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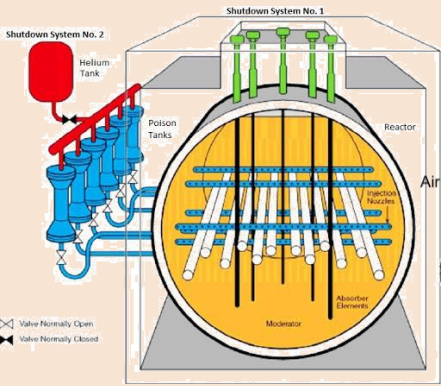
11TH IMA INTERNATIONAL CONFERENCE ON MODELLING IN
INDUSTRIAL MAINTENANCE AND RELIABILITY (MIMAR)

Risk Modelling Incorporating Complex Maintenance Strategies

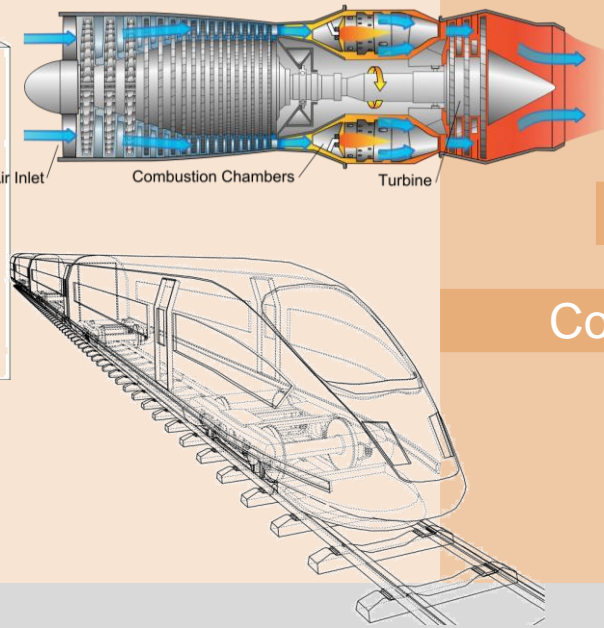
Silvia Tolo, Andrew Jackson and John Andrews



FAMILIAR MODELLING LANGUAGE



REALISTIC RISK MODELLING



Dependencies

Non-Constant Failure Rates

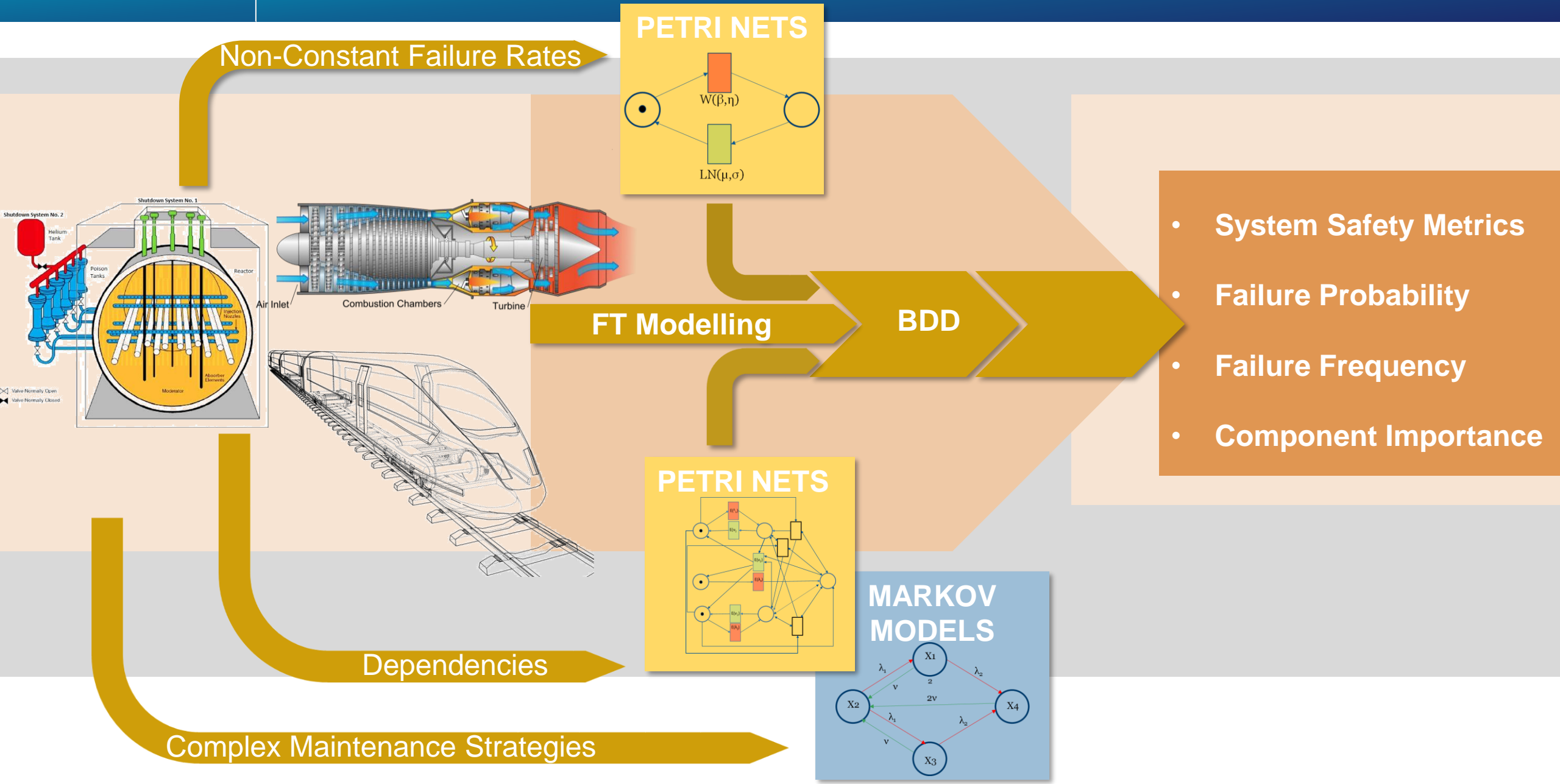
Complex Maintenance Strategies

ANALYSIS ACCURACY

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

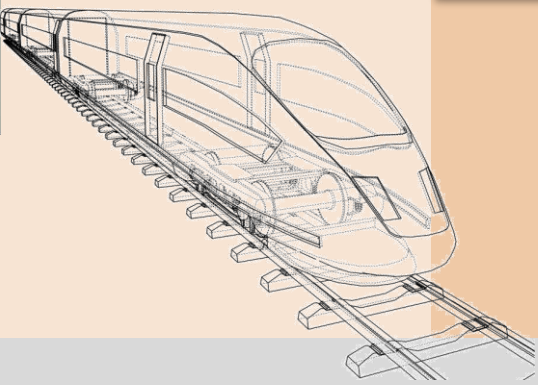
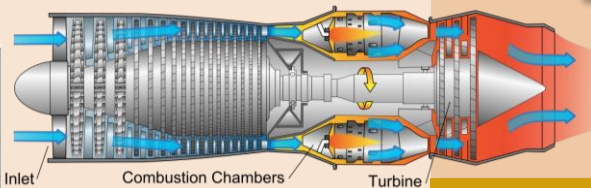
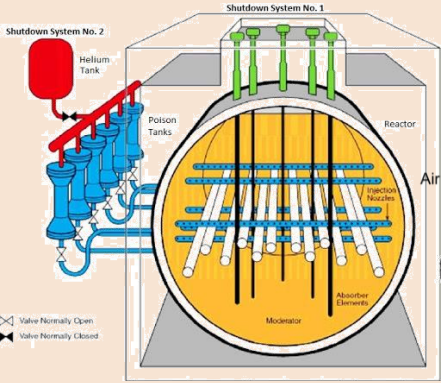
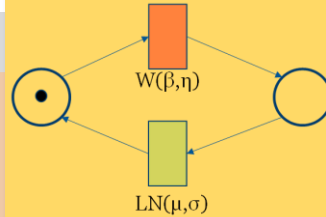
COMPUTATIONAL FEASIBILITY

Methodology Overview



Non-Constant Failure Rates

PETRI NETS

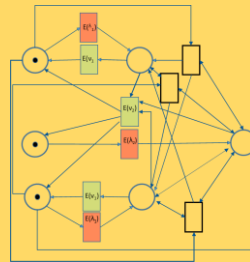


FT Modelling

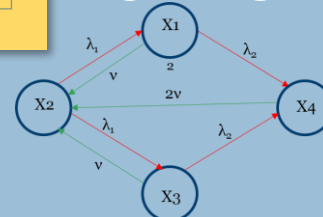
BDD

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

PETRI NETS



MARKOV MODELS



Dependencies

Complex Maintenance Strategies

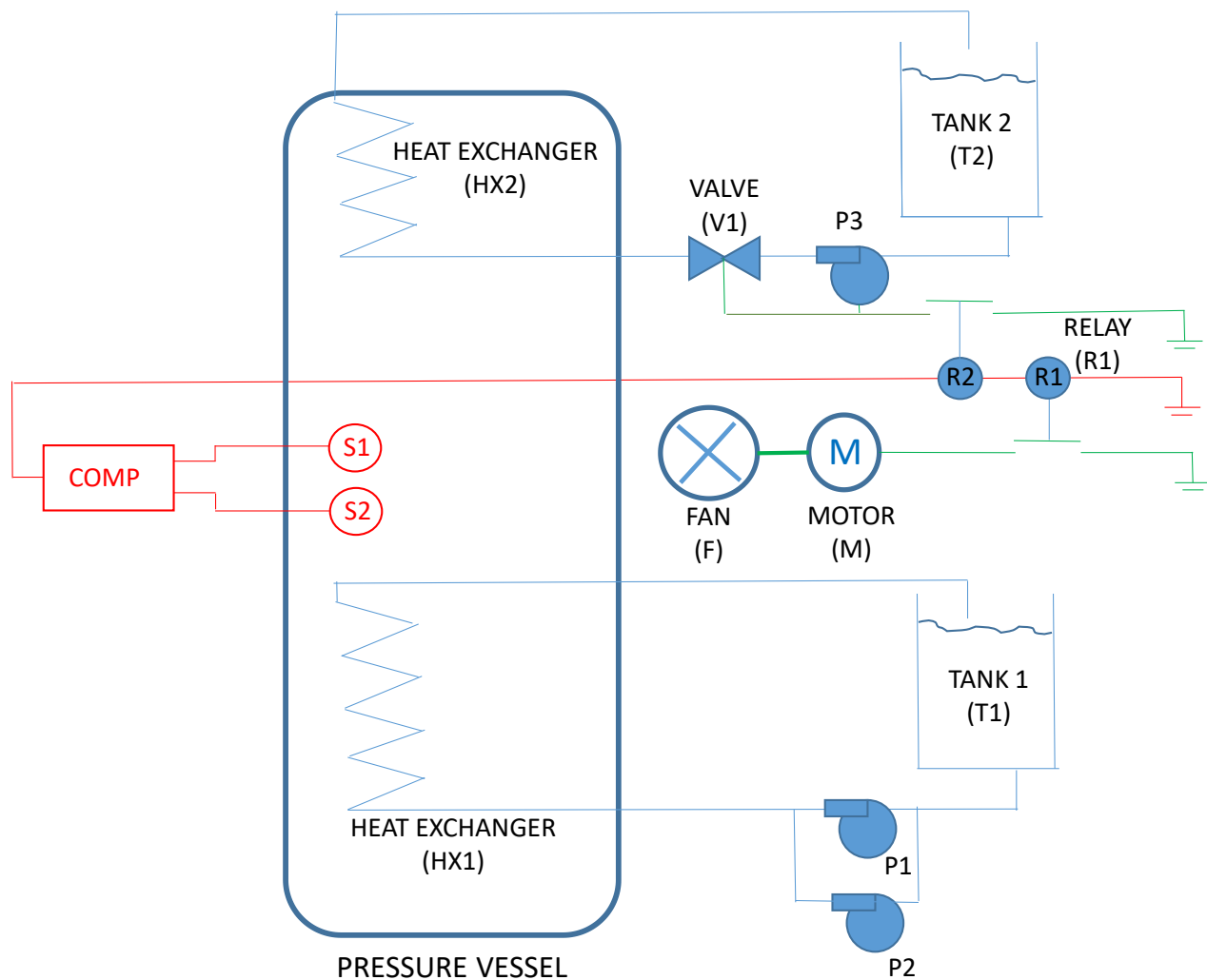


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Case-Study

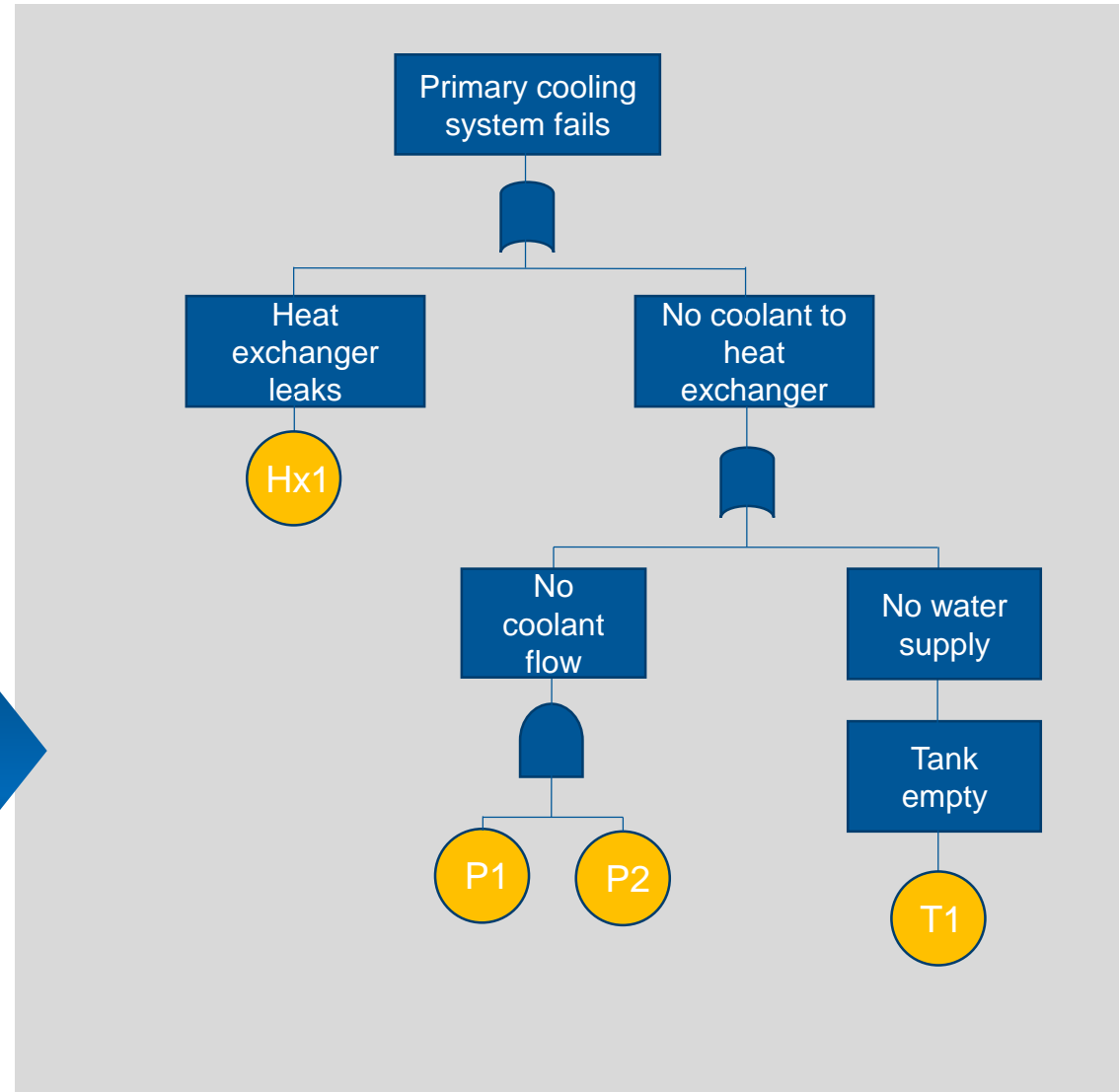
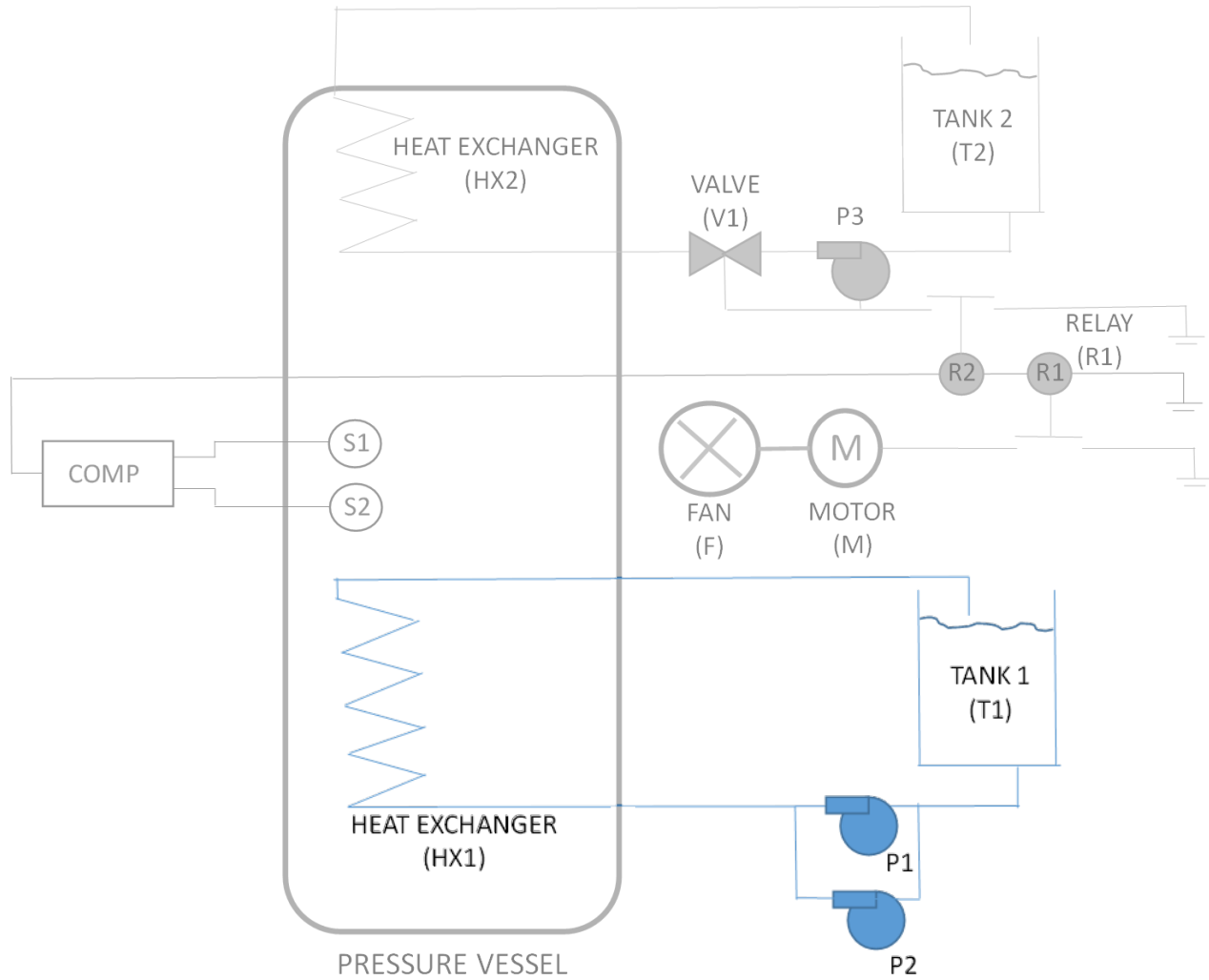
Hands On



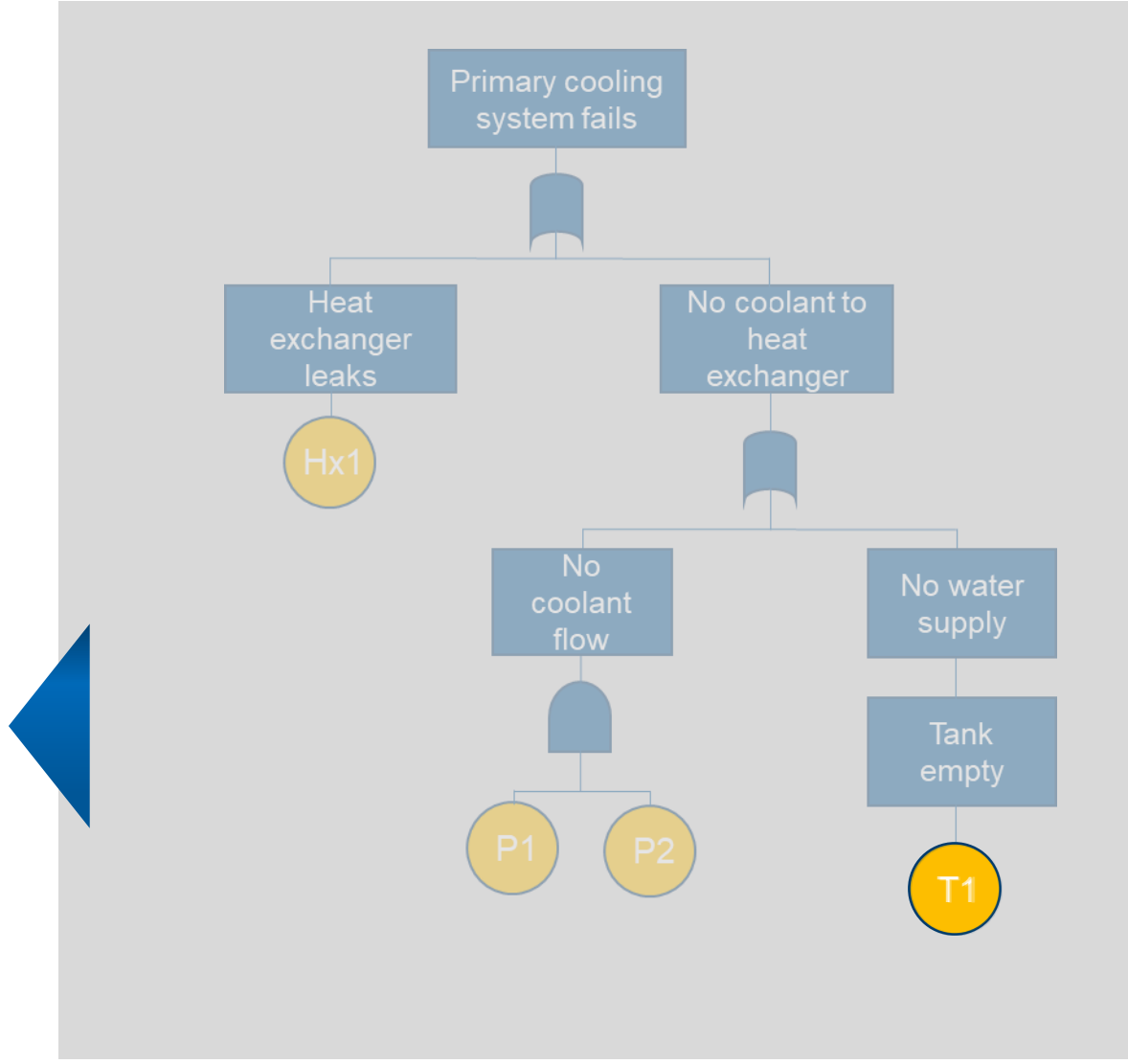
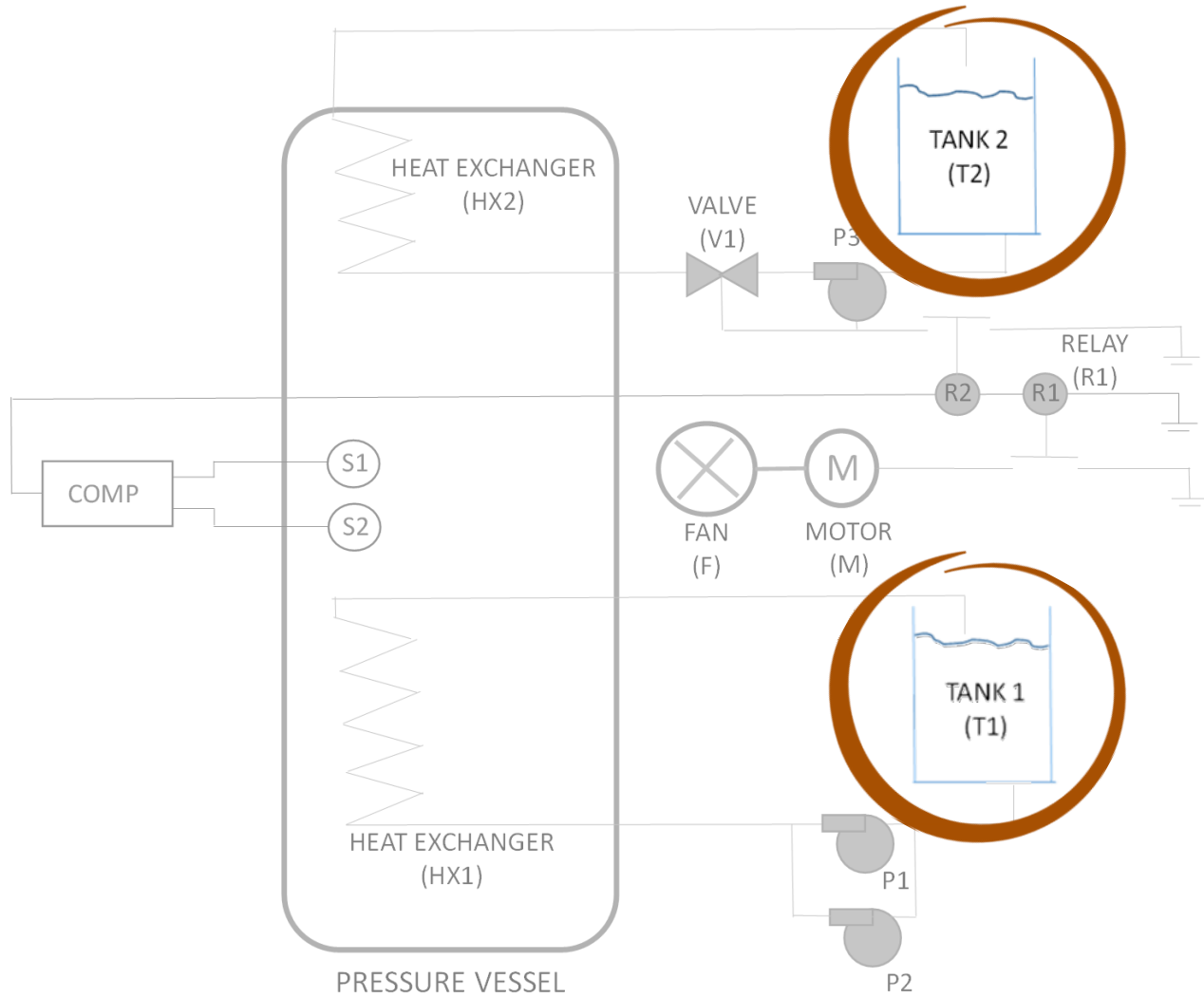
Overview:

- Industrial cooling system
- Four subsystems
- 20y life cycle
- Complex features:
 - Aging Components;
 - Complex Maintenance Strategies
 - Component Dependencies

Subsystems: Primary Cooling Water System

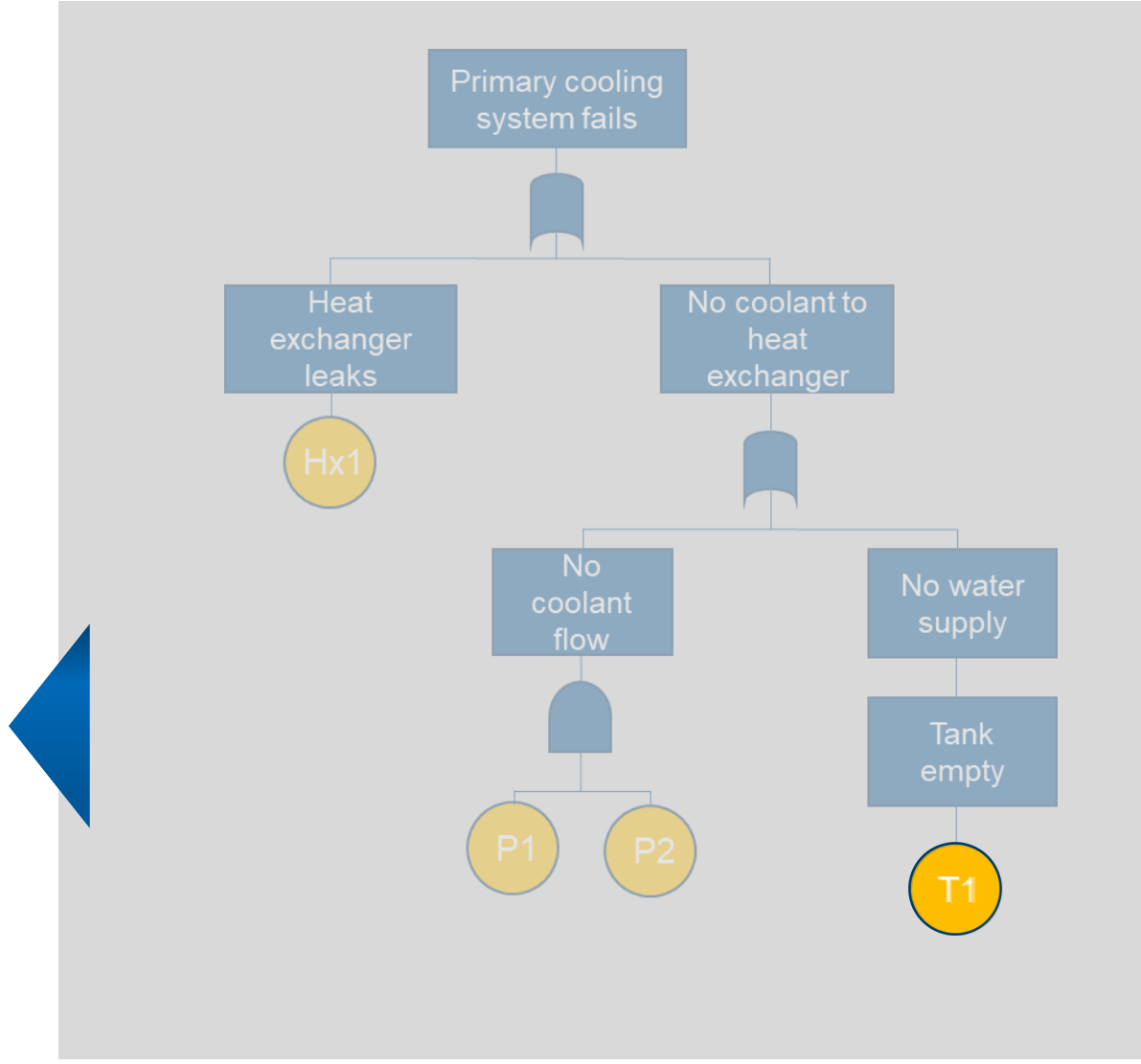
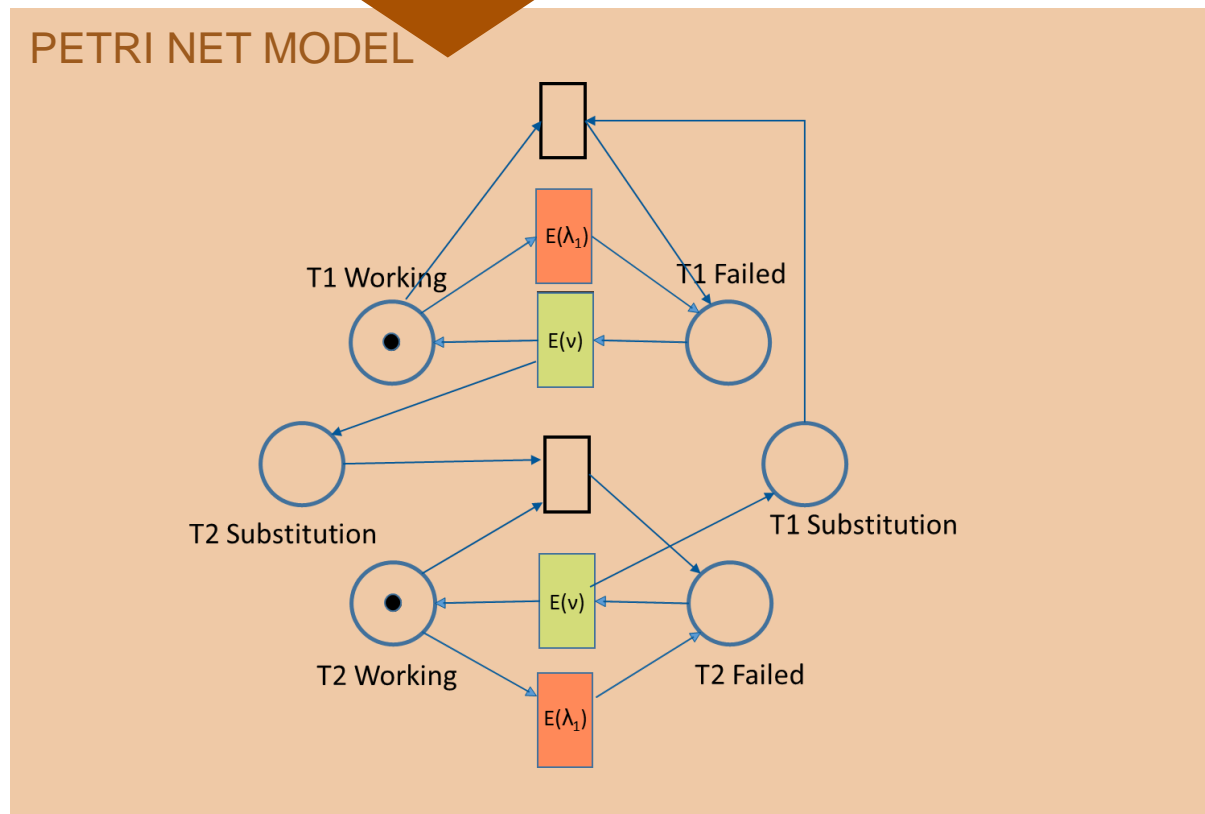


Subsystems: Primary Cooling Water System



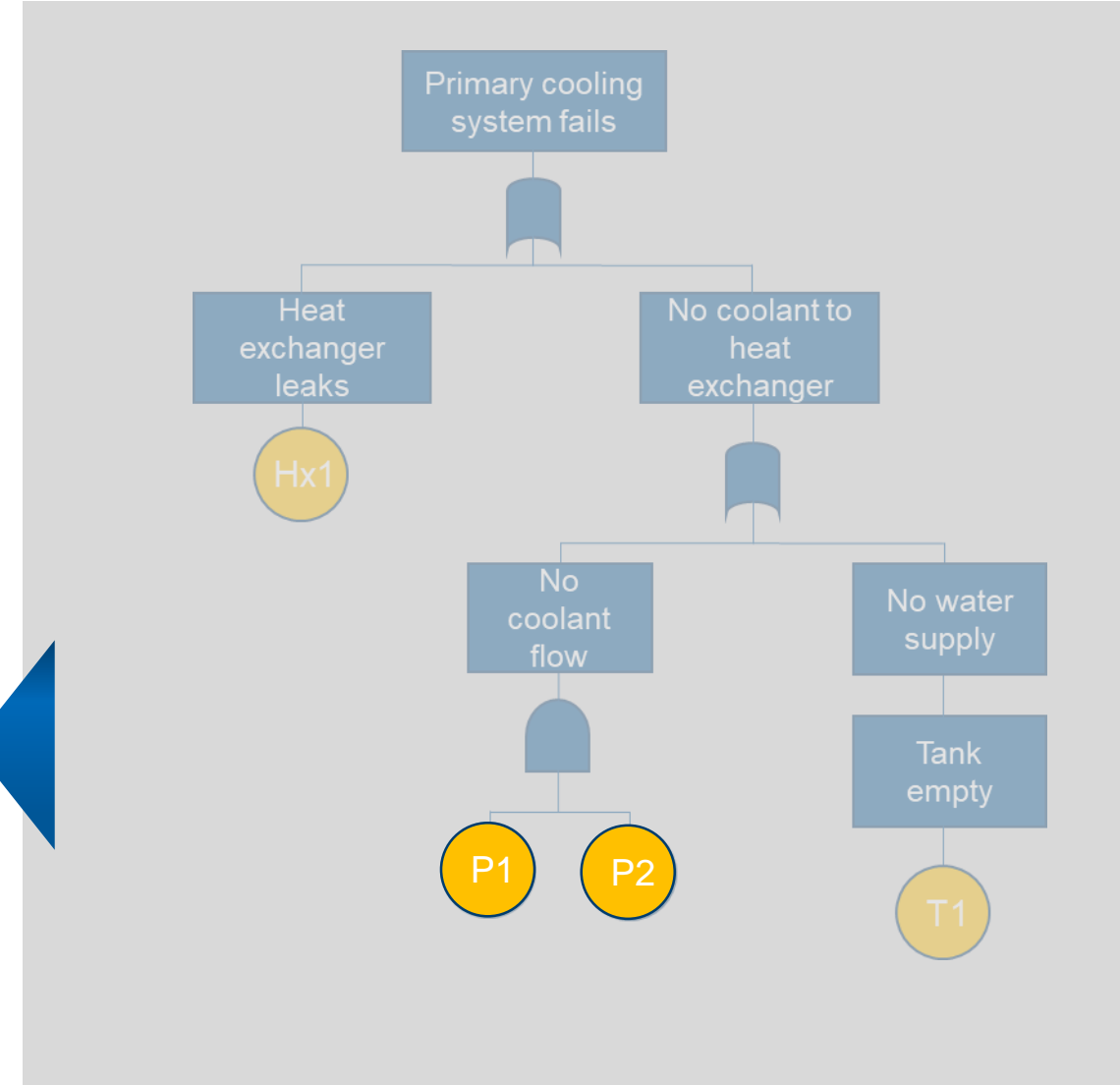
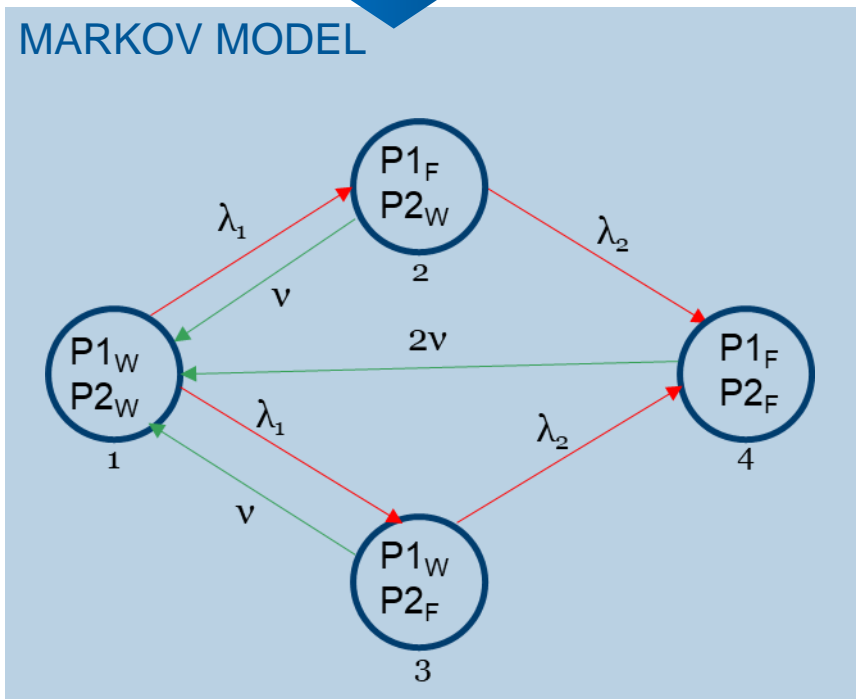
T1&T2 Maintenance Strategy

When one fails, both are replaced (subsequently)

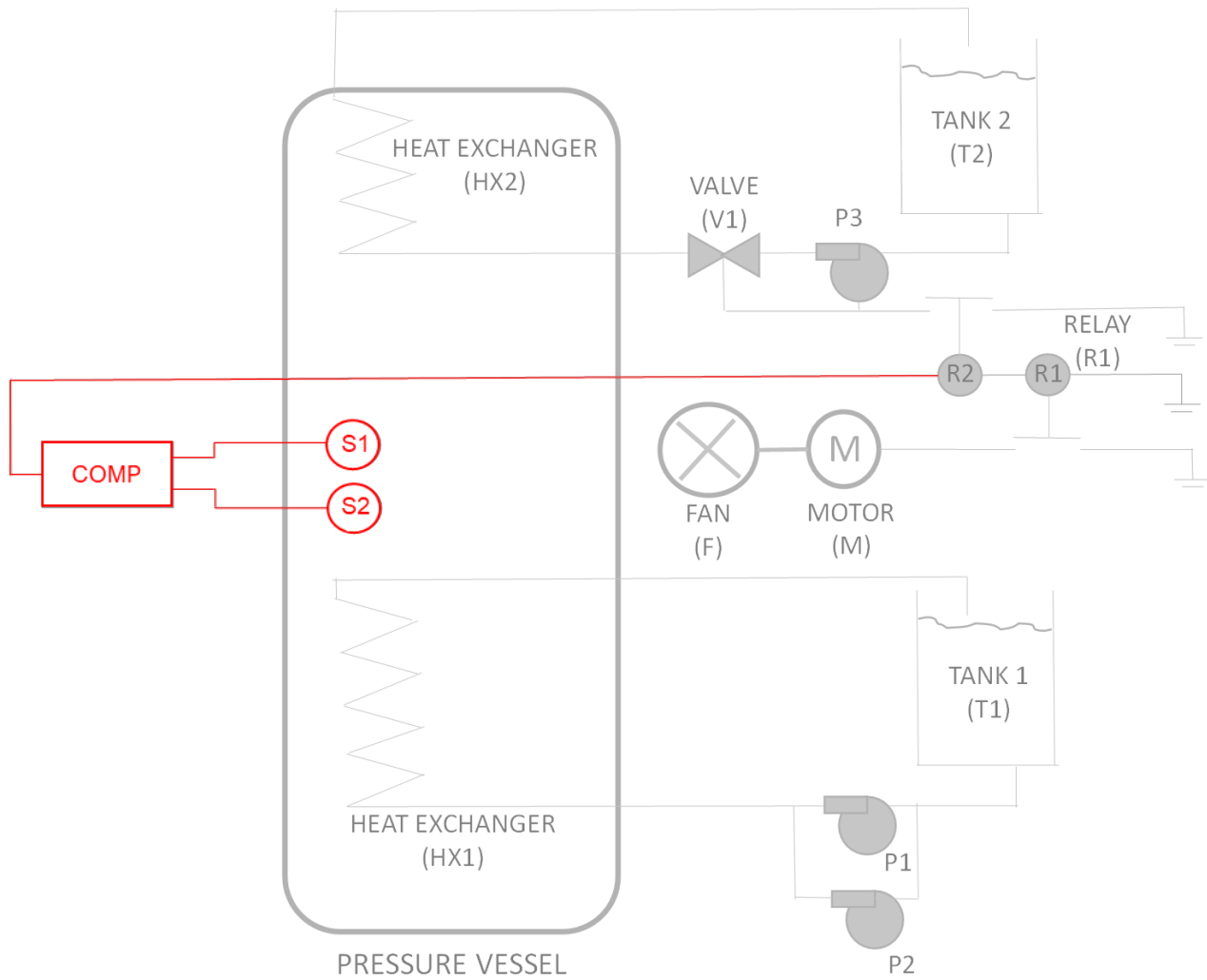


P1&P2 Dependency

Failure of P1 (P2) increases load and failure rate of P2 (P1)

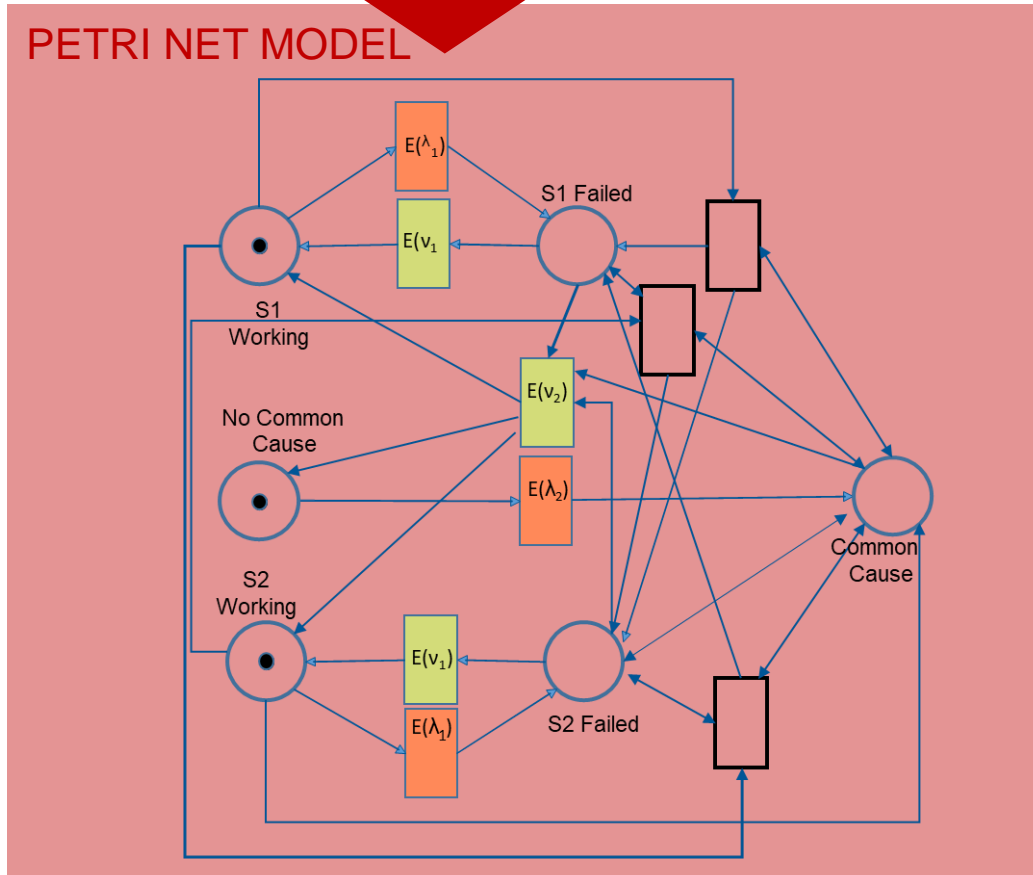


Subsystems: Detection System

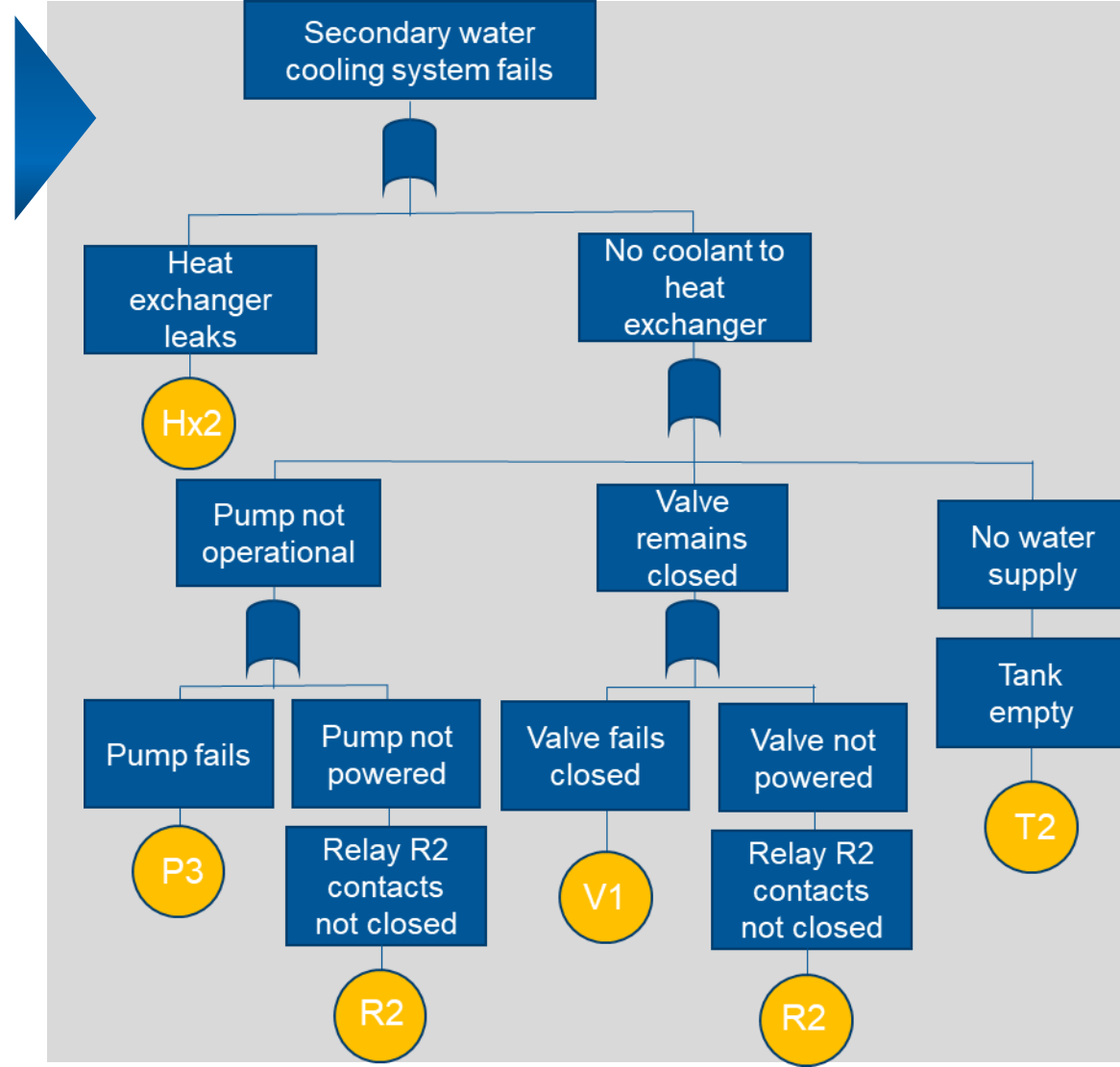
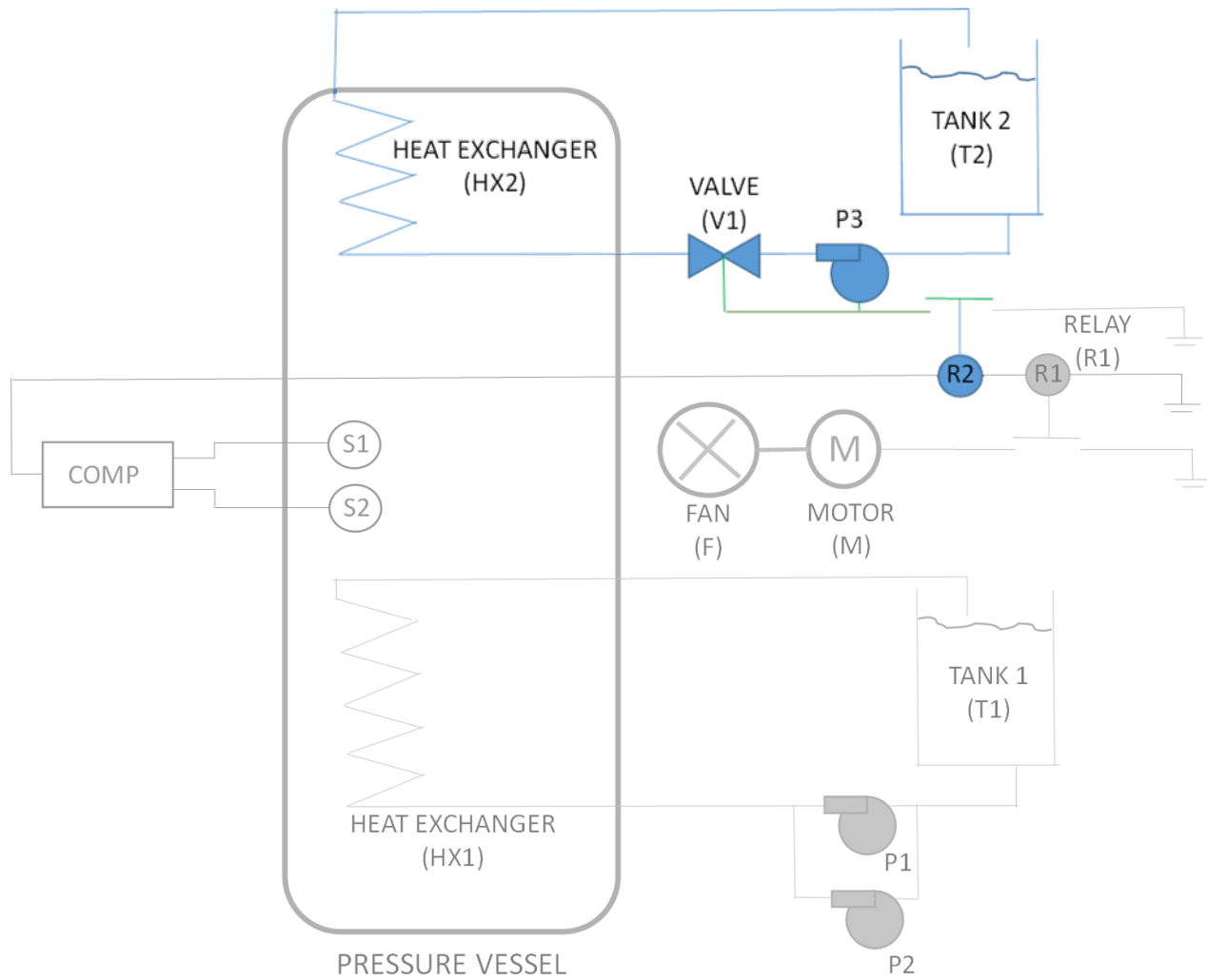


S1&S2 Common Cause Failure

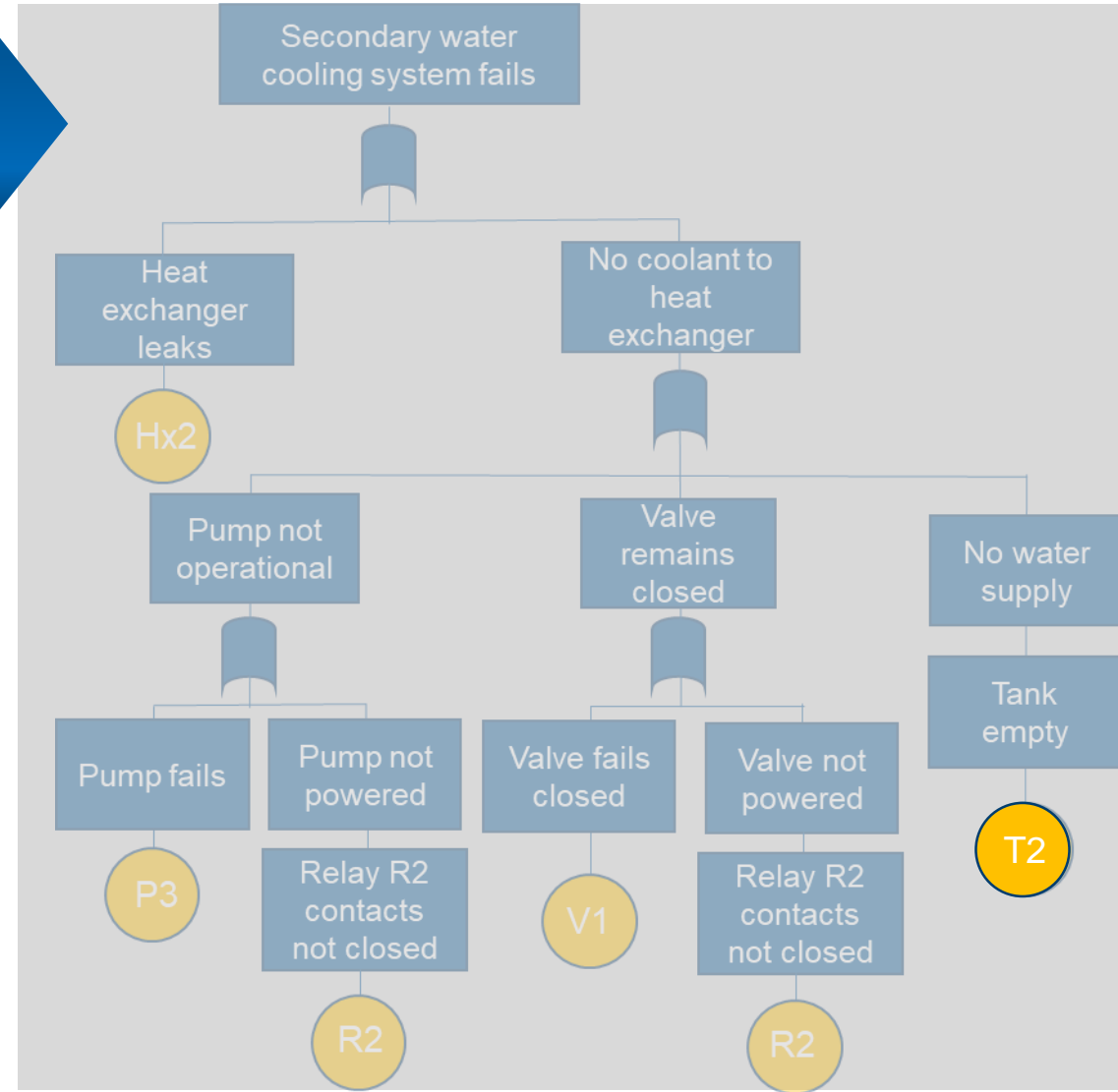
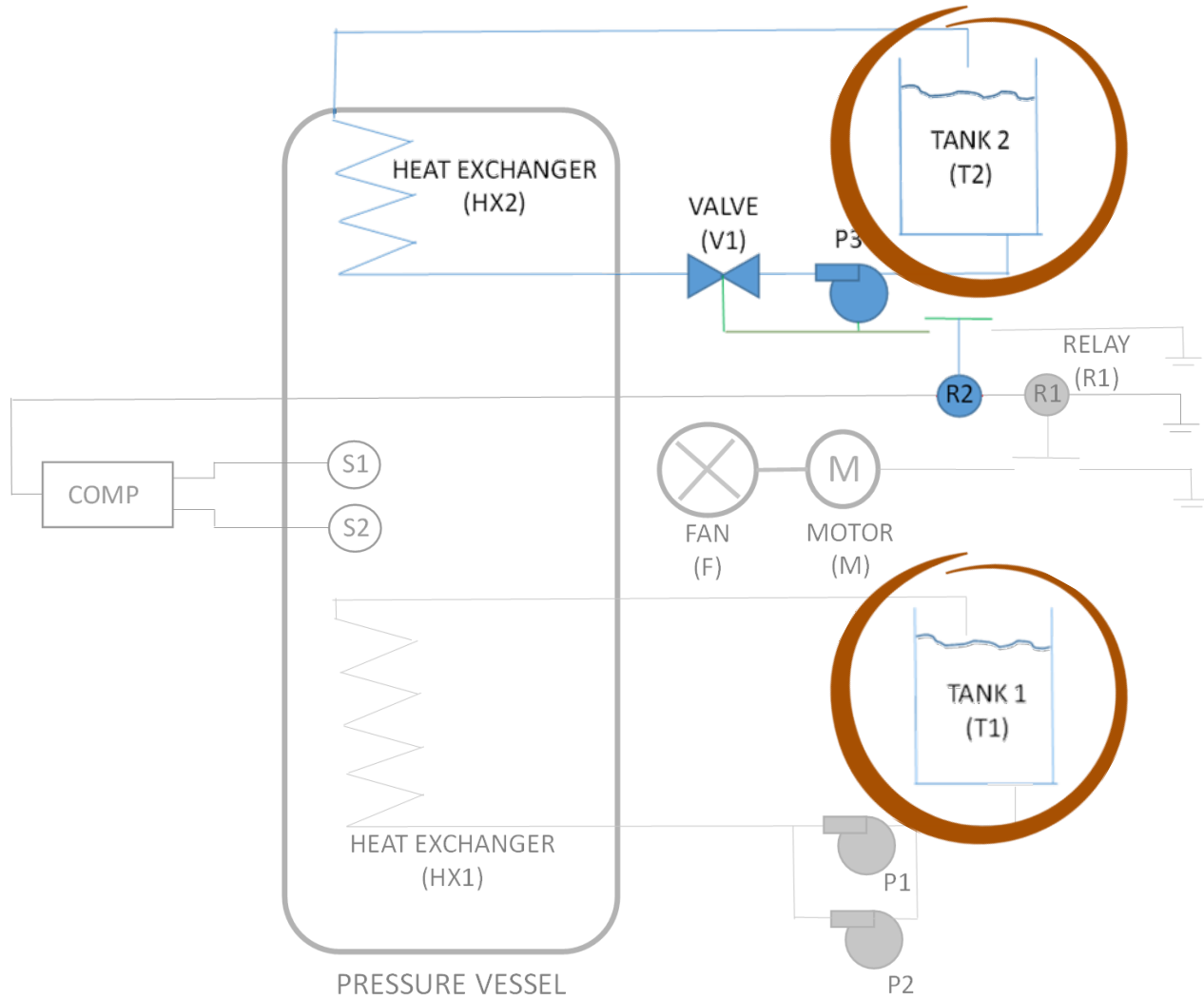
Calibration failure in both sensors when event CC occurs



Subsystems: Secondary Cooling Water System

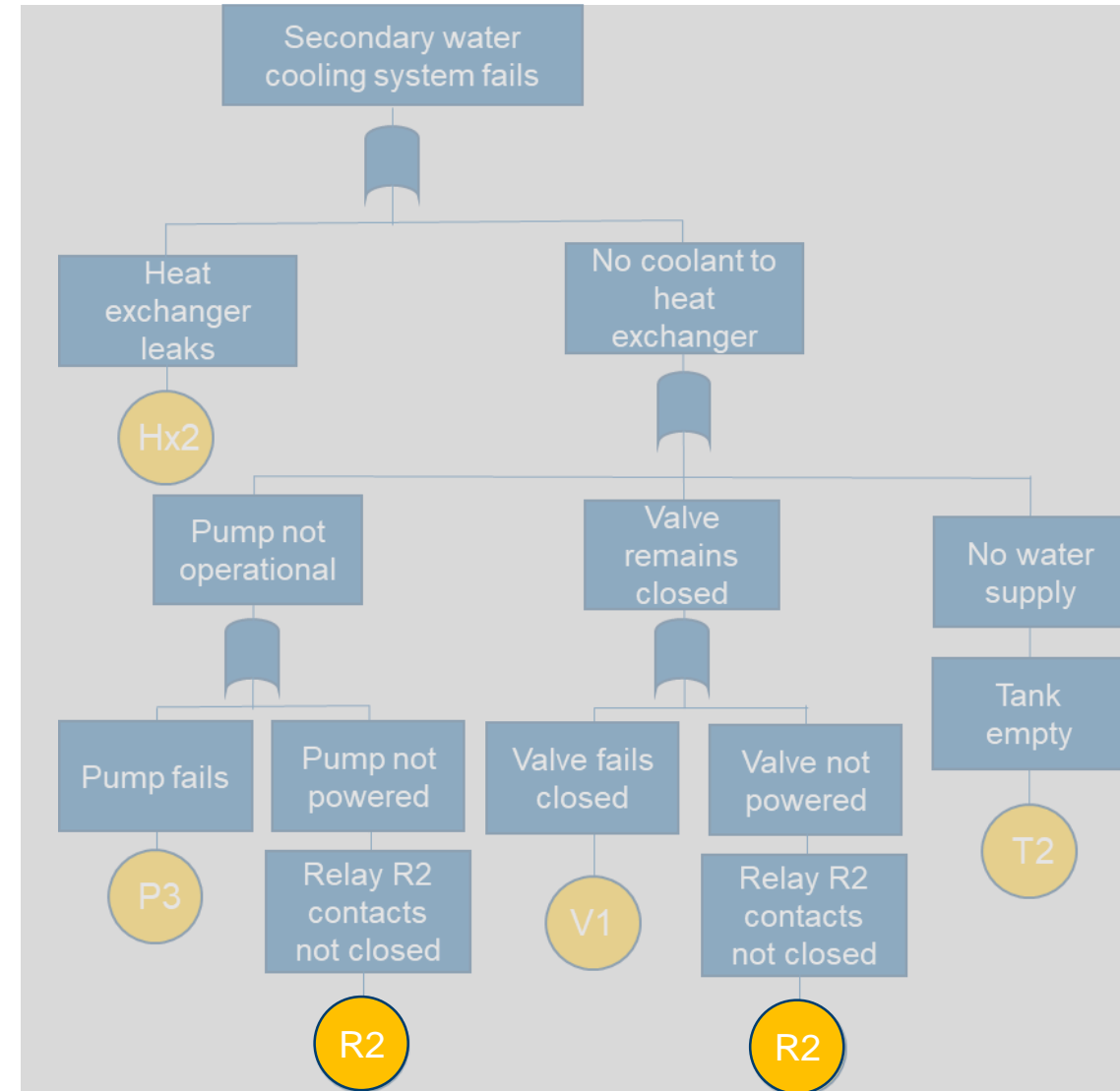
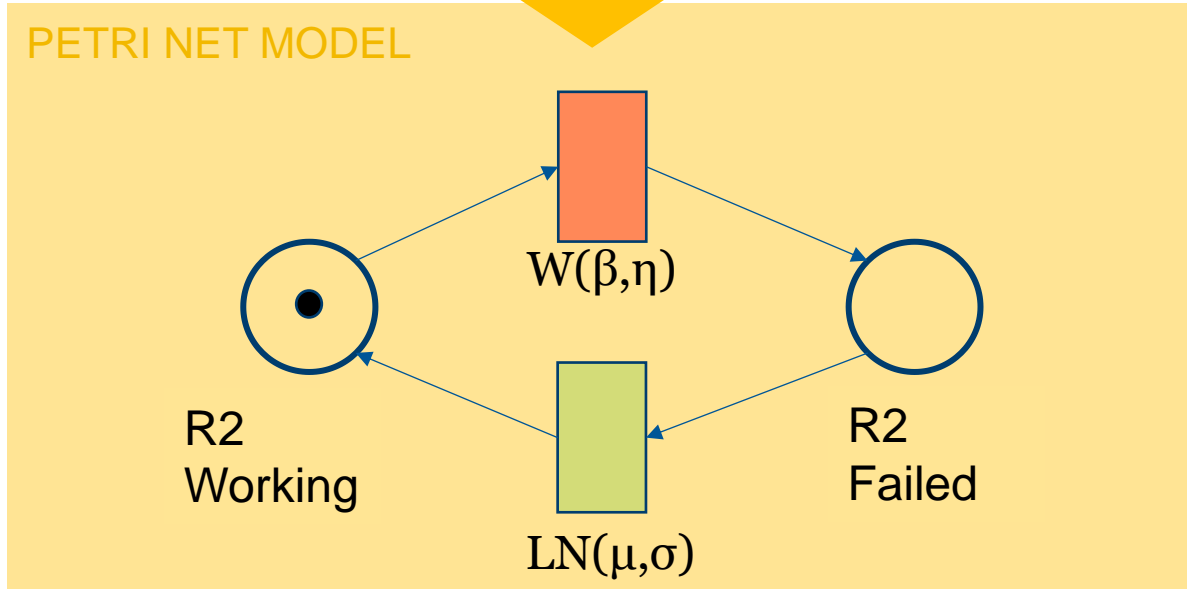


Subsystems: Secondary Cooling Water System

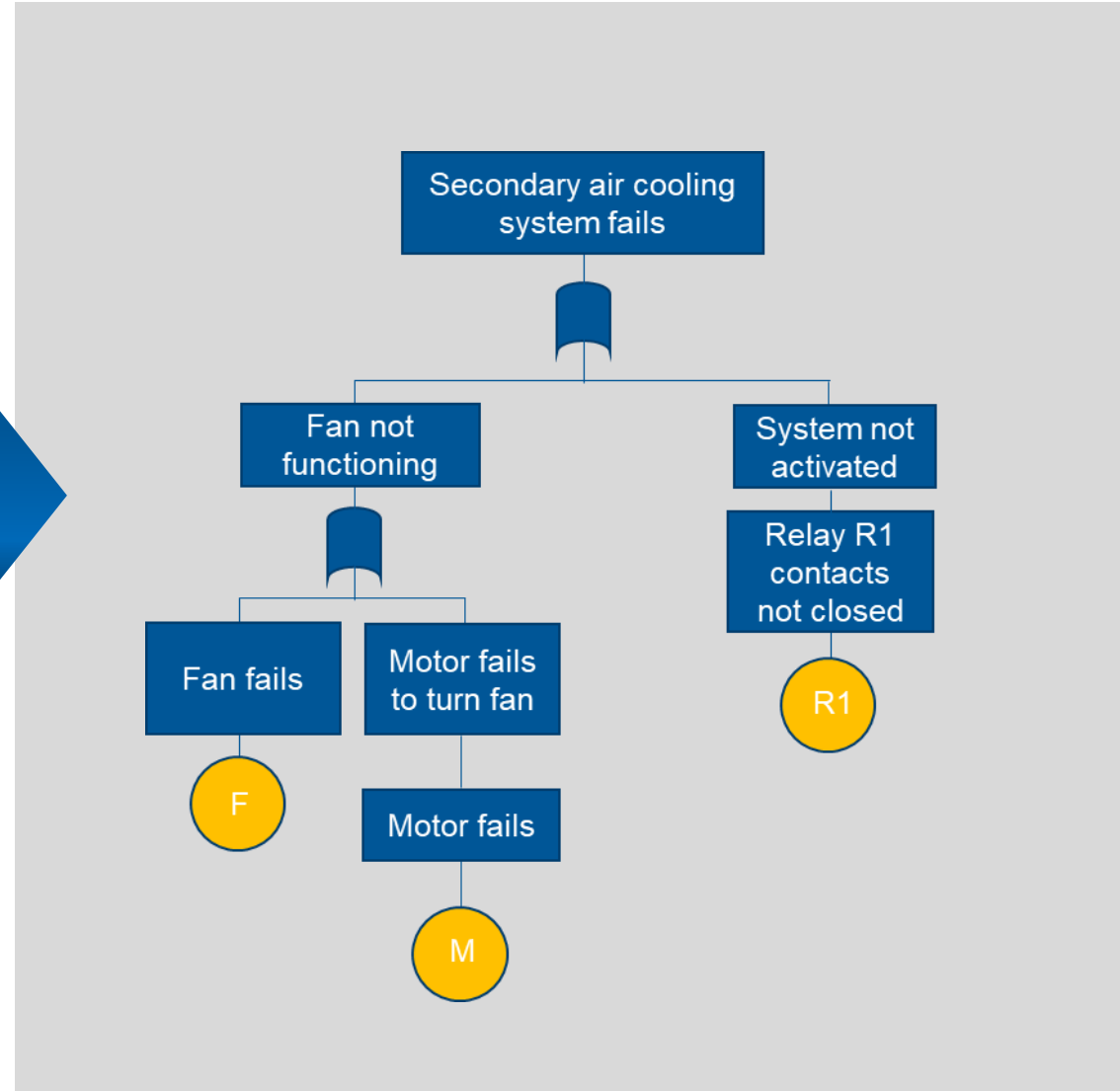
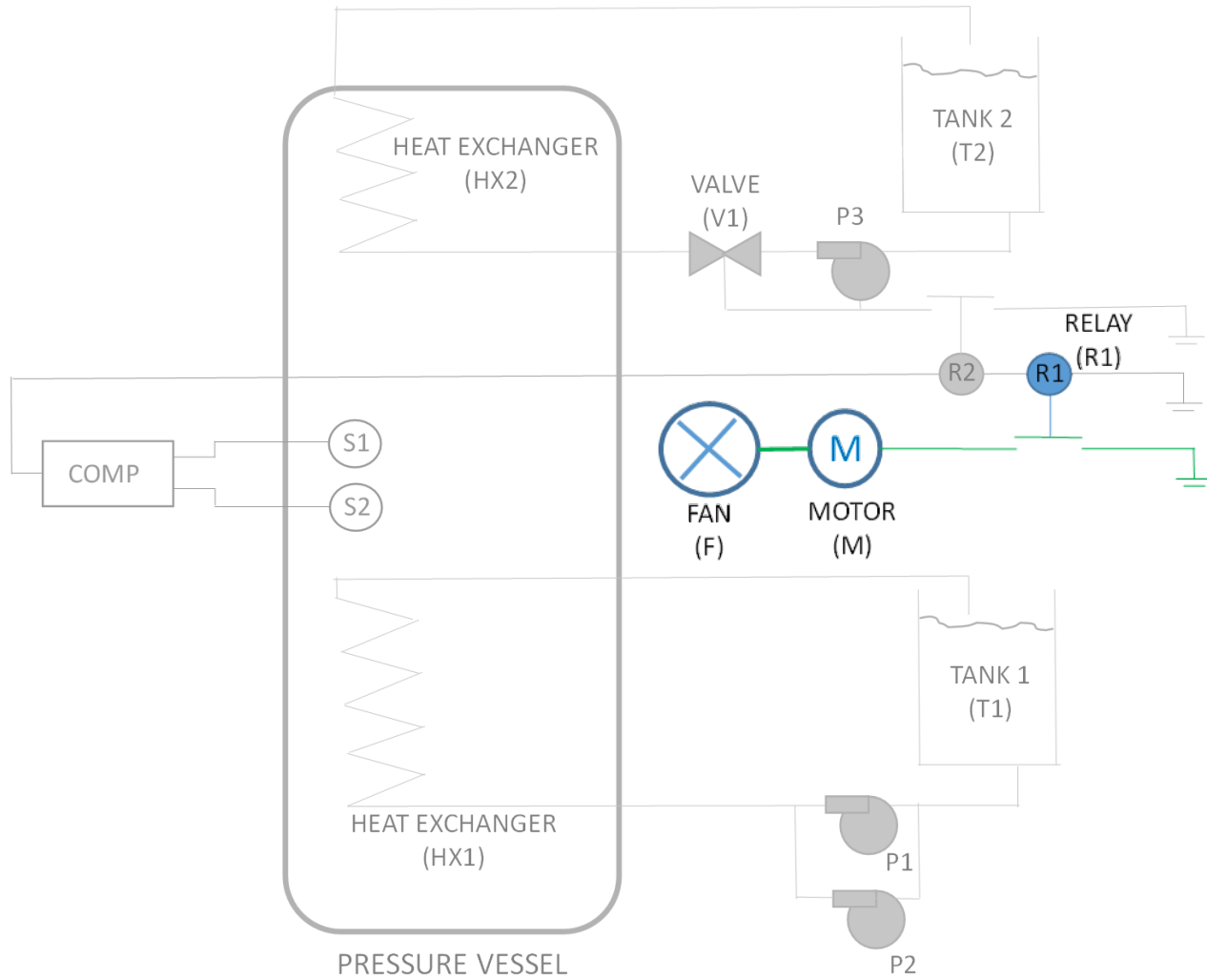


R2 Aging Component

Characterised by non-constant failure and repair rates

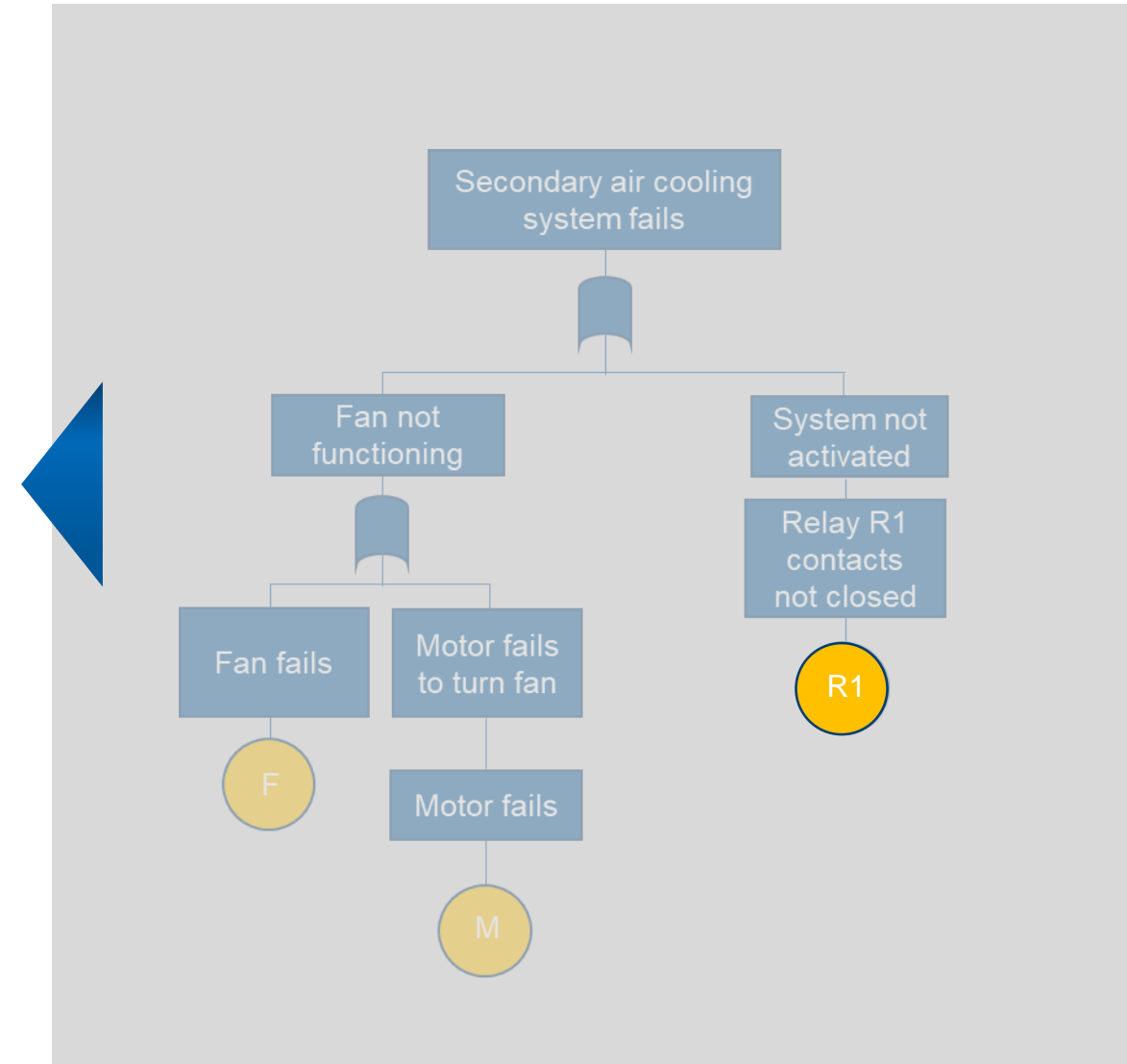
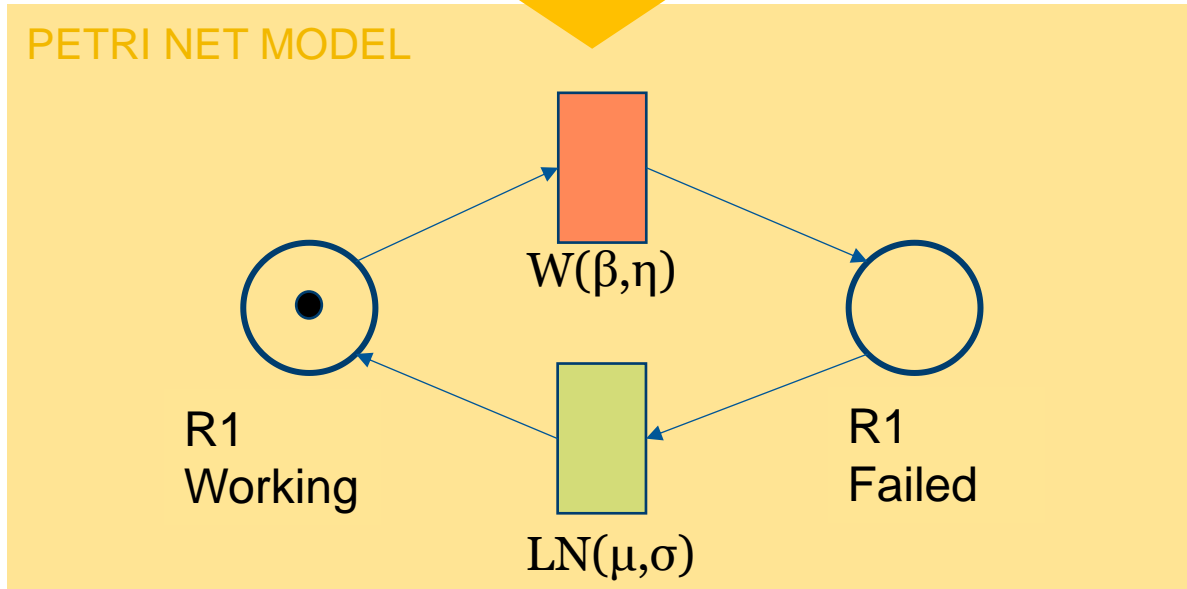


Subsystems: Secondary Cooling Air System



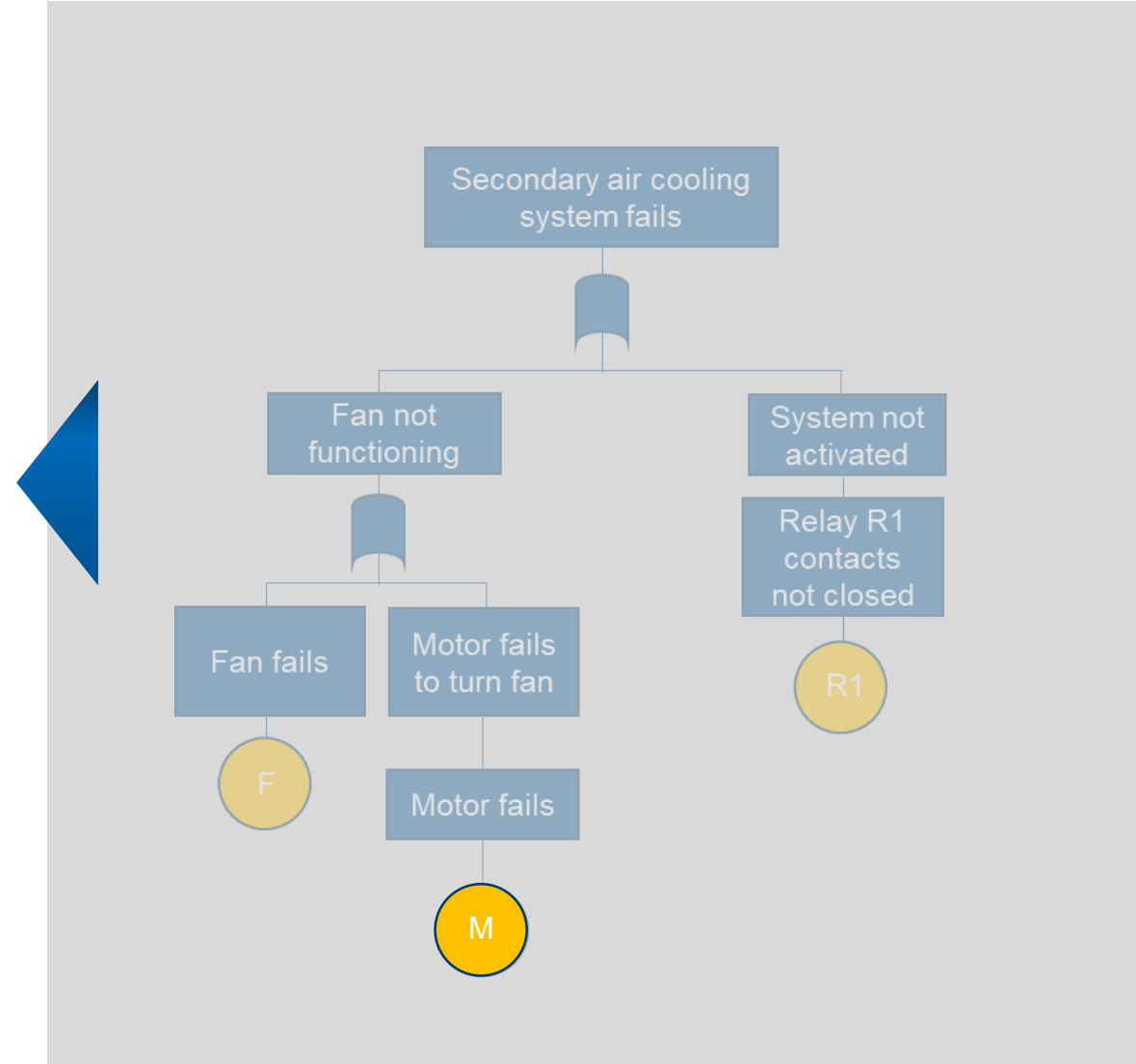
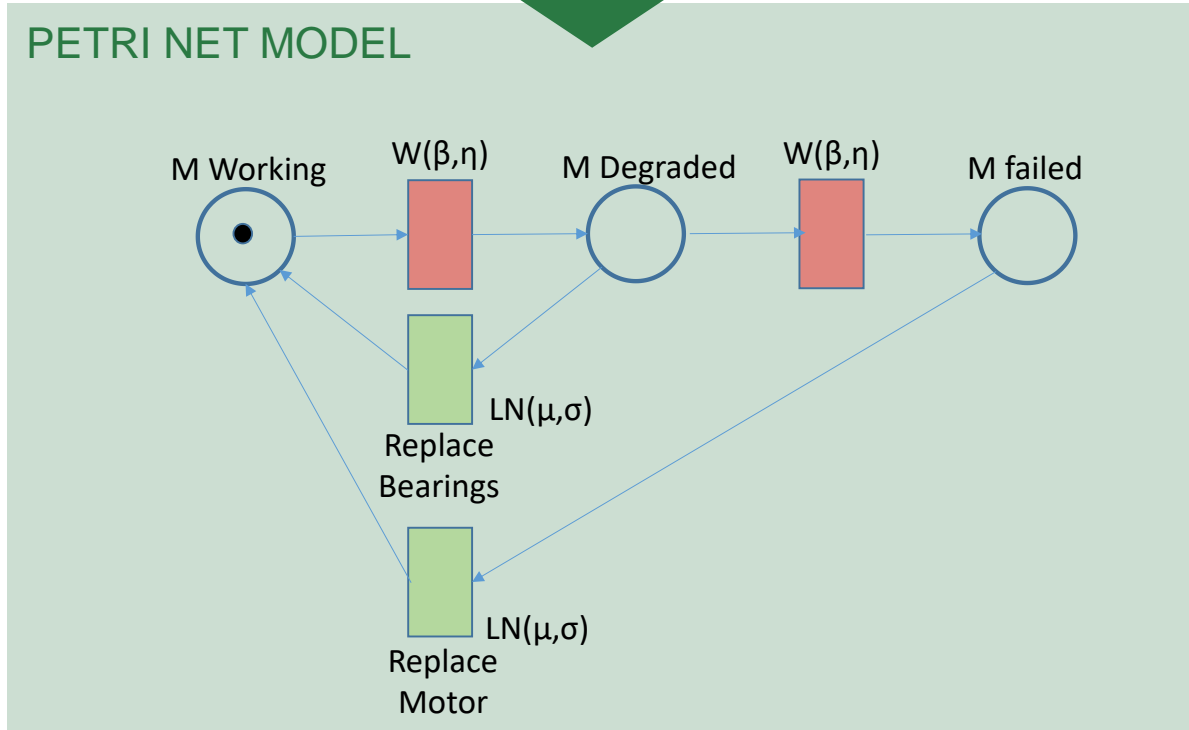
R1 Aging Component

Characterised by non-constant failure and repair rates



M Complex Maintenance Strategy

Condition monitoring system with different maintenance actions





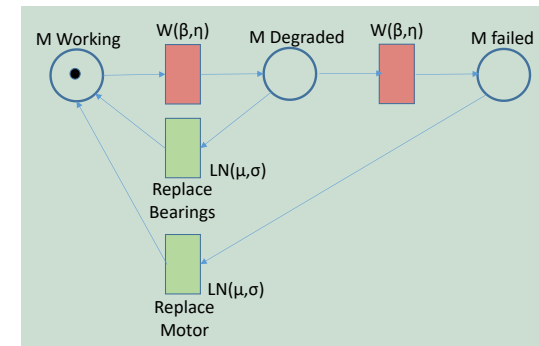
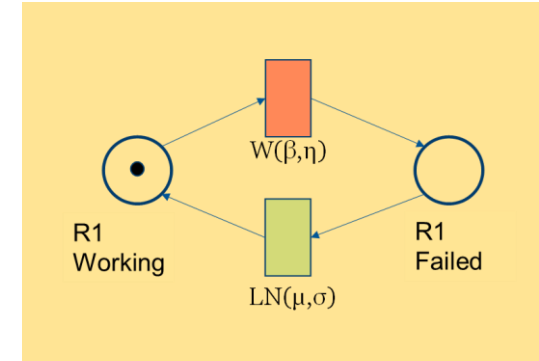
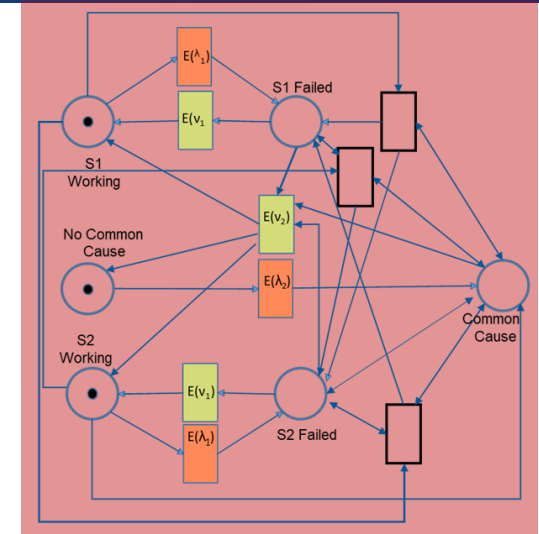
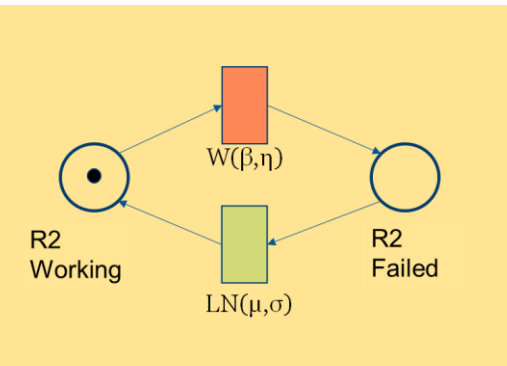
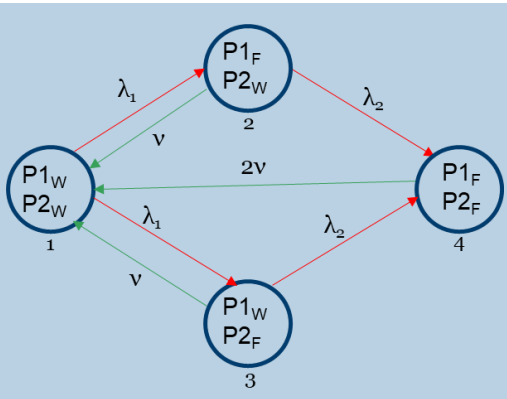
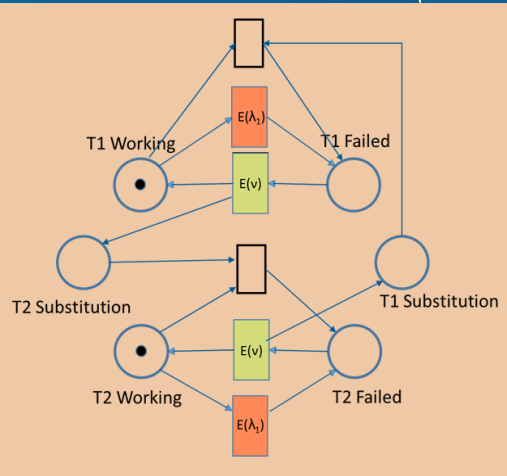
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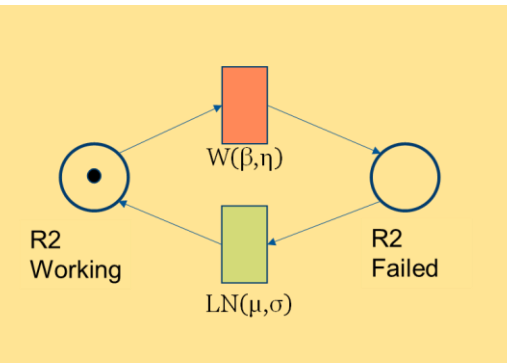
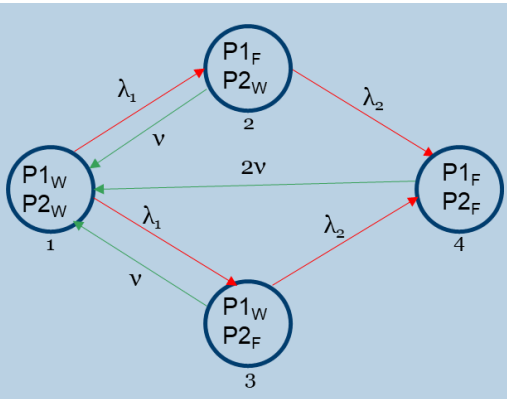
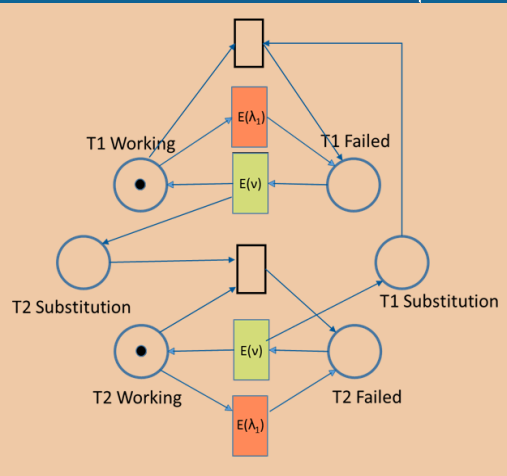
Numerical Solution

Numbers In

STEP 1: Complex Feature Reliability

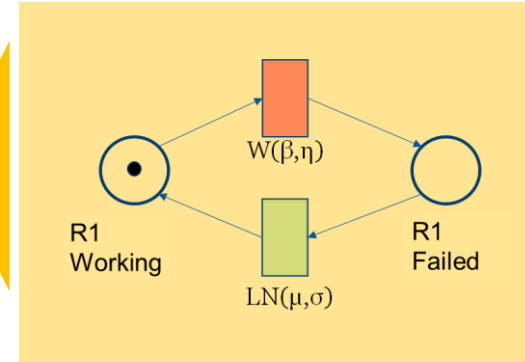
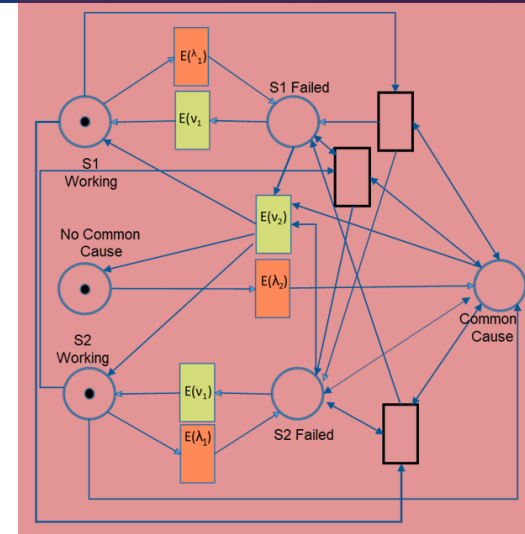


STEP 1: Complex Feature Reliability

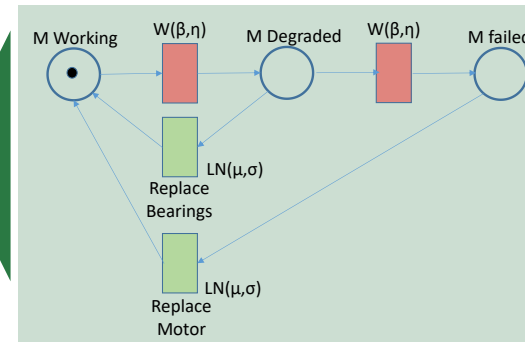


State	Probability	Frequency
$R2_F$	$6.1135e-03$	$2.2018e-03$

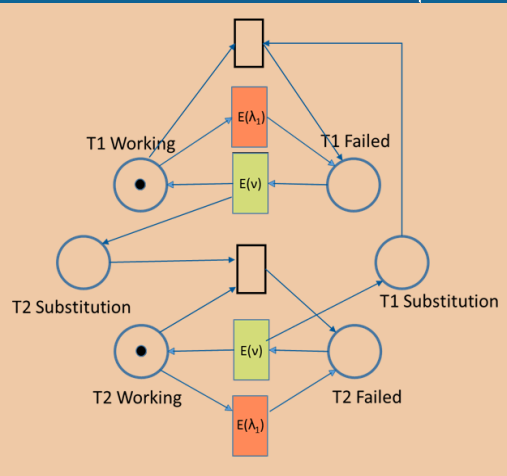
State	Probability	Frequency
$R1_F$	$6.1827e-03$	$2.2346e-03$



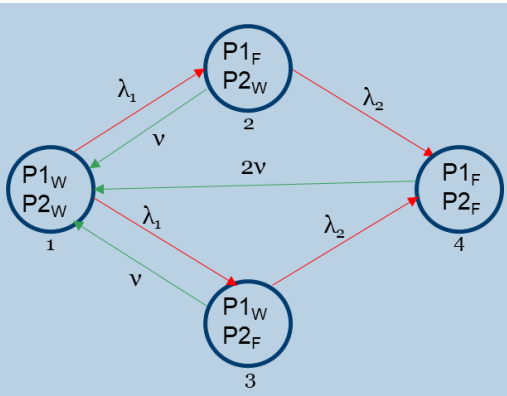
State	Probability	Frequency
M_F	$3.6821e-02$	$4.4349e-03$



STEP 1: Complex Feature Reliability

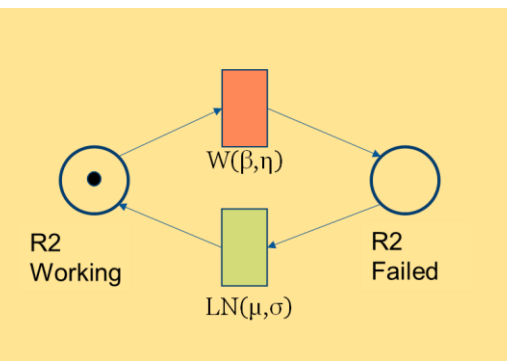


State	Probability	Frequency
T1 _F , T2 _F	1.1883e-02	2.9661e-03
T1 _F , T2 _W	9.3168e-02	1.3130e-02
T1 _W , T2 _F	9.3193e-02	1.3113e-02
T1 _W , T2 _W	8.0175e-01	2.3277e-02



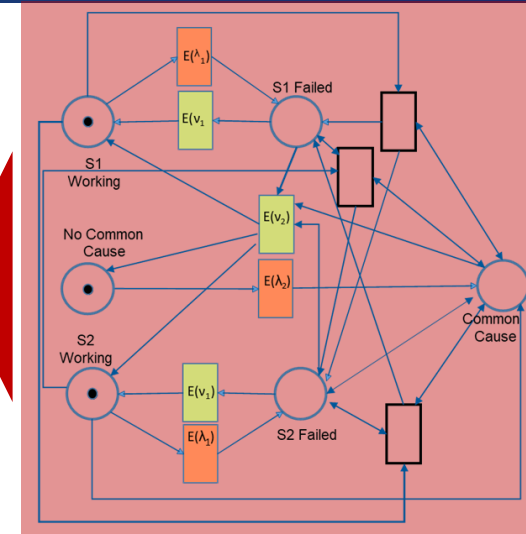
State	Probability	Frequency
P1 _F , P2 _F	1.1765e-02	7.0588e-02
P1 _F , P2 _W	3.5294e-02	4.5882e-01
P1 _W , P2 _F	3.5294e-02	4.5882e-01
P1 _W , P2 _W	9.1765e-01	9.1765e-01

*steady state solutions

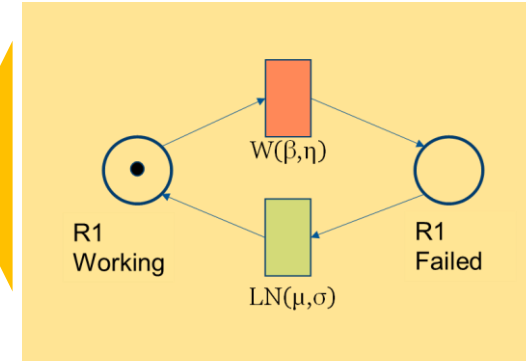


State	Probability	Frequency
R2 _F	6.1135e-03	2.2018e-03

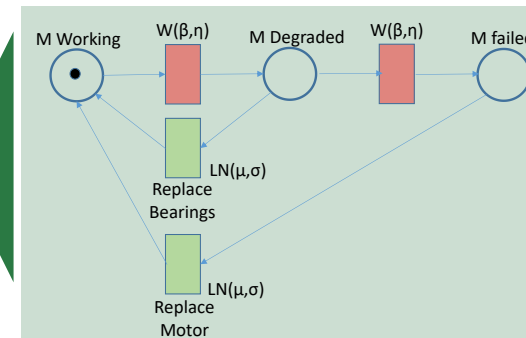
State	Probability	Frequency
S1 _F , S2 _F	4.8023e-04	5.1446e-05
S1 _F , S2 _W	3.3018e-06	1.5221e-06
S1 _W , S2 _F	4.4003e-06	1.4459e-06
S1 _W , S2 _W	9.9951e-01	5.4414e-05



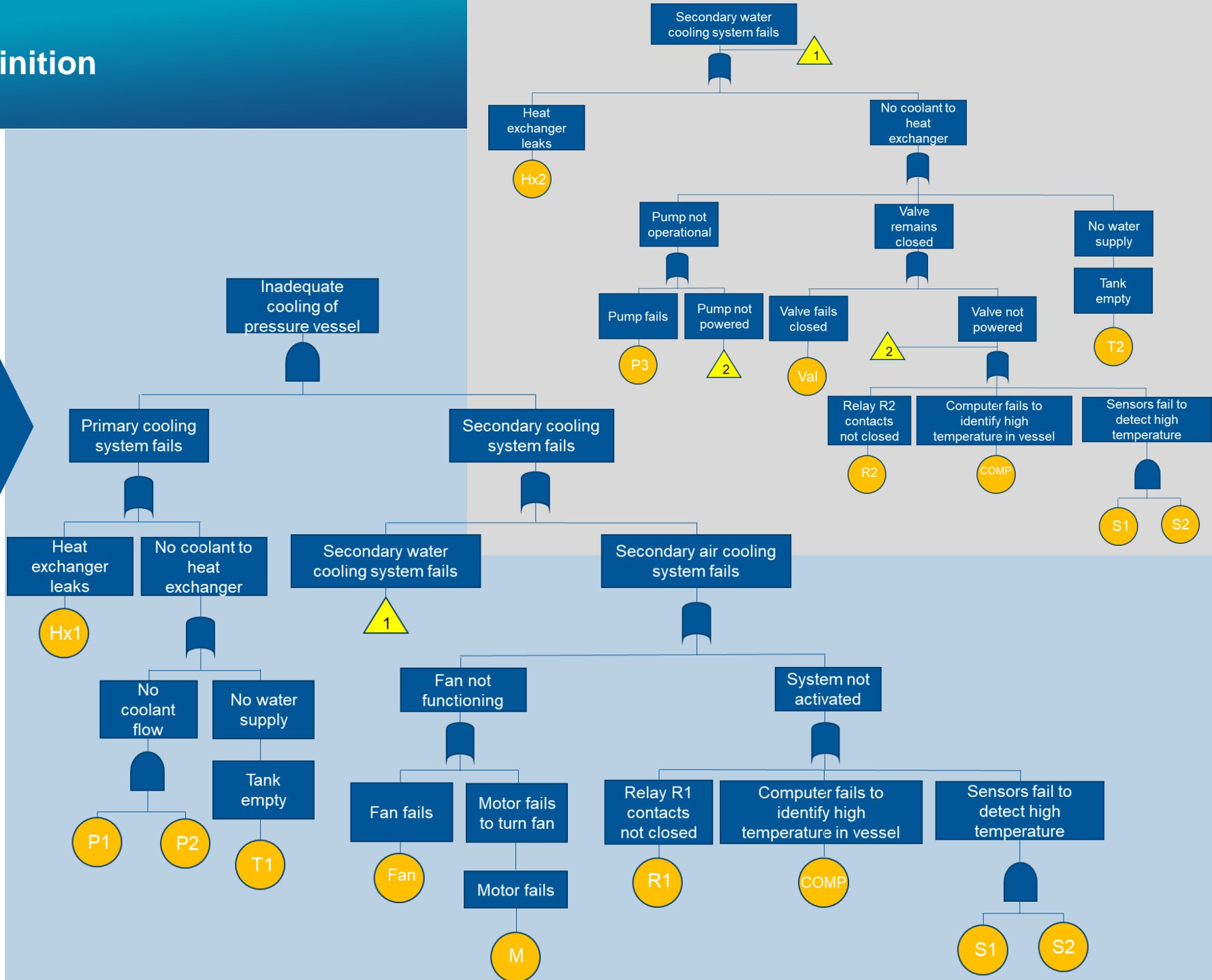
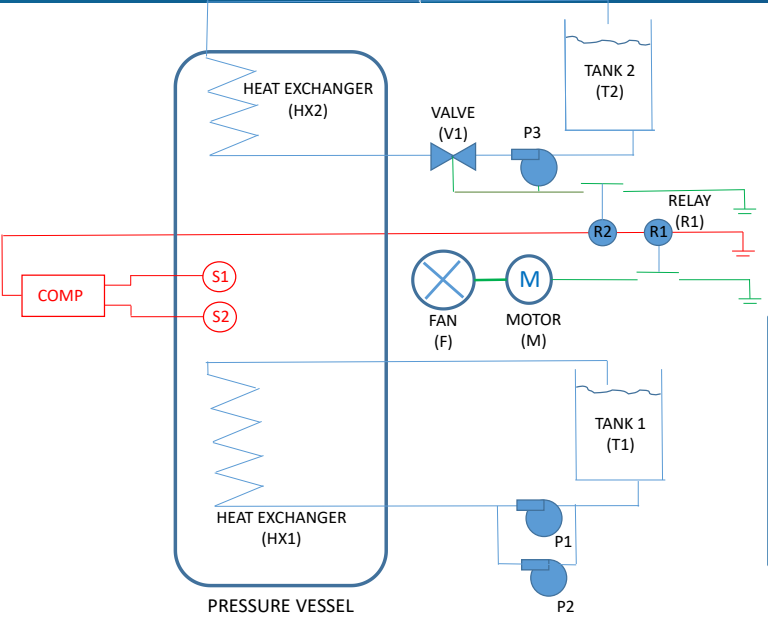
State	Probability	Frequency
R1 _F	6.1827e-03	2.2346e-03



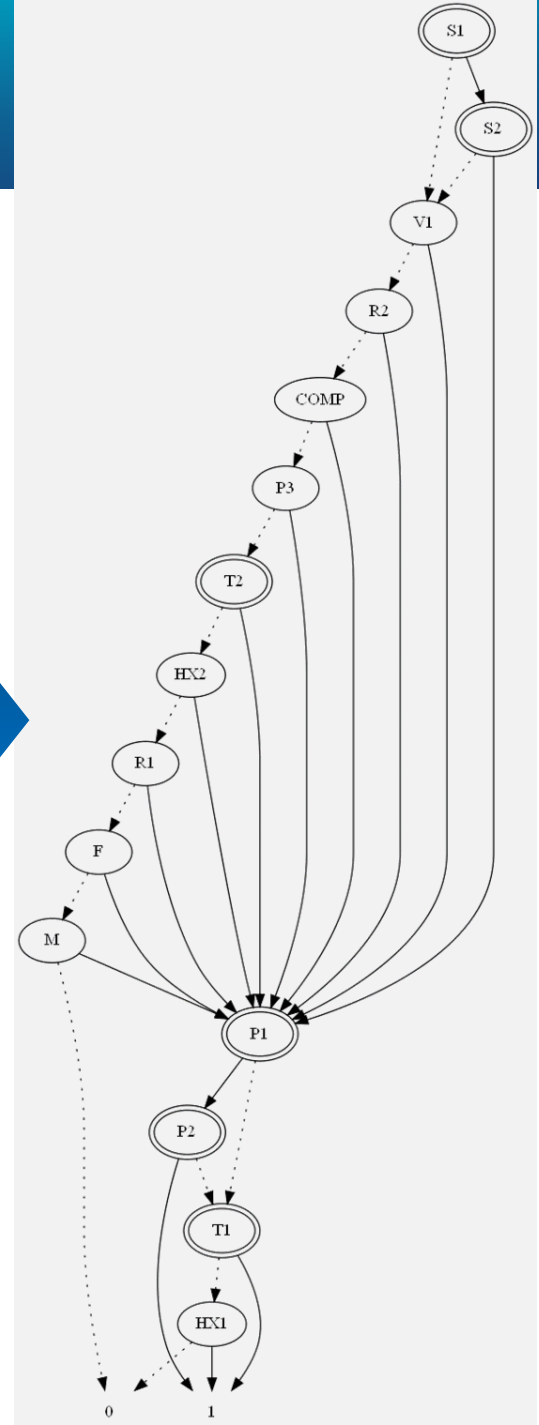
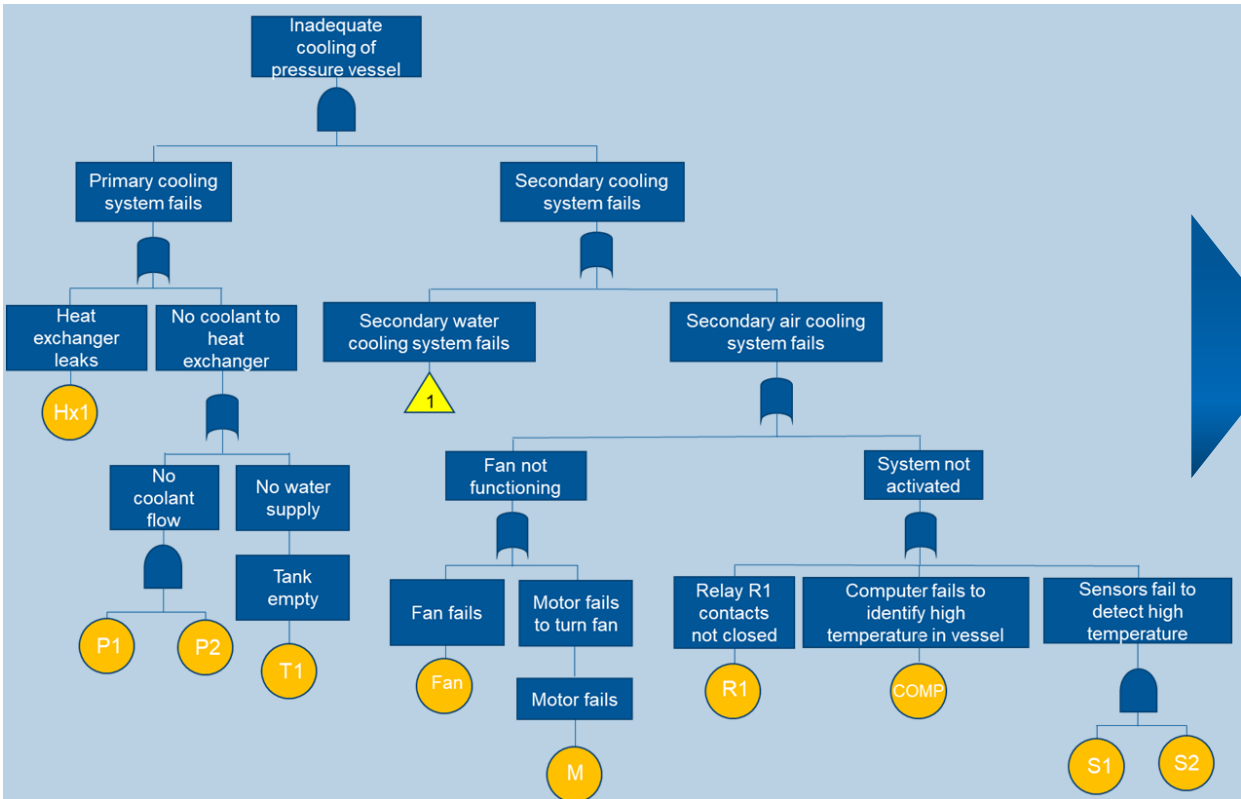
State	Probability	Frequency
M _F	3.6821e-02	4.4349e-03



STEP 2: FT definition

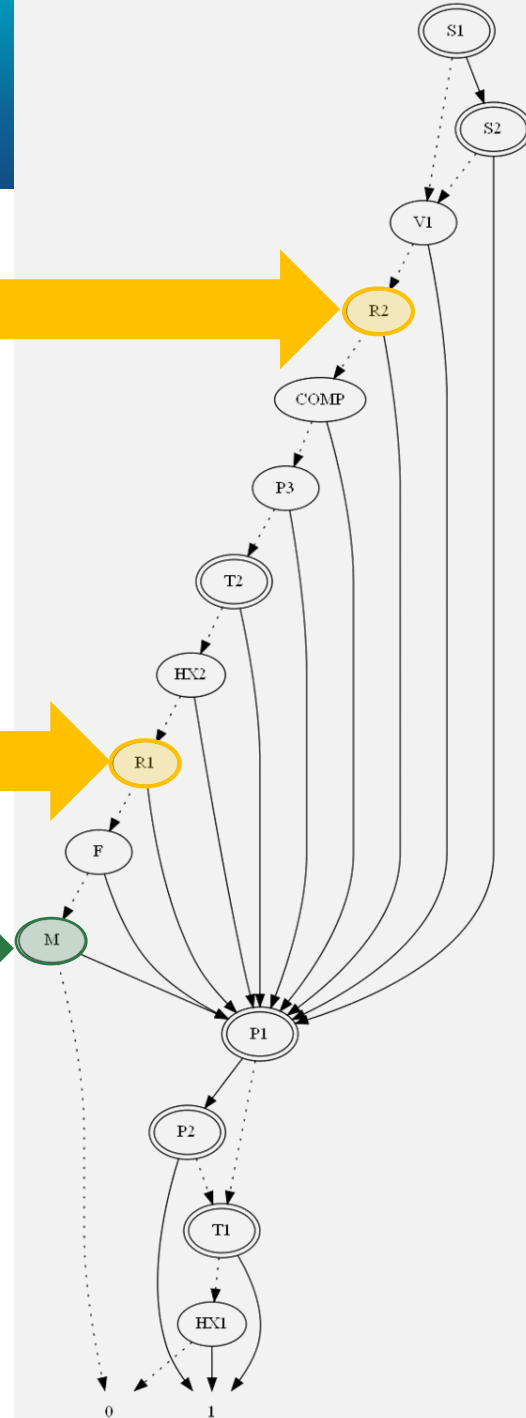
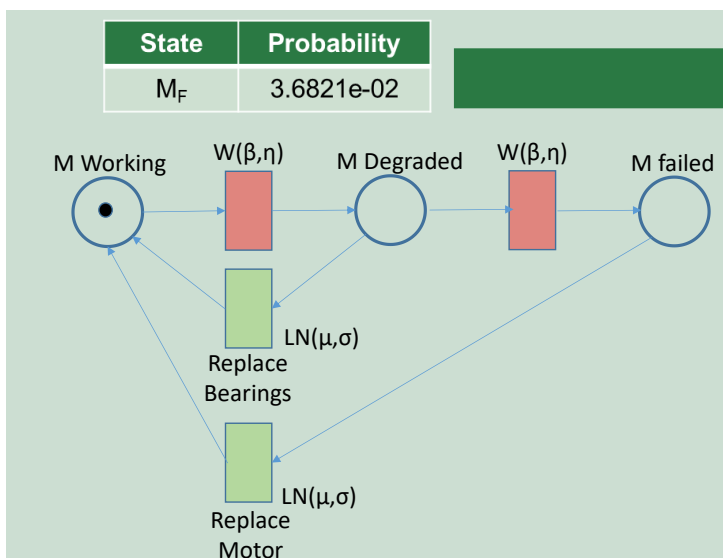
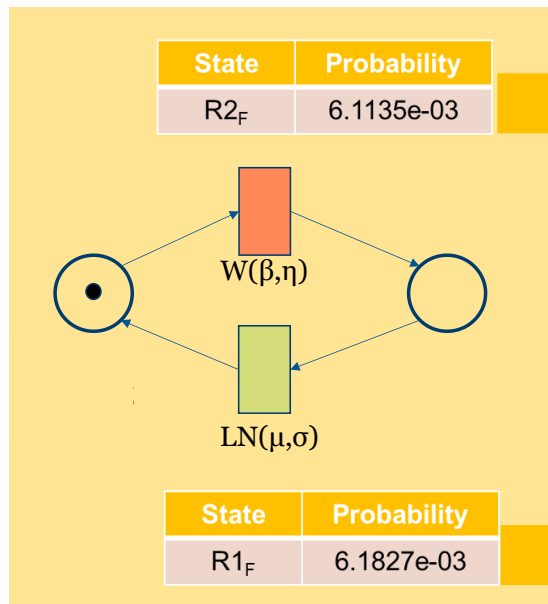


STEP 2: FT conversion

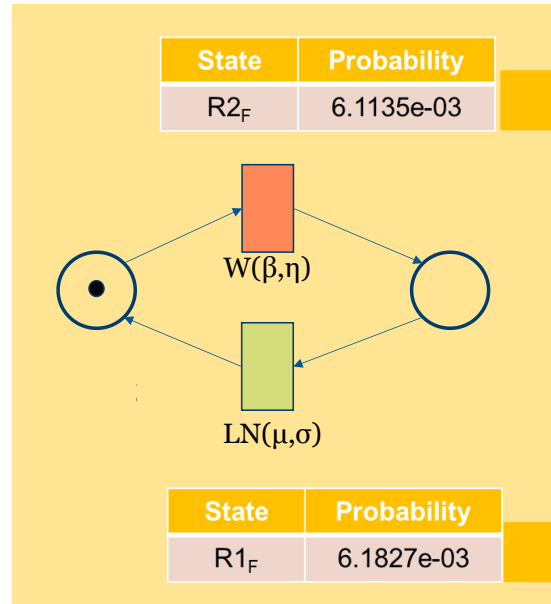




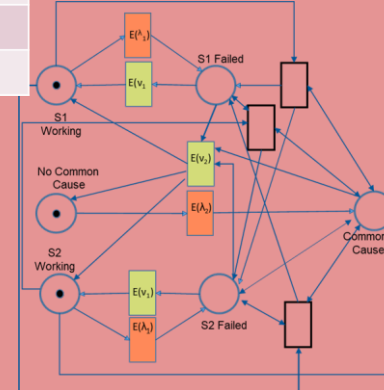
STEP 3: BDD Processing



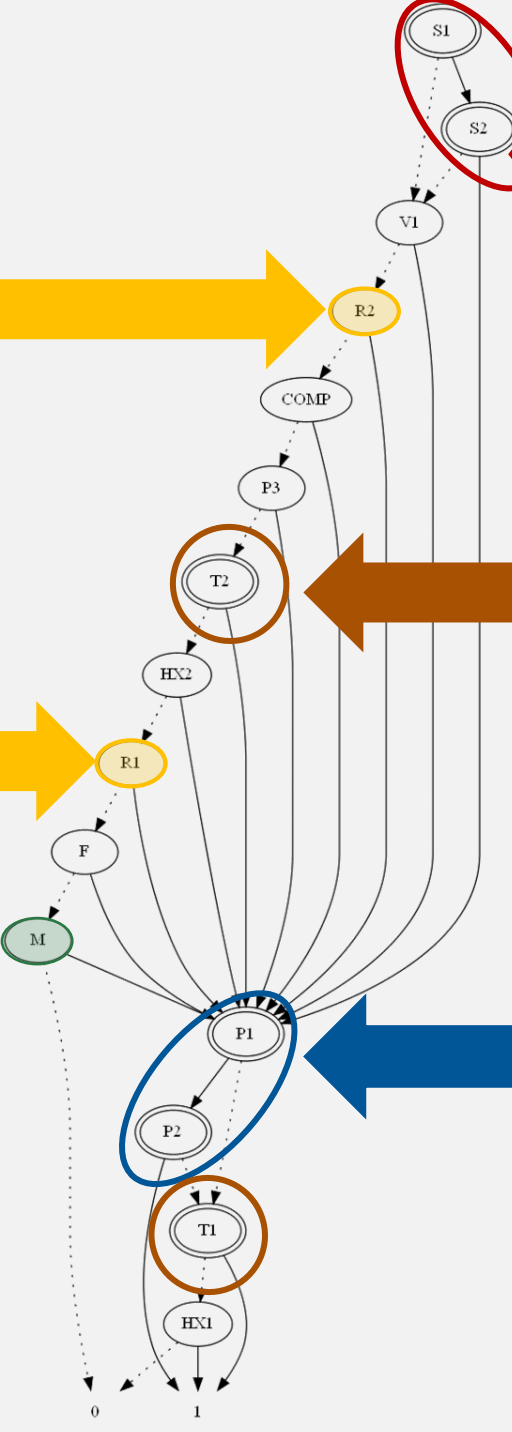
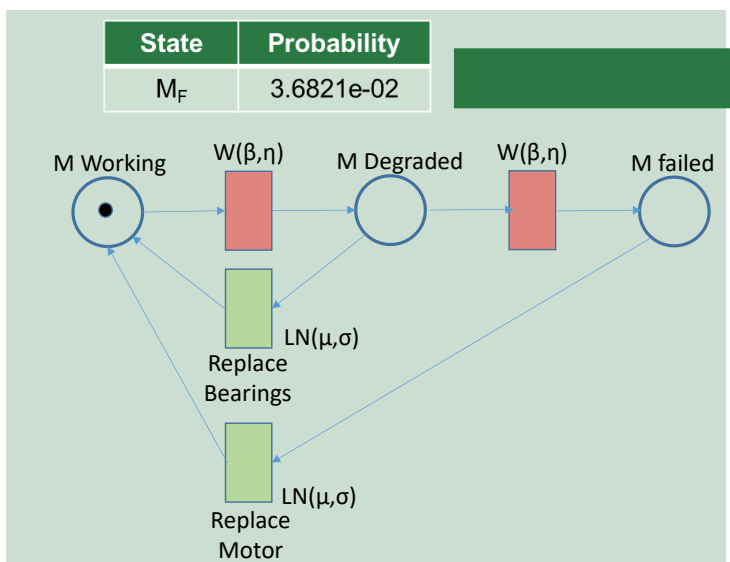
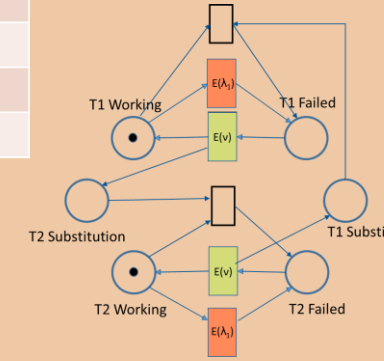
STEP 3: BDD Processing



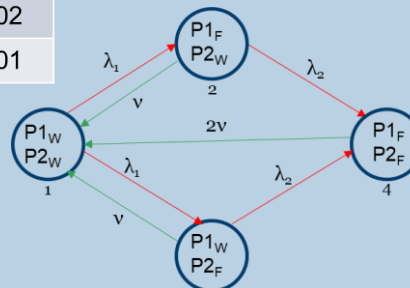
State	Probability
S1 _F , S2 _F	4.8023e-04
S1 _F , S2 _W	3.3018e-06
S1 _W , S2 _F	4.4003e-06
S1 _W , S2 _W	9.9951e-01



State	Probability
T1 _F , T2 _F	1.1883e-02
T1 _F , T2 _W	9.3168e-02
T1 _W , T2 _F	9.3193e-02
T1 _W , T2 _W	8.0175e-01

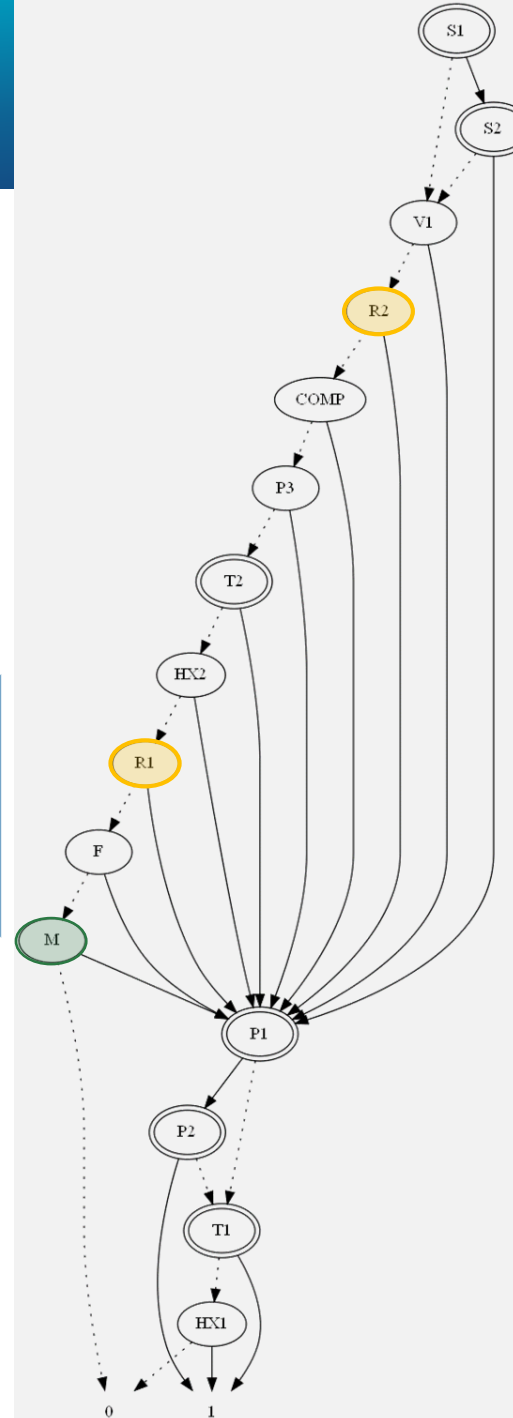


State	Probability
P1 _F , P2 _F	1.1765e-02
P1 _F , P2 _W	3.5294e-02
P1 _W , P2 _F	3.5294e-02
P1 _W , P2 _W	9.1765e-01



System Reliability = $1.8653e-02$

Component	Birnbaum
S1	0.09637
S2	0.09615
V1	0.09698
R2	0.09758
COMP	0.09699
P3	0.09761
T2	0.11725
HX2	0.09699
R1	0.09759
F	0.09699
M	0.10069
P1	0.03436
P2	0.03436
T1	0.16026
HX1	0.13583





CONCLUSIONS

- Novel method to incorporate complex features in system safety analysis
- Three step procedure:
 - Complex Features Simulation
 - FT→BDD conversion
 - BDD computation including complex reliability information
- Exploiting MMs, PNs
- Analytical solution offered through BDDs-based FT analysis
- Computational feasibility challenge for industrial systems