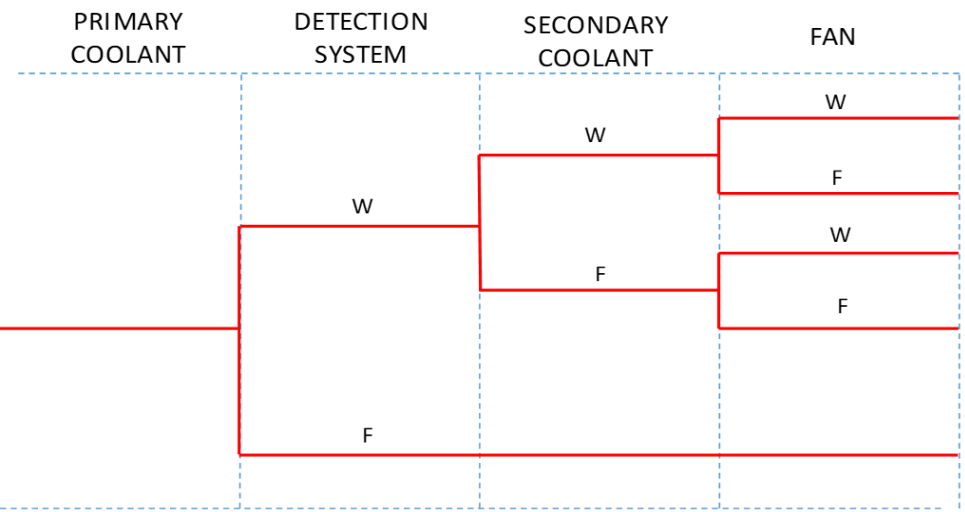
Need for different BDD algorithm

$$q(Primary) = 1.7460e^{-04}$$



$$q(Secondary) = 5.4615e^{-03}$$

Step 5: ET Computation



NO LOSS

PARTIAL LOSS

PARTIAL LOSS

TOTAL LOSS

TOTAL LOSS

$$f_{NoLoss} = f_{primary} \cdot q(\overline{Secondary}) \cdot q(\overline{Detection}) \cdot q(\overline{Fan})$$

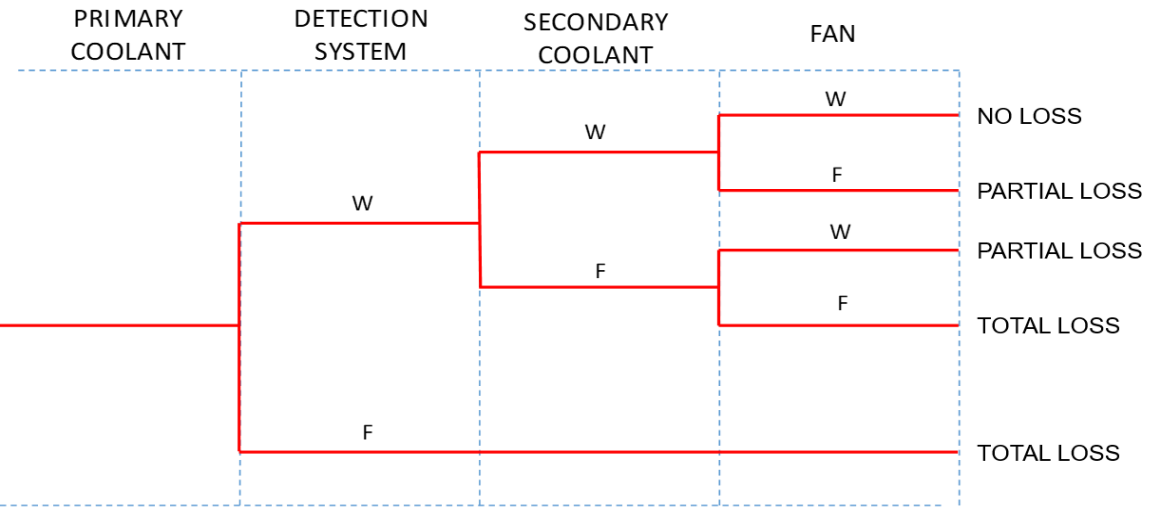
$$f_{PartialLoss1} = f_{primary} \cdot q(\overline{Secondary}) \cdot q(\overline{Detection}) \cdot q(Fan)$$

$$f_{PartialLoss2} = f_{primary} \cdot q(Secondary) \cdot q(\overline{Detection}) \cdot q(\overline{Fan})$$

$$f_{TotalLoss1} = f_{primary} \cdot q(Secondary) \cdot q(\overline{Detection}) \cdot Q(Fan)$$

$$f_{TotalLoss2} = f_{primary} \cdot q(Detection)$$

Step 5: ET Computation



CONSEQUENCE FREQUENCIES

$$F_{NoLoss} = 3.5639\ e^{-05} h^{-1}$$

$$F_{PartialLoss} = f_{PartialLoss1} + f_{PartialLoss2} = 6.5588\ e^{-07}\ h^{-1}$$

$$FTotalLo_{ss} = f_{TotalLoss1}{}_{+} f_{TotalLoss1}{}_{=} 2.4793\ e^{-08}\ h^{-1}$$

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Case Study D

A bit of everything

Complex Dependency

COMPONENTS - Notepad

File Edit Format View Help

```
P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
```

DEPENDENCY - Notepad

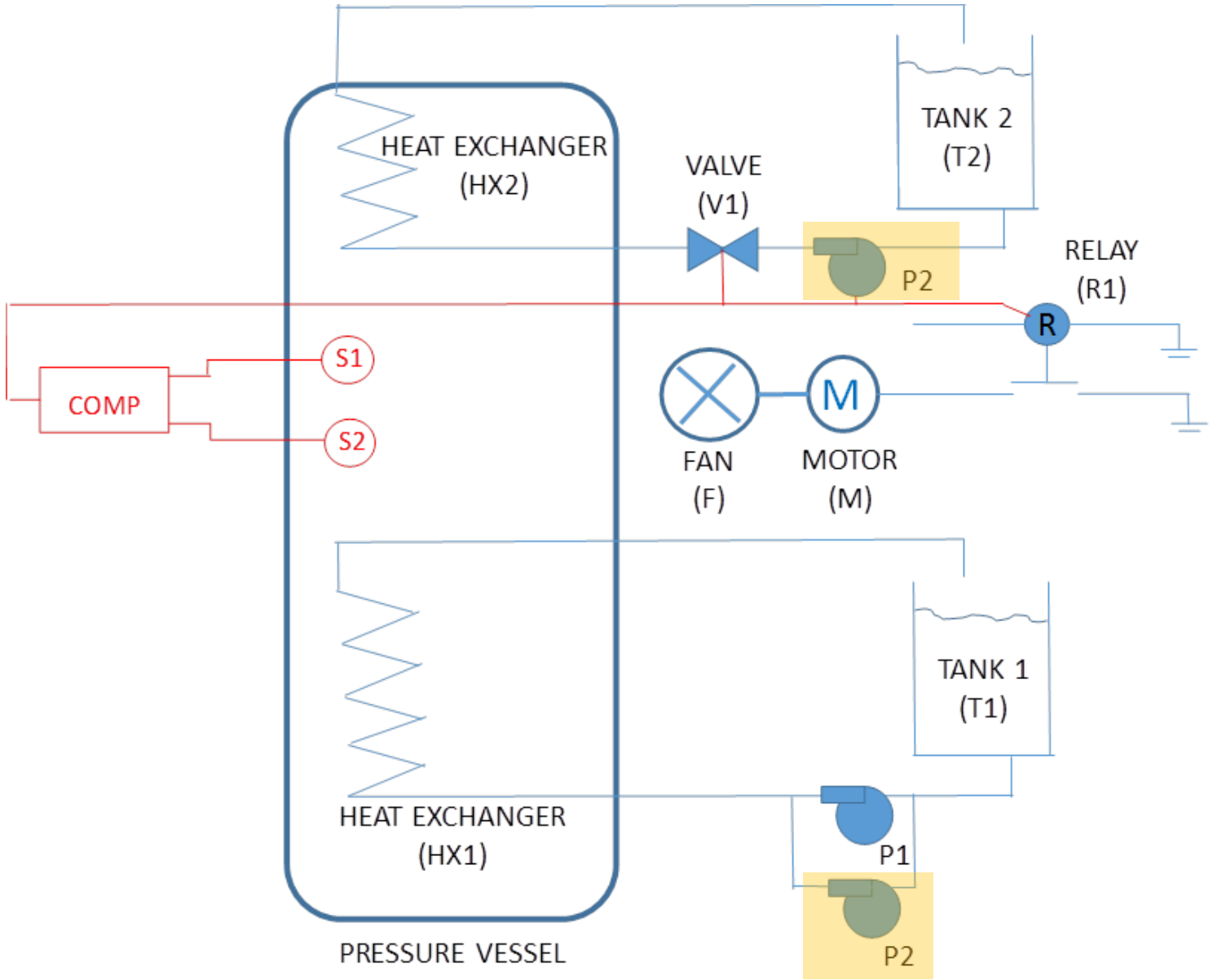
File Edit Format View Help

```
MMs
P1P2_MM

COMMON COMPONENTS
P2:PRIMARY,SECONDARY
```

P1P2_MM - Notepad

File Edit Format View Help

```
STATES
P1_W,P2_W
P1,P2_W
P1_W,P2
P1,P2

TRANSITION MATRIX
-1,0.5,0.5,0
12,-13,0,1
12,0,-13,1
6,0,0,-6
```



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Step 1: Component Reliability

COMPONENTS - Notepad

File Edit Format View Help

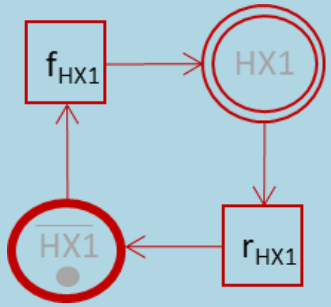
```
HX1
FAIL
1.7e-6
REPAIR
0.0417

T1
FAIL
2.7e-8
REPAIR
0.1250

P1
DEP

P2
DEP

HX2
FAIL
1.7e-6
REPAIR
0.0714
INSPECTION
4380

T2
FAIL
2.7e-8
REPAIR
0.1250
INSPECTION
```

Exponentially Distributed?

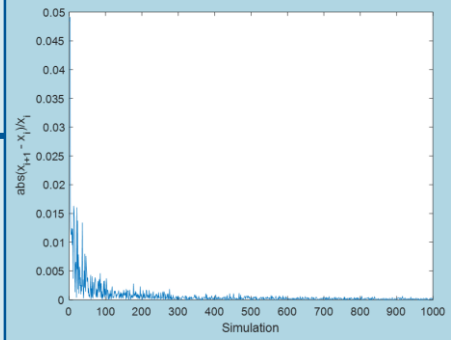
N

NON-CONSTANT FAILURE/REPAIR RATES

GENERATE PN



RUN TO CONVERGENCE



STORE OUTPUT

HX1	
Unavailability	$3.92e^{-3}$
Failure Frequency [h^{-1}]	$1.63e^{-4}$

Y

CONSTANT FAILURE/REPAIR RATES

IDENTIFY MODEL

- Non-Repairable
- **Corrective Maintenance**
- Scheduled Maintenance

COMPUTE RELIABILITY

$$q(P1) = \frac{\lambda}{\lambda + \nu}$$

$$f(P1) = \lambda * (1 - q(P1))$$

[λ= failure rate, ν = repair rate]

STORE OUTPUT

P1	
Unavailability	$6.40e^{-03}$
Failure Frequency [h^{-1}]	$7.95e^{-04}$

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Step 2: Independent FTs Definition

INPUT FTs

PRIMARY - Notepad

File Edit Format View Help

```
PRIMARY,1,G1,G2
G2,0,P1,P2
G1,1,HX1,T1
```

SECONDARY_FT - Notepad

File Edit Format View Help

```
SECONDARY,1,F2,F1
F2,1,V1,P2
F1,1,HX2,T2
```

DETECTION_FT - Notepad

File Edit Format View Help

```
DETECTION,1,K1,COMP
K1,0,S1,S2
```

FAN - Notepad

File Edit Format View Help

```
FAN,1,R1,H1
H1,1,M,F
```

INDEPENDENT ?

DEPENDENCY - Notepad

File Edit Format View Help

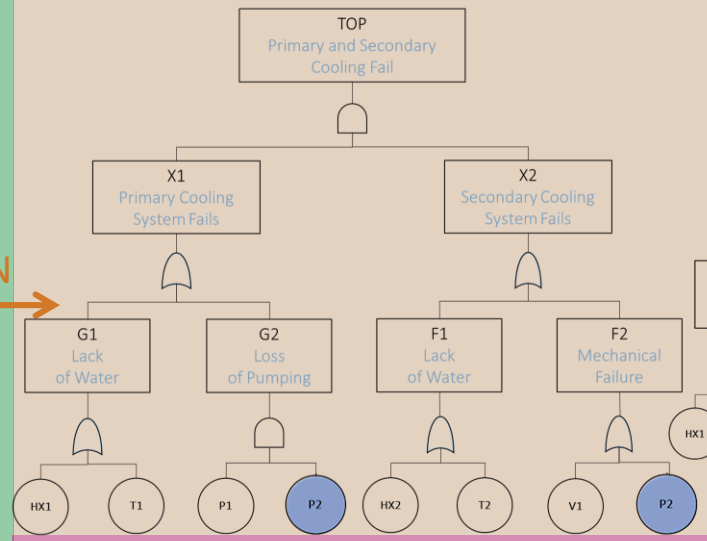
```
MMs
P1P2_MM

COMMON COMPONENTS
P2:PRIMARY,SECONDARY
```

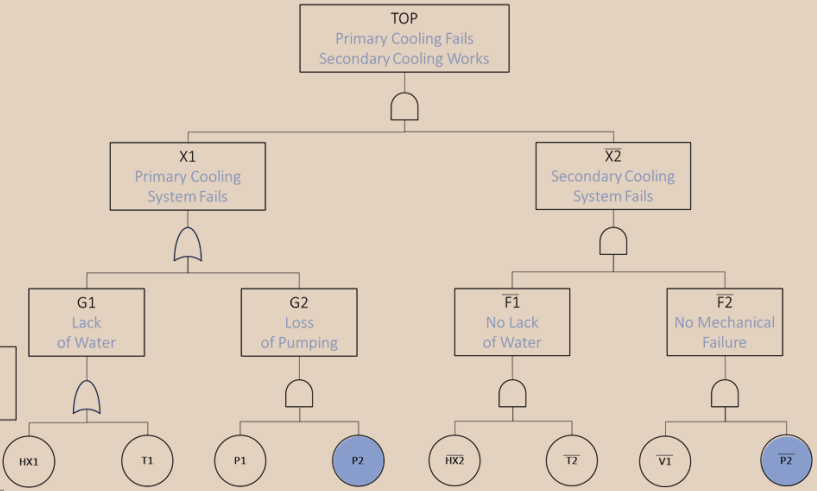
N

Y

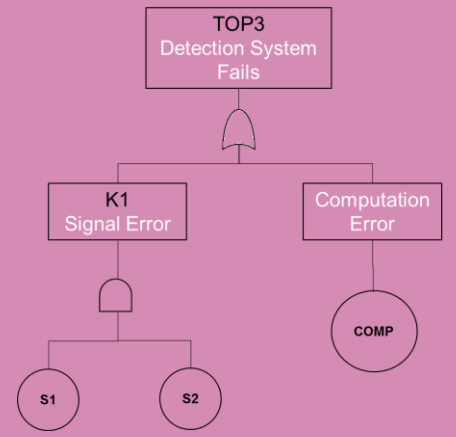
Y

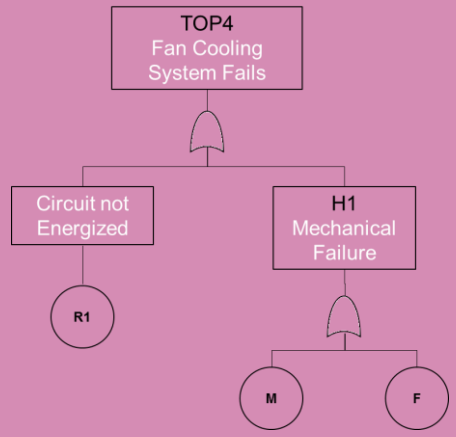
MERGE DEPENDENT FTs





STORE INDEPENDENT FTs





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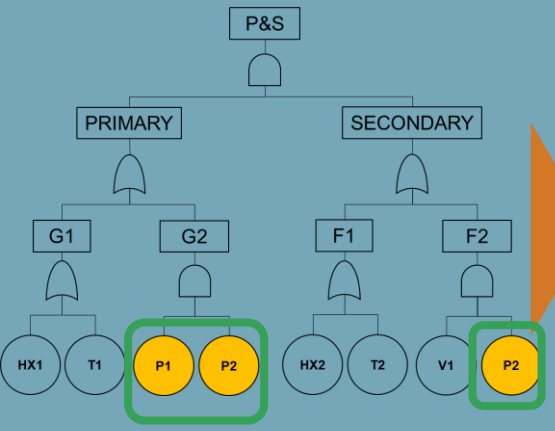
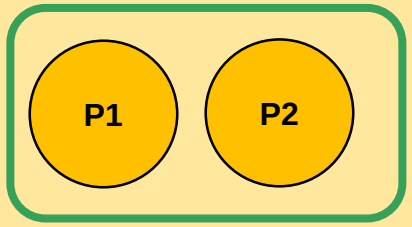
Step 3: Dependency Group Computation

FT 1



DEPENDENCY GROUPS



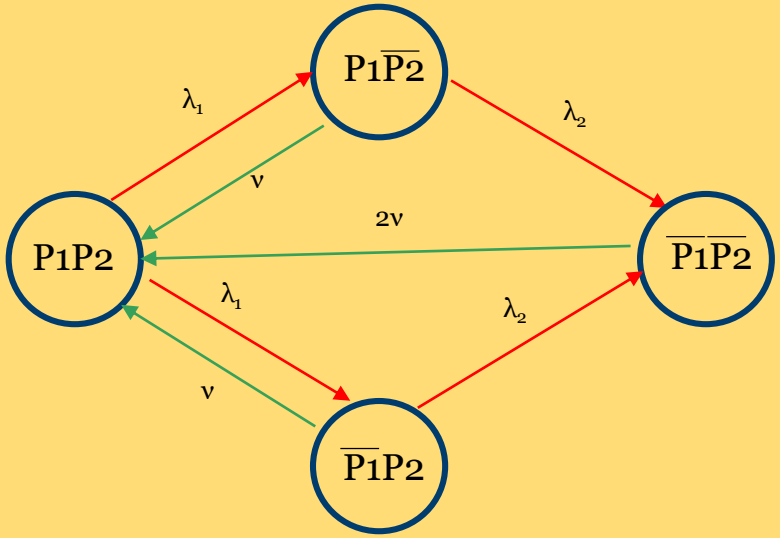
P1P2_MM - Notepad

File Edit Format View Help

```
STATES
P1_W,P2_W
P1,P2_W
P1_W,P2
P1,P2

TRANSITION MATRIX
-1,0.5,0.5,0
12,-13,0,1
12,0,-13,1
6,0,0,-6
```

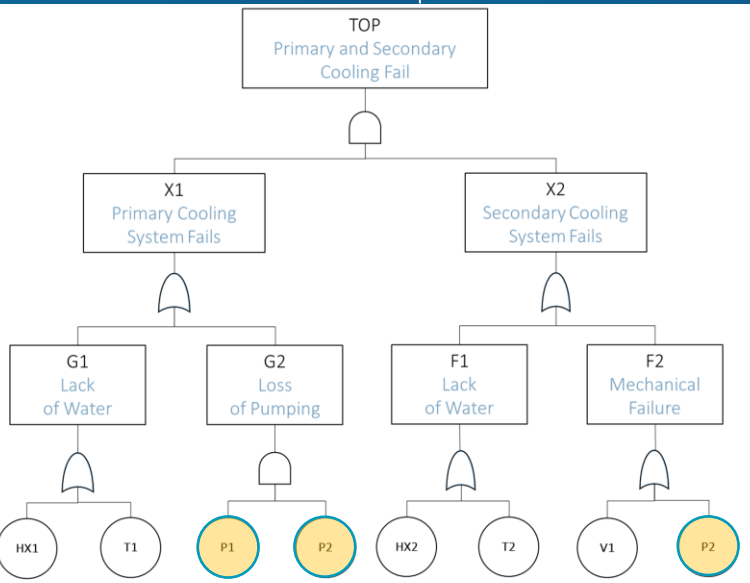
MM GENERATION

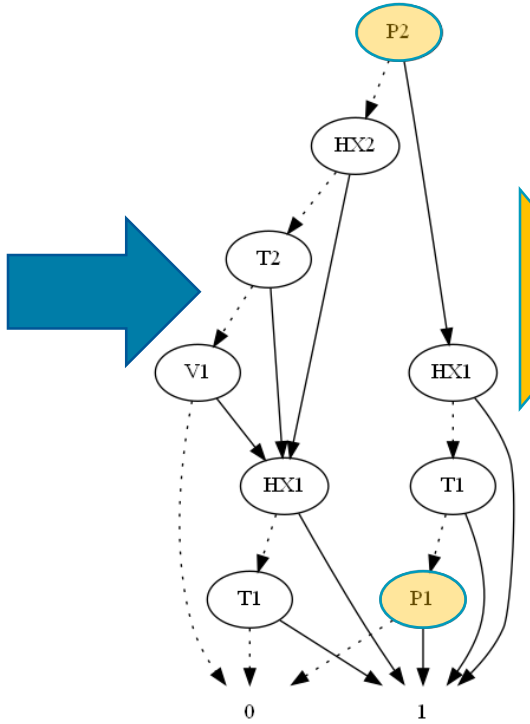


MM CALCULATION

STATE	PROBABILITY	FREQUENCY
$P1, P2$	$1.3362e^{-04}$	$3.3406e^{-05}$
$P1, \overline{P2}$	$6.1863e^{-03}$	$7.8999e^{-04}$
$\overline{P1}, P2$	$6.1863e^{-03}$	$7.8999e^{-04}$
$\overline{P1}, \overline{P2}$	$9.8749e^{-01}$	$1.5799e^{-03}$

Step 4: FTs Computation

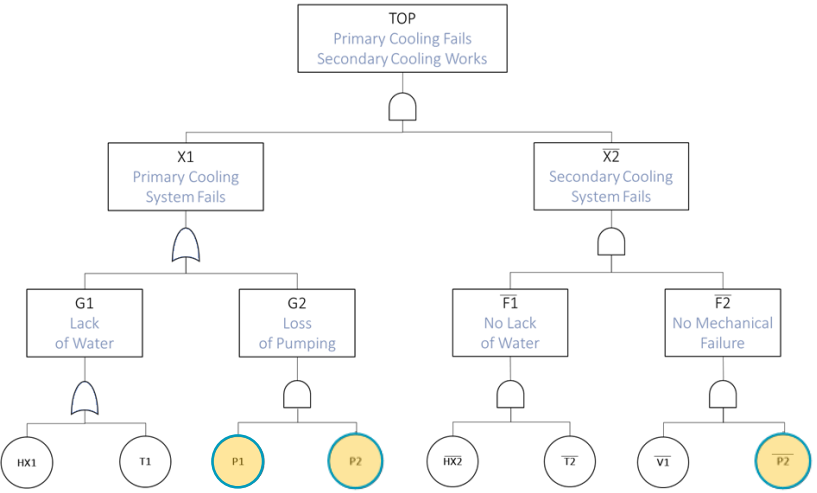


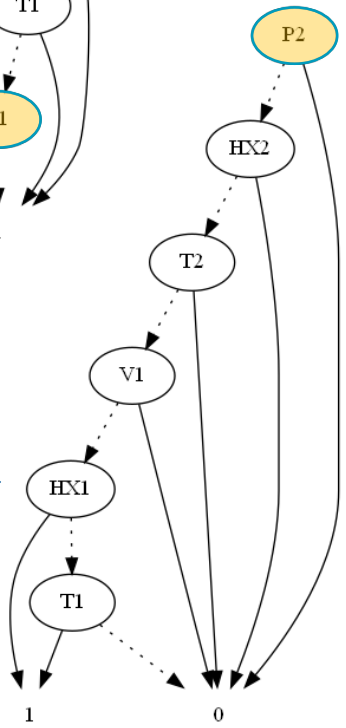


Need for different BDD algorithm

$$q(Primary, Secondary) = 1.3405e^{-04}$$

$[was\ \ 4.1399e^{-05}\ \ in\ case\ C]$



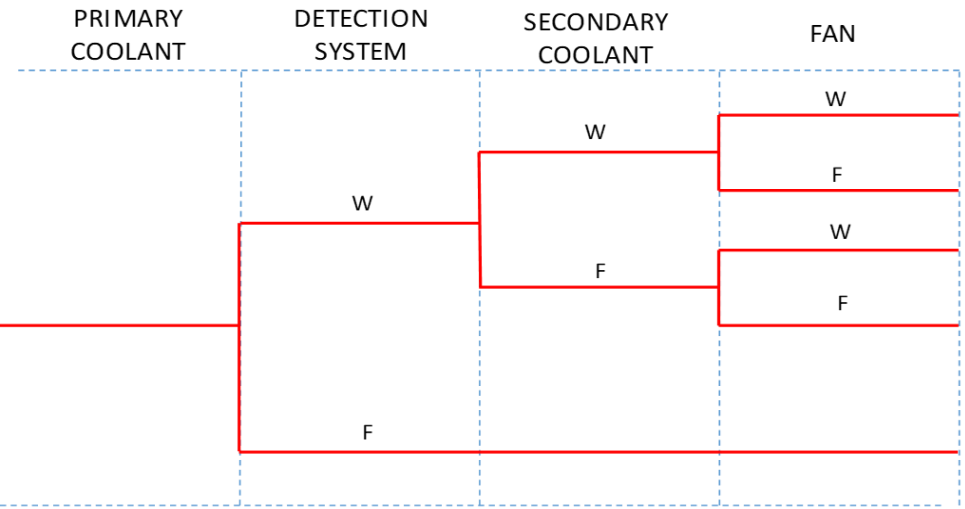


Need for different BDD algorithm

$$q\left(Primary, \overline{Secondary}\right) = 1.7459e^{-05}$$

$[was\ 8.1942e^{-05} in\ case\ C]$

Step 5: ET Computation



NO LOSS

PARTIAL LOSS

PARTIAL LOSS

TOTAL LOSS

TOTAL LOSS

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$$f_{TotalLoss2} = f_{primary} \cdot q(Detection)$$

Challenges and Current Work

Conclusions

Computational Feasibility and Flexibility

- BDD computation algorithm considering dependencies more computational demanding than traditional solutions
  - → need to minimise the use of the algorithm to the smallest section of the model containing dependencies
  - → **Faunet reduction and modularisation** (already implemented)

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  - → PN expected to be of limited size
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  - → PN expected to be of limited size
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- BDD merging (instead of FT merging for dependent FTs)