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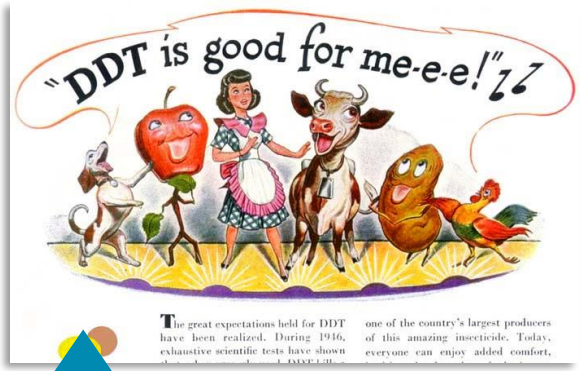
Towards autonomous digital twins: uncertainty, data, computing, simulation, and ethics
ESRA Symposium
University of Strathclyde
Glasgow, UK
30th November – 1st December 2023

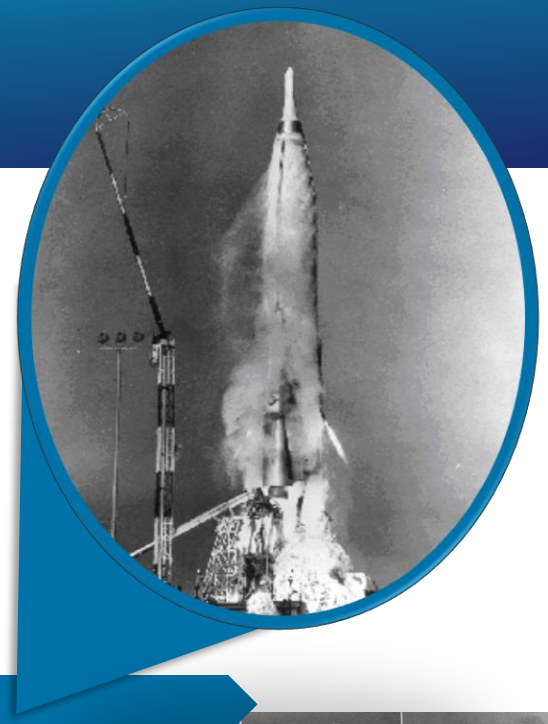
Modelling dependencies in complex systems: Dynamic and Dependent Tree Theory (D^2T^2)

Dr Silvia Tolo

Foundation

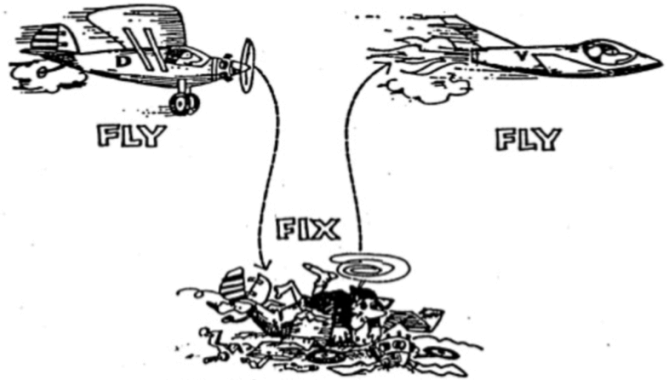
Why system safety?





40s

50s



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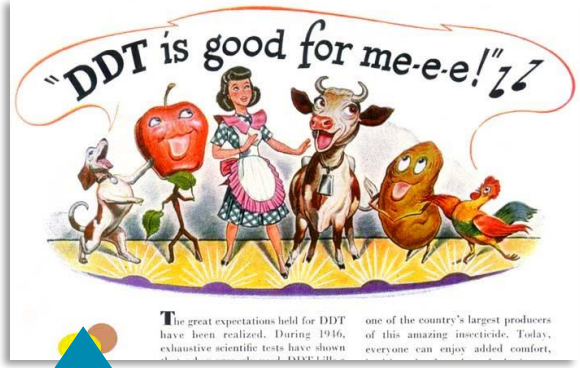

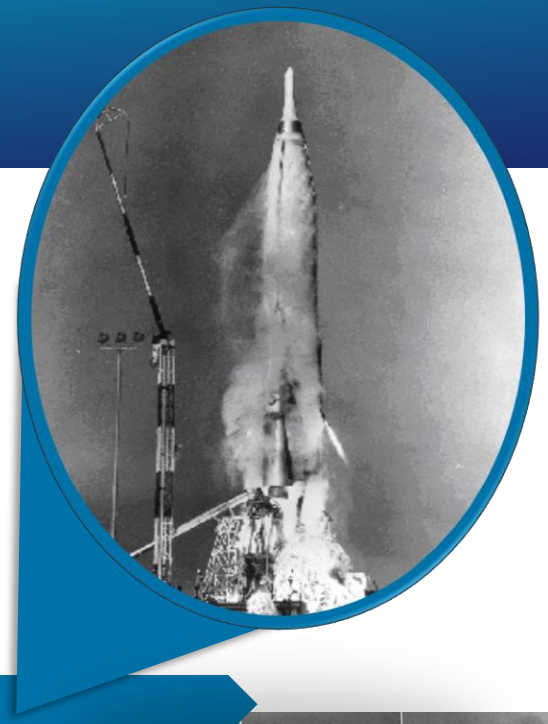

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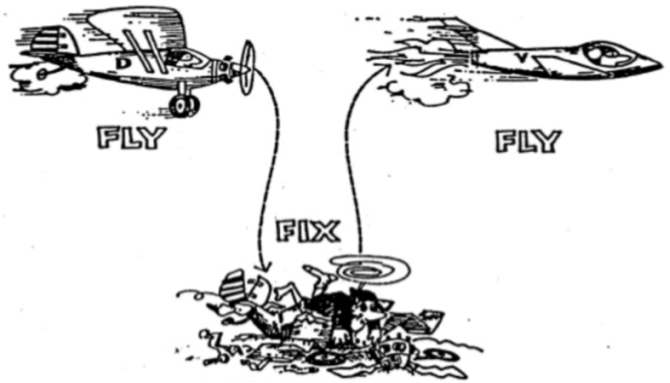

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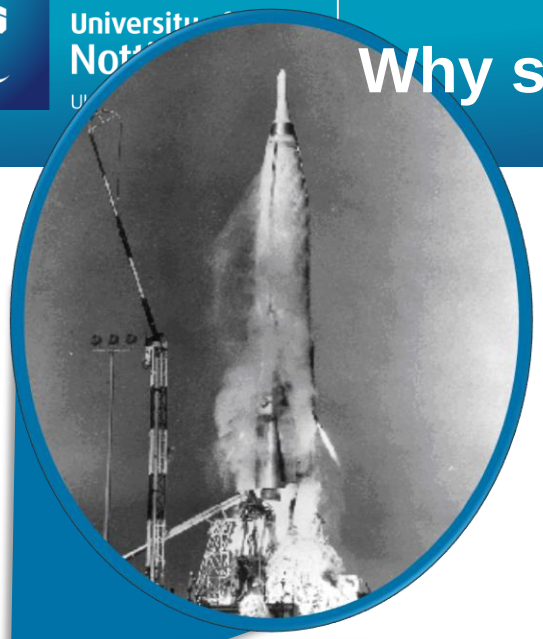


60s

WEATHER
Forecast for Tucson: generally fair, little change
Temperatures
Yesterday: HIGH 74 LOW 36
Year Ago: HIGH 55 LOW 39
U.S. WEATHER BUREAU

The Arizona Daily Star

FINAL
TEN CENTS

★ An Independent NEWSpaper Printing The News Impartially ★

VOL. 126 NO. 28 TUCSON, ARIZONA, SATURDAY MORNING, JANUARY 28, 1967 THIRTY PAGES

Apollo Training Craft Explodes

ASTRONAUTS DIE IN FIERY CAPSULE

VIRGIL I. GRISSOM ... Veteran command pilot
EDWARD H. WHITE II ... Spacewalk hero
ROGER B. CHAFFEE ... Rookie astronaut

U.S. Signs Outer Space N-Treaty

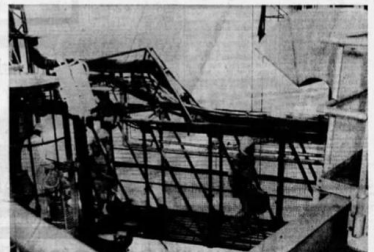
'Inspiring Moment' Hailed By Johnson

By MAX FRANKEL

WASHINGTON — President Johnson presided yesterday over a White House ceremony at which the United States, the Soviet Union and 60 other countries signed a treaty to limit military activities in outer space.

Johnson hailed it as an "inspiring moment in the history of the human race" and described the treaty as a "first firm step toward keeping outer space free forever from the implements of war."

Similar ceremonies were held earlier yesterday in Moscow and London. But the treaty will not take effect until it is ratified by the U.S., the Soviet Union, Britain, and two other nations.



3 Spacemen Trained In Arizona

The three Apollo astronauts killed last night had trained at several scientific installations in Arizona.

Beginning with the Gemini program, astronauts had spent many hours at Kitt Peak, the observatory southwest of Tucson on the Papago Reservation, at Lowell Observatory in Flagstaff and at the Grand Canyon.

Sites in northern Arizona were selected for features closely resembling the moon, including volcanic regions, lava flows, meteor craters and geological phenomena like the Grand Canyon.

Three-Man Crew Killed Instantly

CAPE KENNEDY, Fla., (AP) —The three Apollo I Astronauts were killed last night by a flash fire that trapped them aboard the huge spacecraft designed to take a man to the moon by 1970.

Locked behind sealed hatches and killed instantly just 218 feet above the ground were:

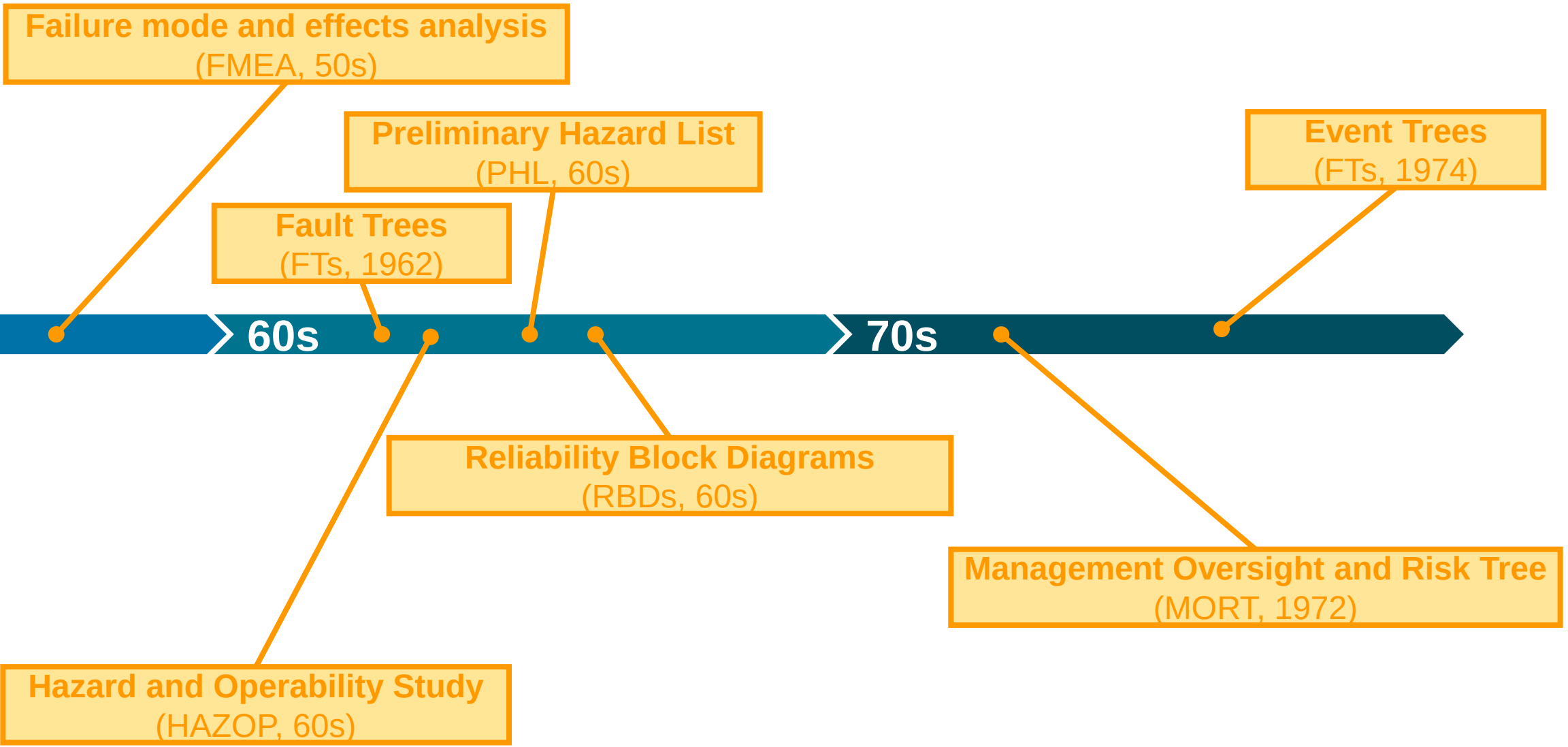
Air Force Col. Virgil (Gus) Grissom, a space pioneer and the first man to soar twice into the heavens; Air Force Col. Edward H. White II, First American to walk in space, and Navy Lt. Cmdr. Roger B. Chaffee, a rookie eagerly awaiting his first flight.

The three were hooked into a pure oxygen breathing system in their spacesuits and the oxygen fed the fire. Valiant pad workers trying to rescue the trapped men fell back one by one as they fought through dense, acid smoke toward the capsule.

Although the tragedy postponed indefinitely the Apollo's scheduled Feb. 21 blast off, space officials and

Tragedy Will Hurt

Why system safety?



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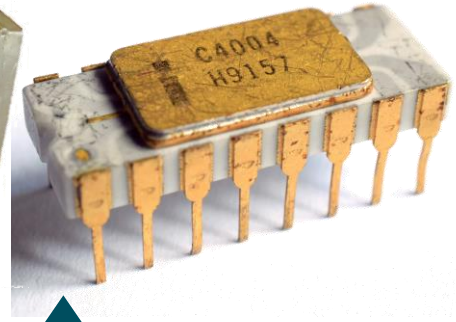
Why system safety?

Failure mode and effects analysis
(FMEA, 50s)

Preliminary H
(PHL, 6

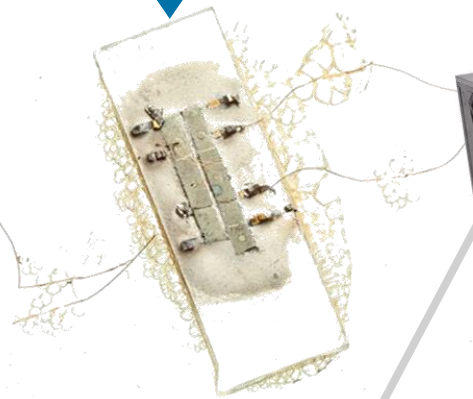
Fault Trees
(FTs, 1962)



Event Trees
(FTs, 1974)

60s

70s



abilit
(

versight and Risk Tree
ORT, 1972)

Hazard and Operability Study
(HAZOP, 60s)

Different systems…different tool?

LARGE-SCALE SYSTEMS

→ High level of complexity

→ Enormous number of components

→ Low probability values

→ Multiple stakeholders

Different systems…different tool?

LARGE-SCALE SYSTEMS

→ High level of complexity

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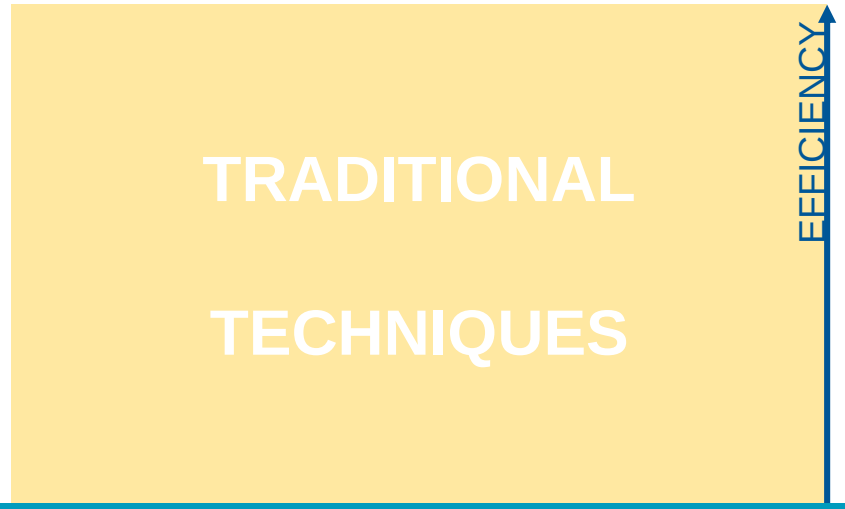
Different systems…different tool?

TRADITIONAL

TECHNIQUES

EFFICIENCY

Different systems…different tool?



HIGH LEVEL OF AUTOMATION AND CONTROL TECHNOLOGY

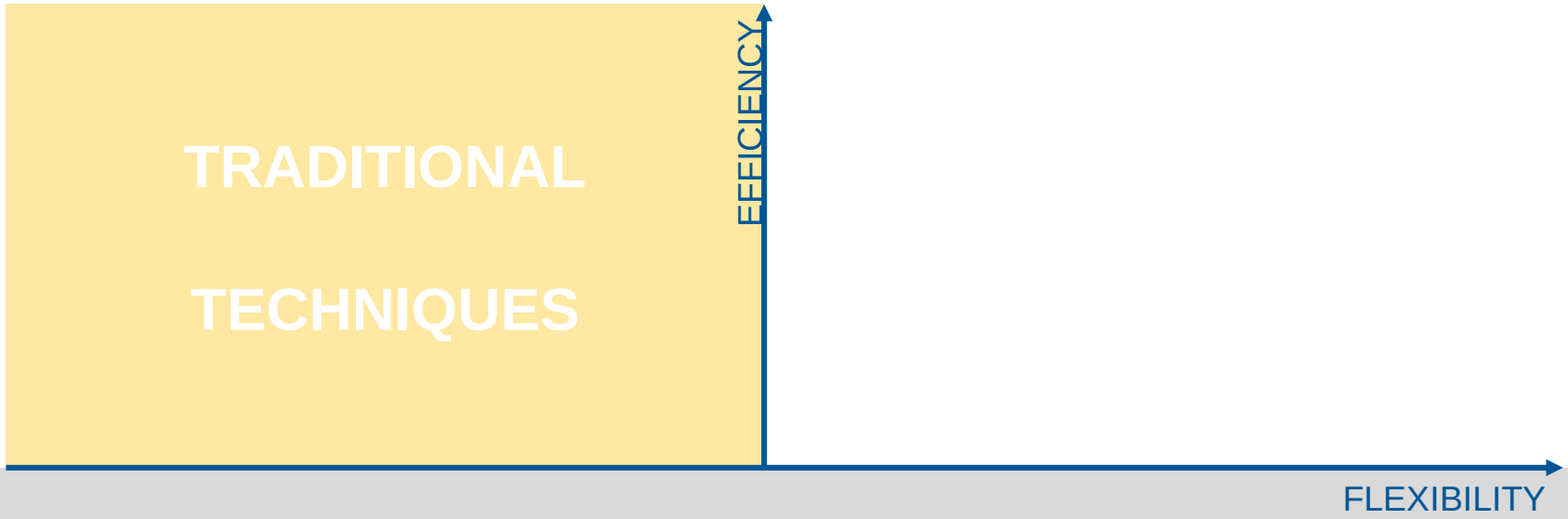
→ systems un-negligibly dynamic

→ human-technology interface

→ increasingly complex maintenance strategies

Dependencies between failure events

Different systems…different tool?



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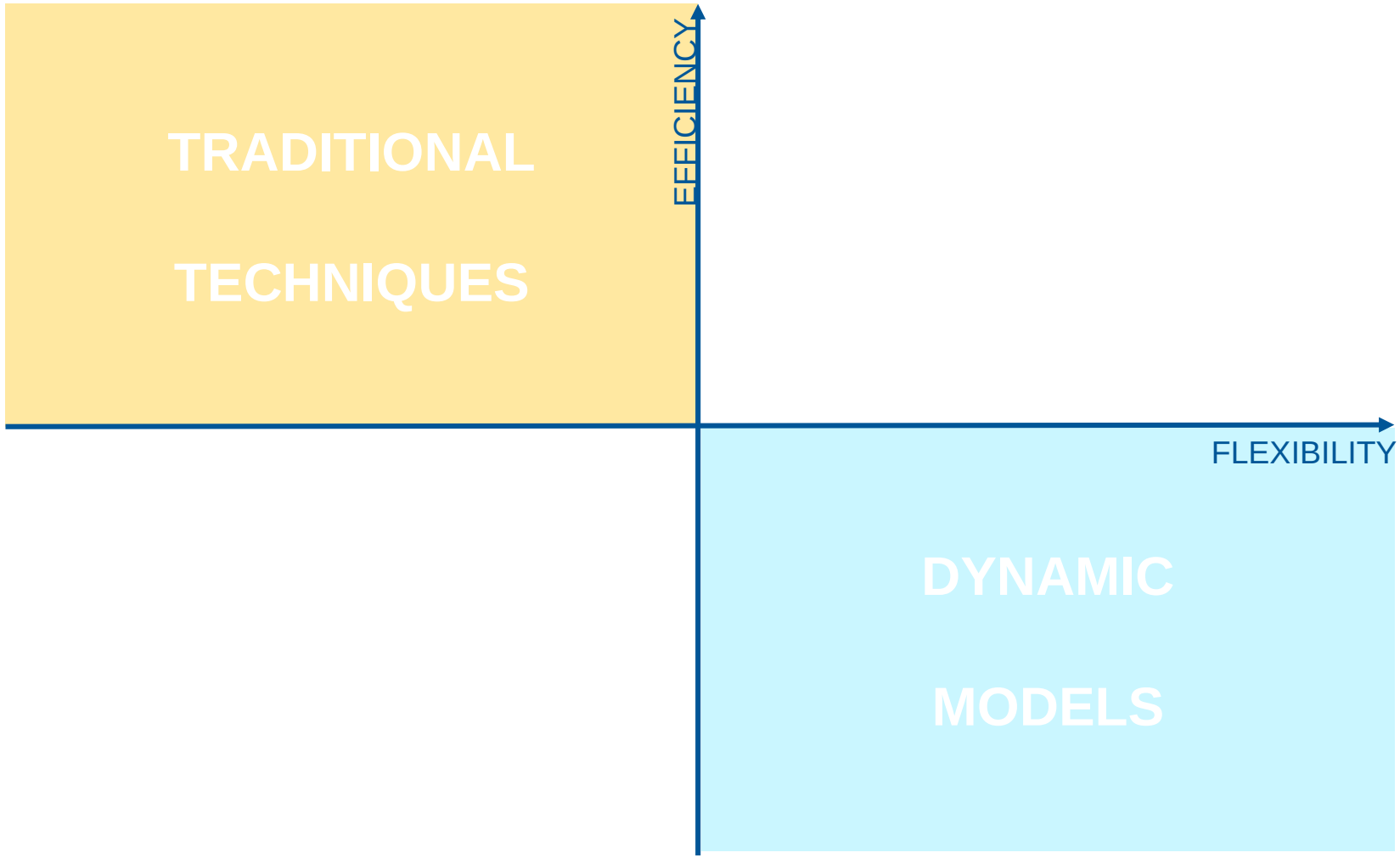

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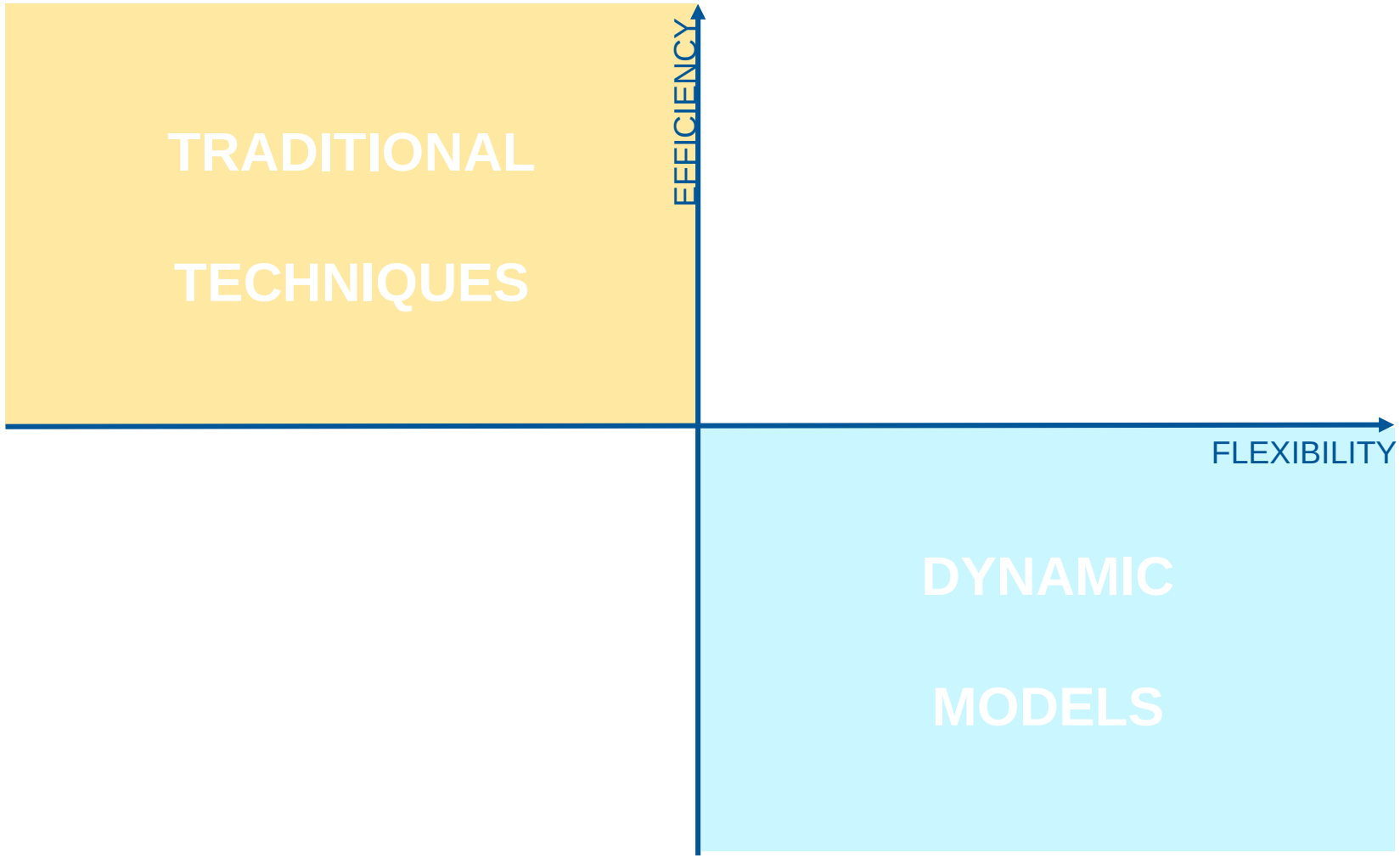


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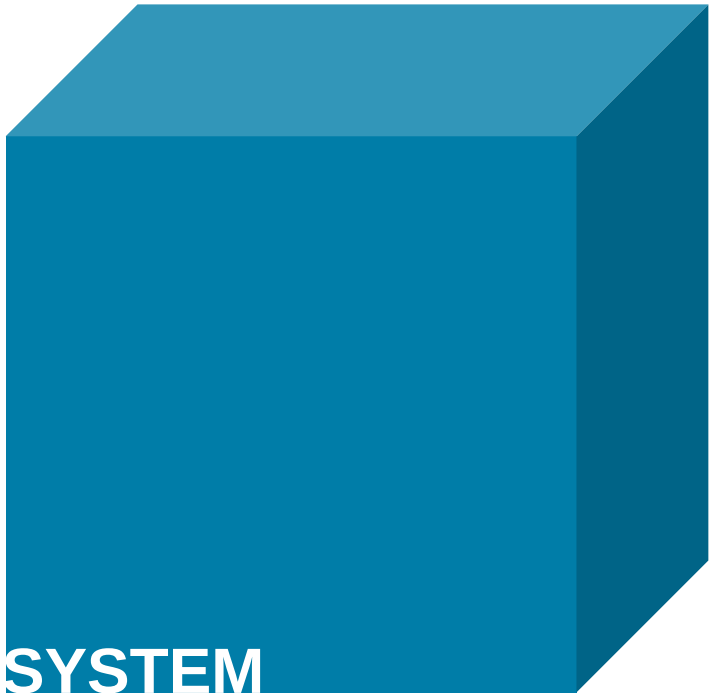
D²T²
Dynamic and Dependent Tree Theory

D^2T^2: The Big Picture



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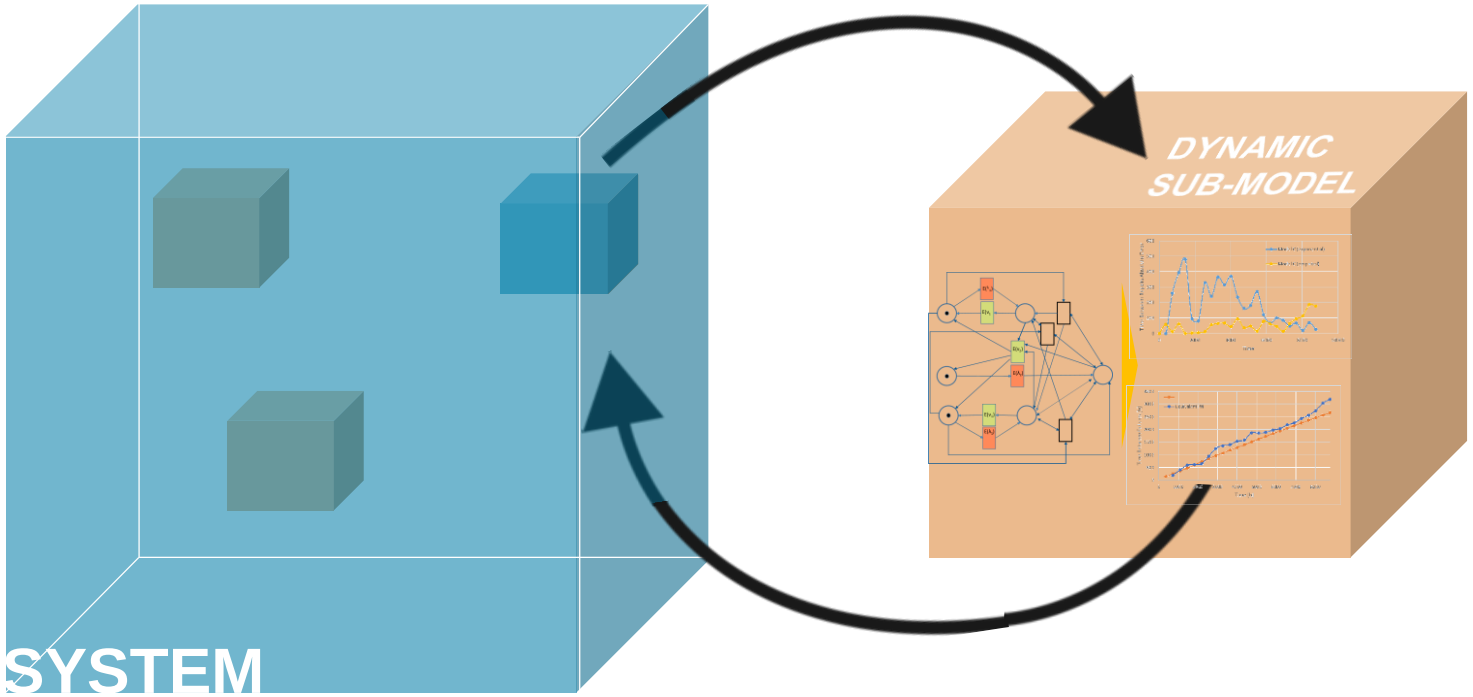
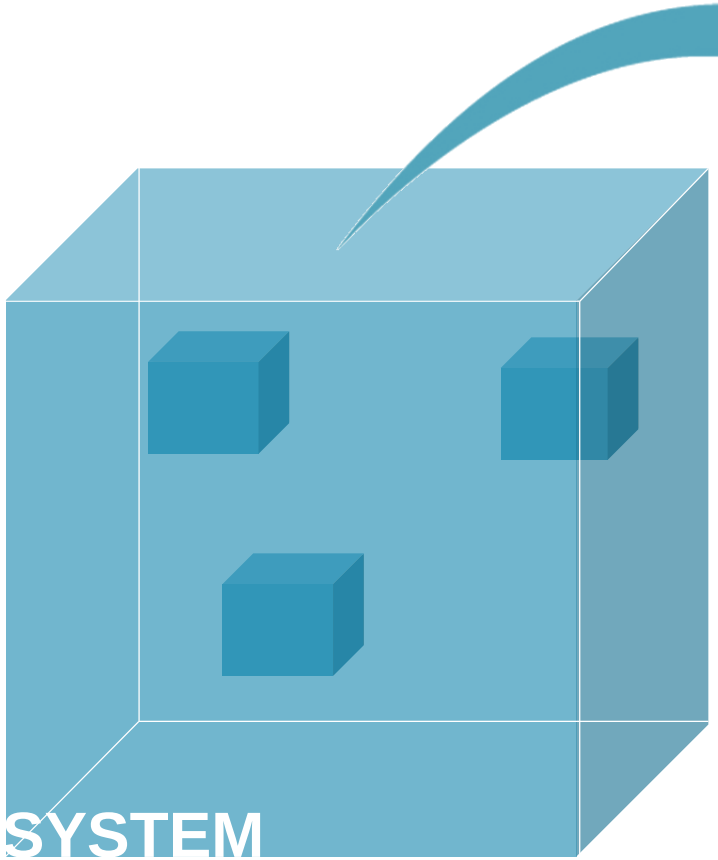
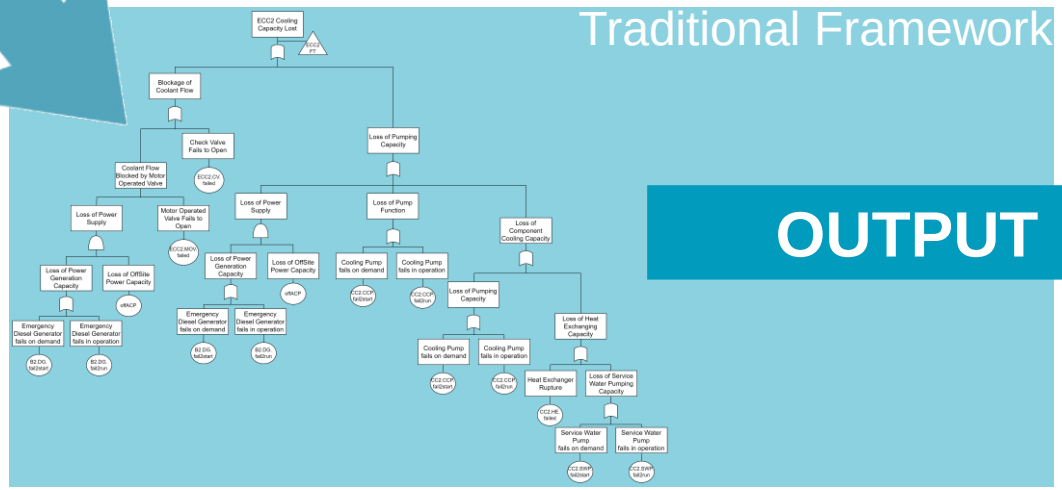
D^2T^2: The Big Picture



D²T²: The Big Picture





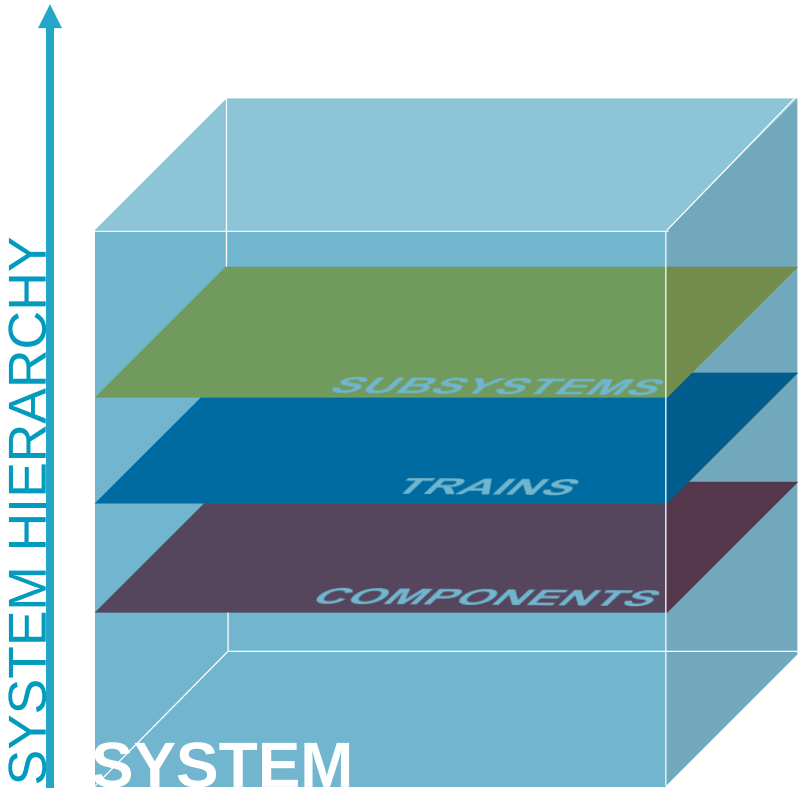
OUTPUT

→Tailored use of ‘expensive’ dynamic models

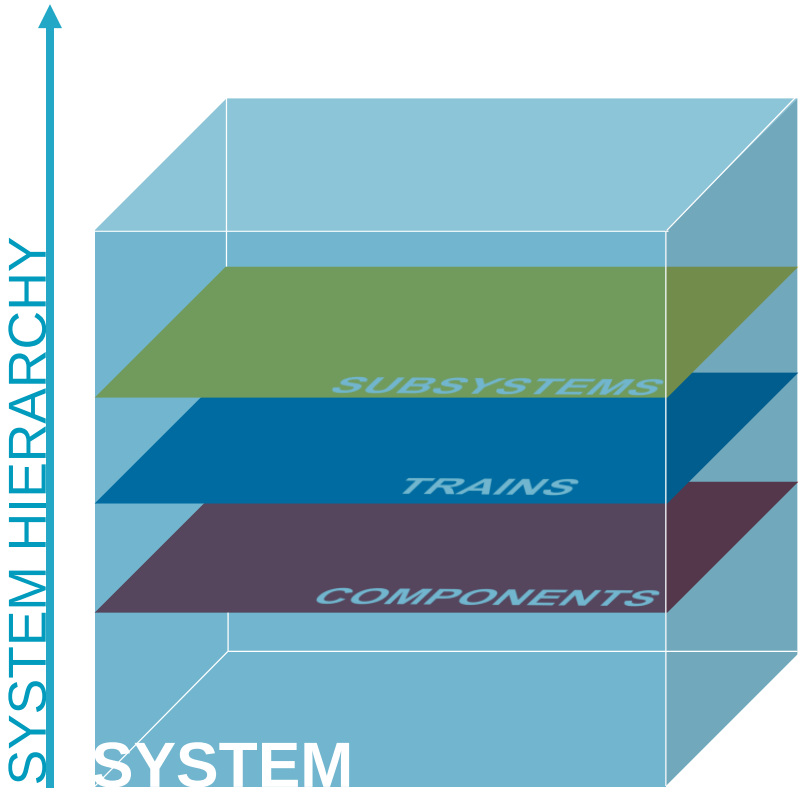
→ Preserves effectiveness of traditional techniques

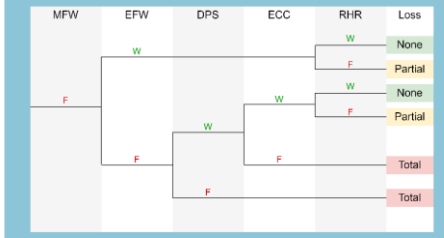
→ Enhances modelling accuracy and flexibility

Modelling Hierarchy



Modelling Hierarchy





Event Tree [ET]:

- Accident Sequence
- Subsystems interaction

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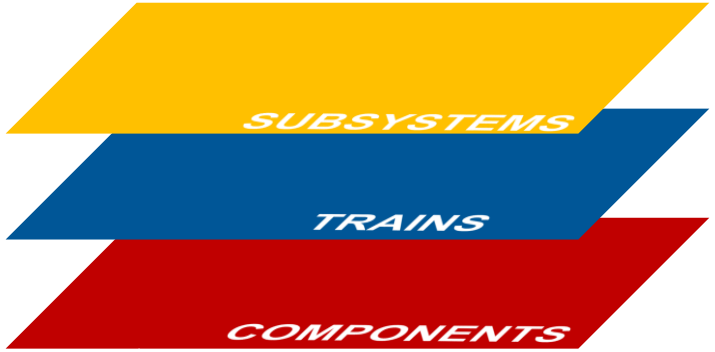
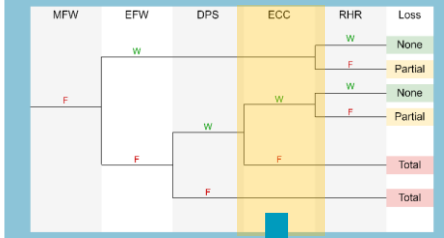
Modelling Hierarchy

SYSTEM HIERARCHY





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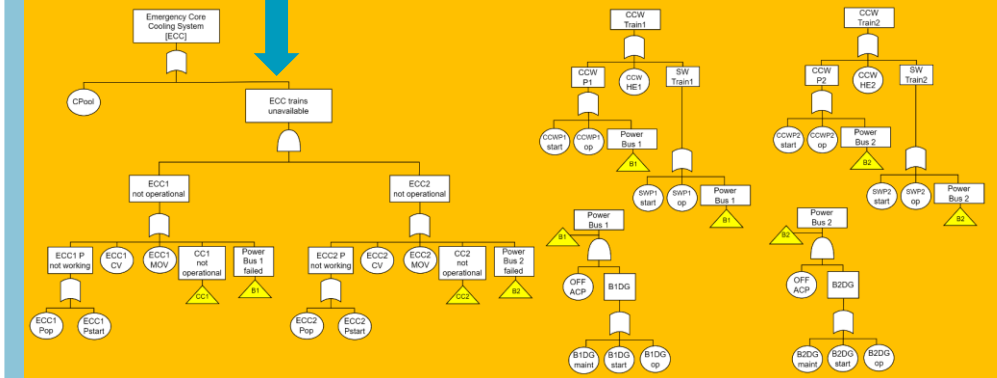

Fault Tree [FT]:

- Sub-system failure

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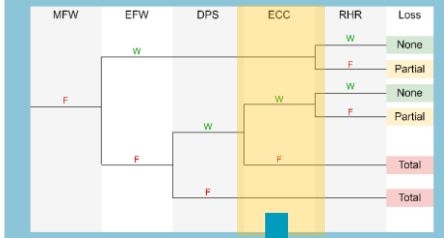
Modelling Hierarchy

SYSTEM HIERARCHY

TRAINS

COMPONENTS



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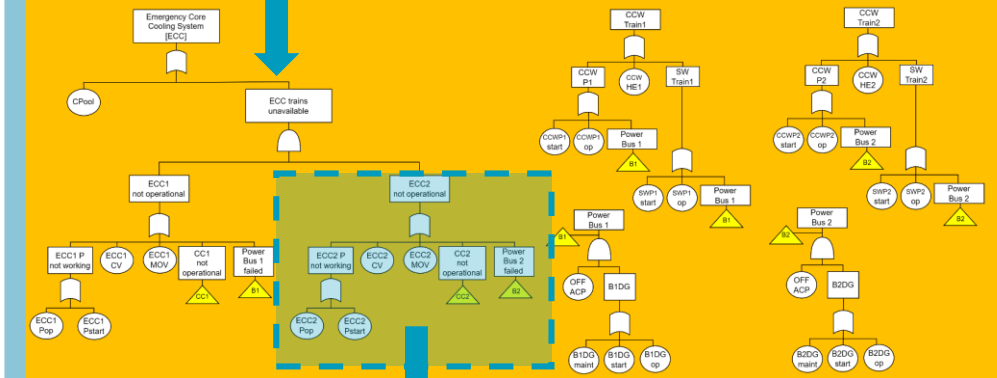

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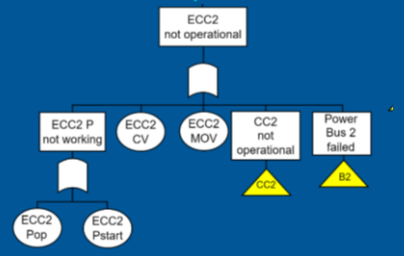

Sub-Tree [FT]:

- Trains of identical components
- Redundancy

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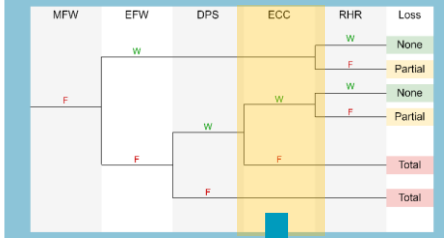
Modelling Hierarchy

SYSTEM HIERARCHY

COMPONENTS



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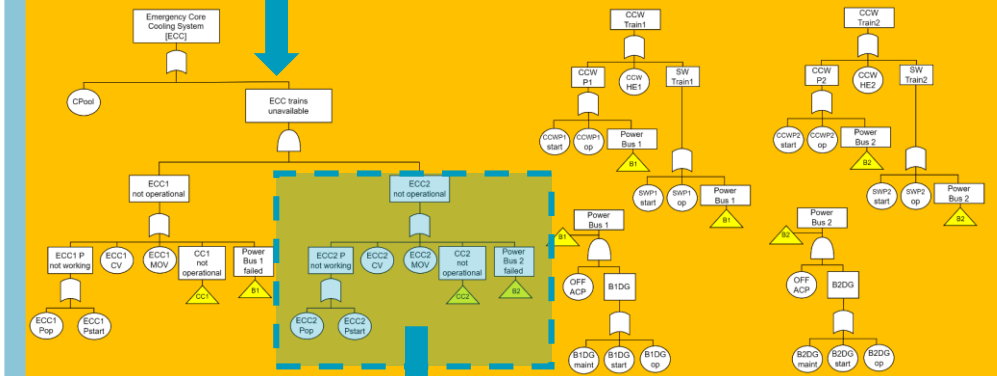

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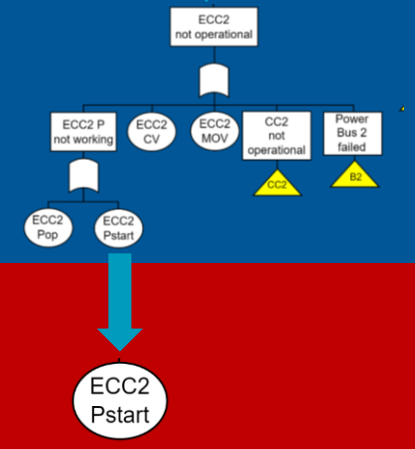

Sub-Tree [FT]:
- Trains of identical components
- Redundancy

Basic Event [BE]:
- Component Failure Mechanism
- Reliability Metrics

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Hands on

D^2T^2 application

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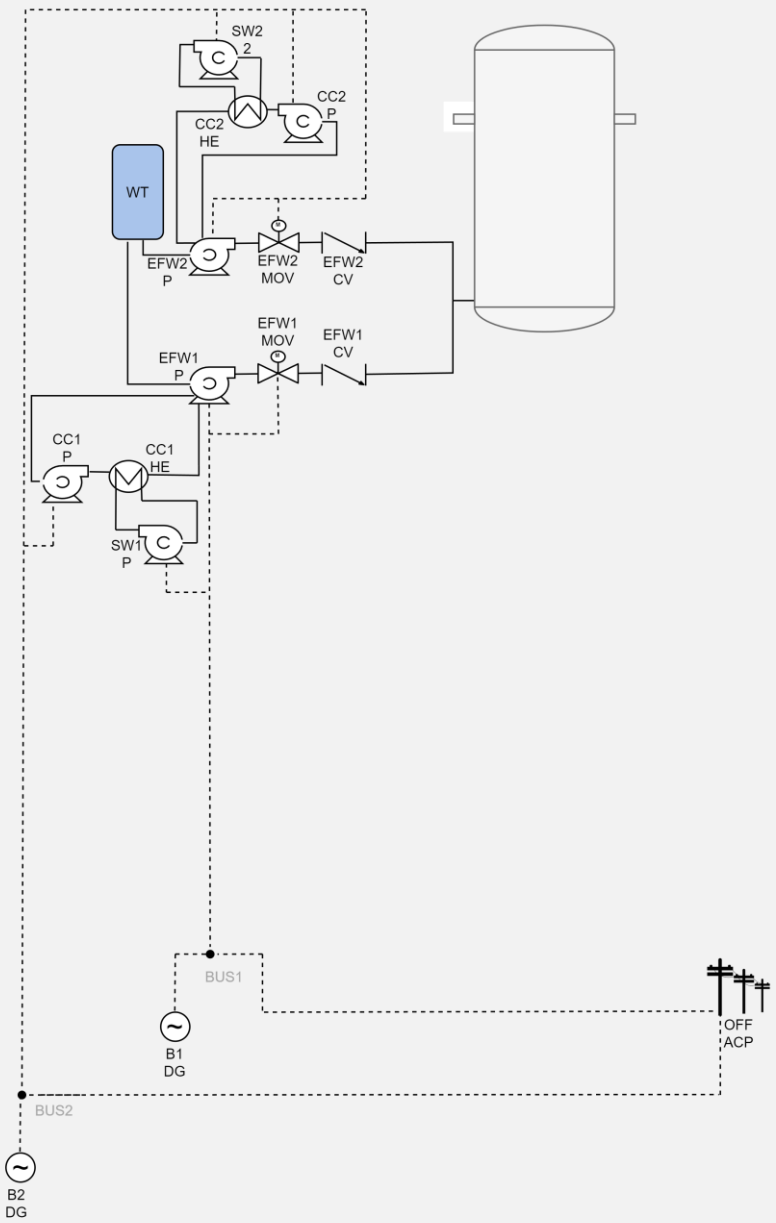
D²T²: Components Dependency

COMPONENTS



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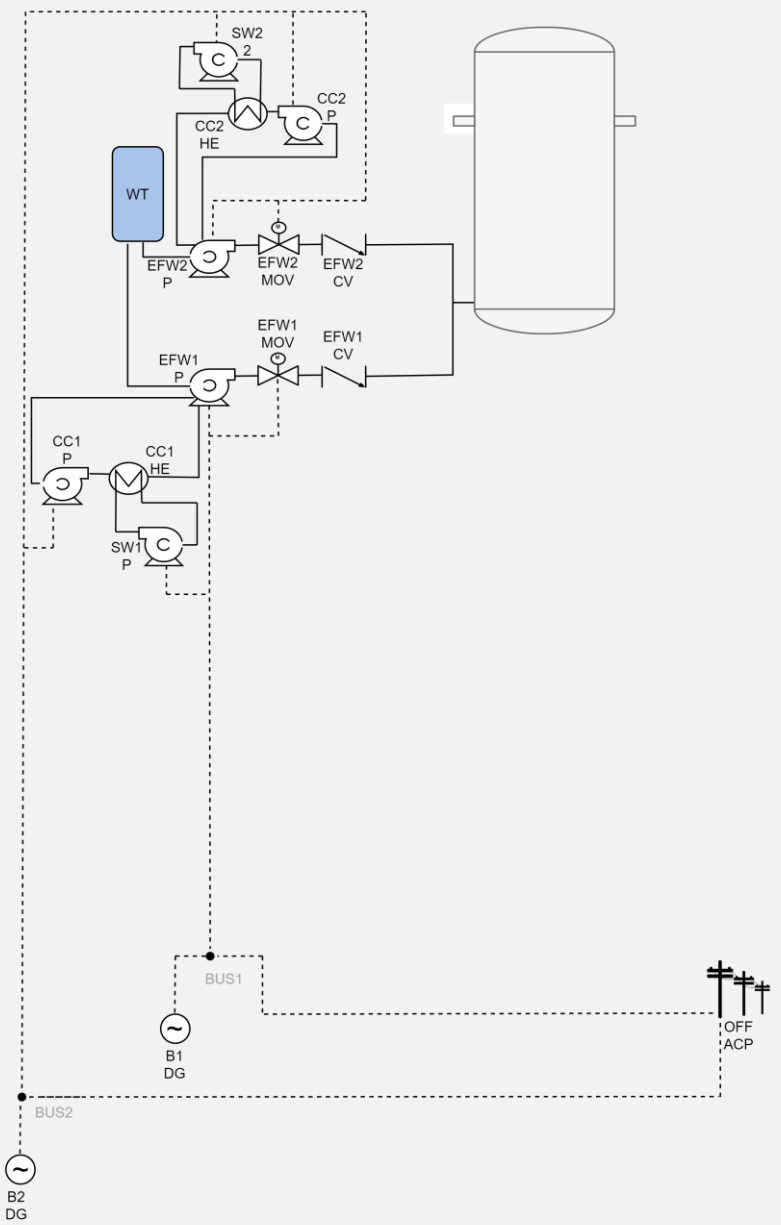

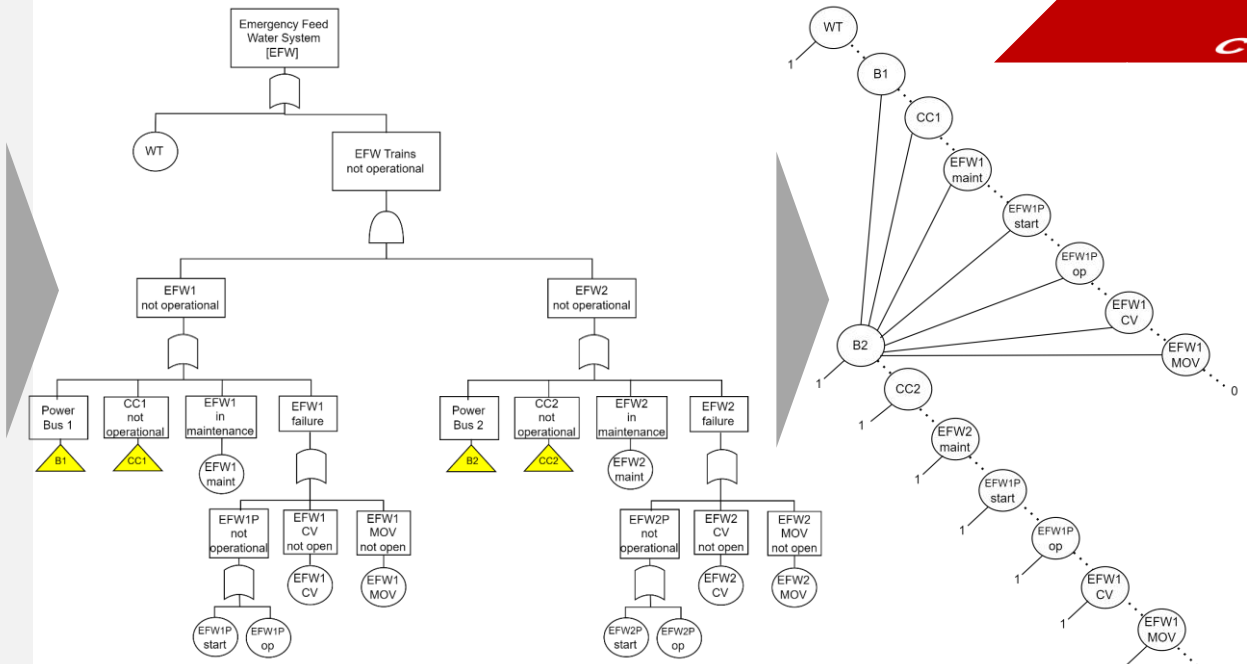

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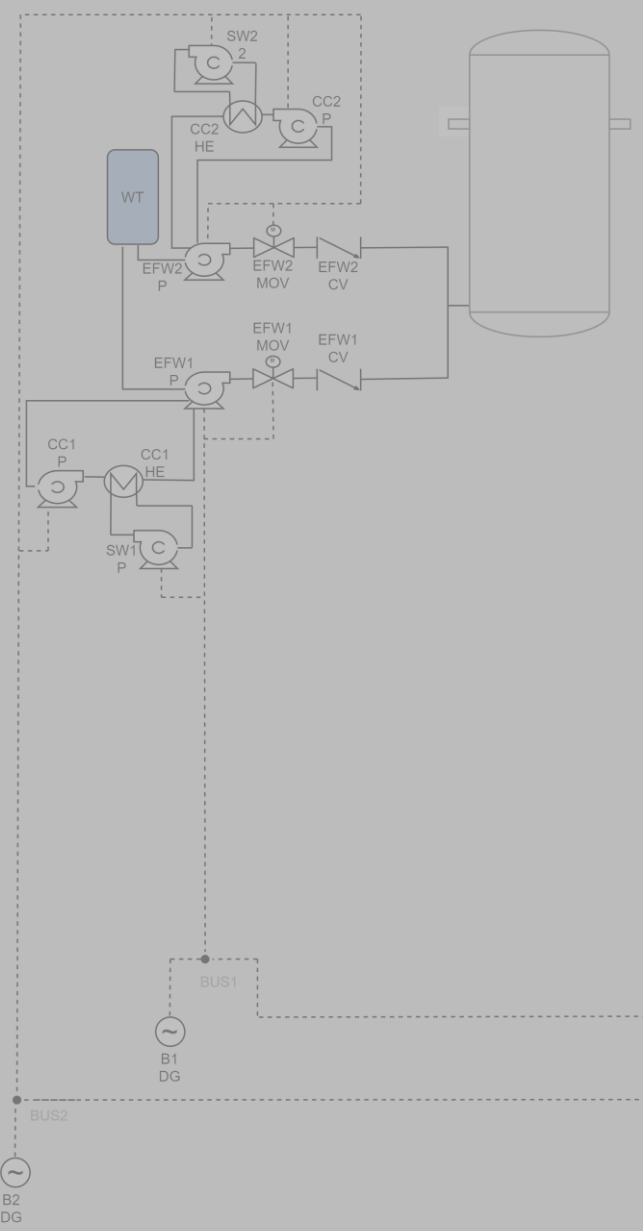

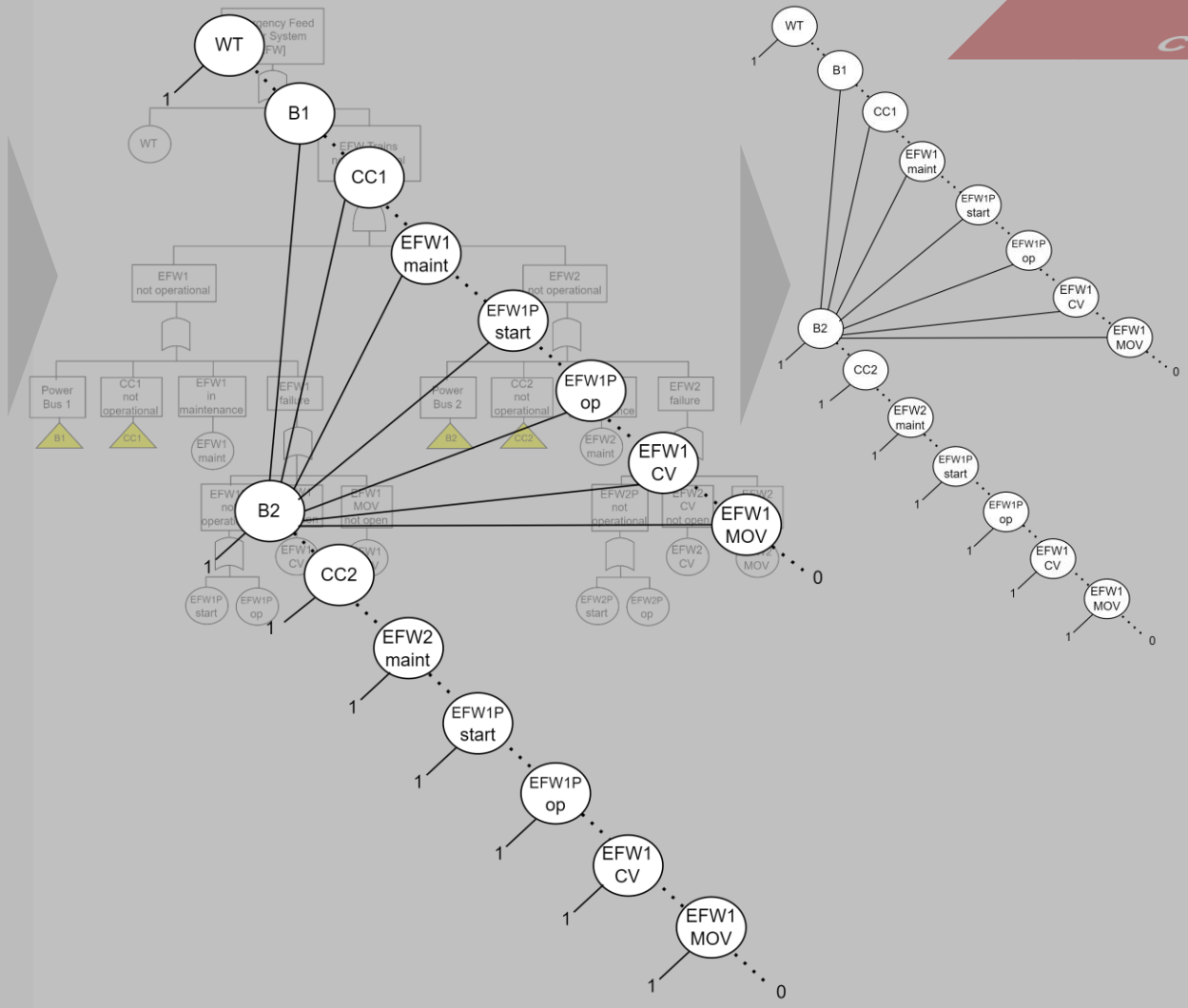

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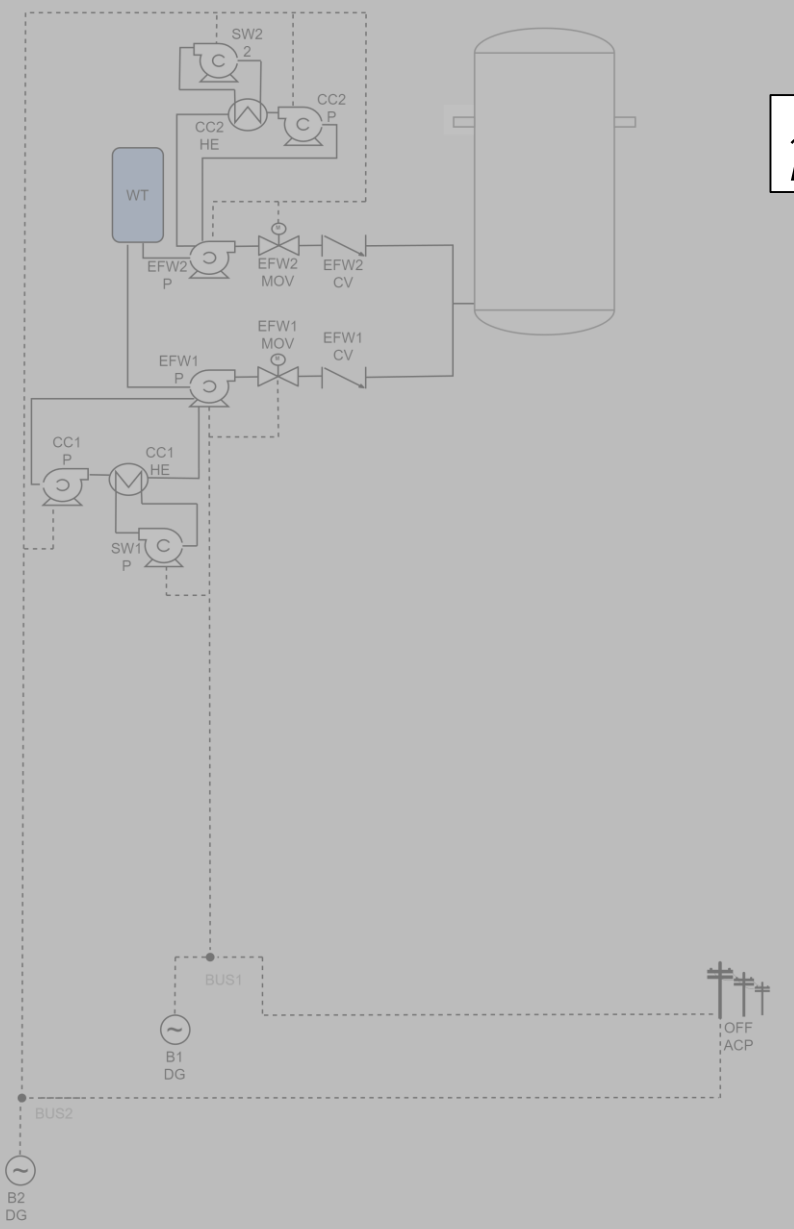

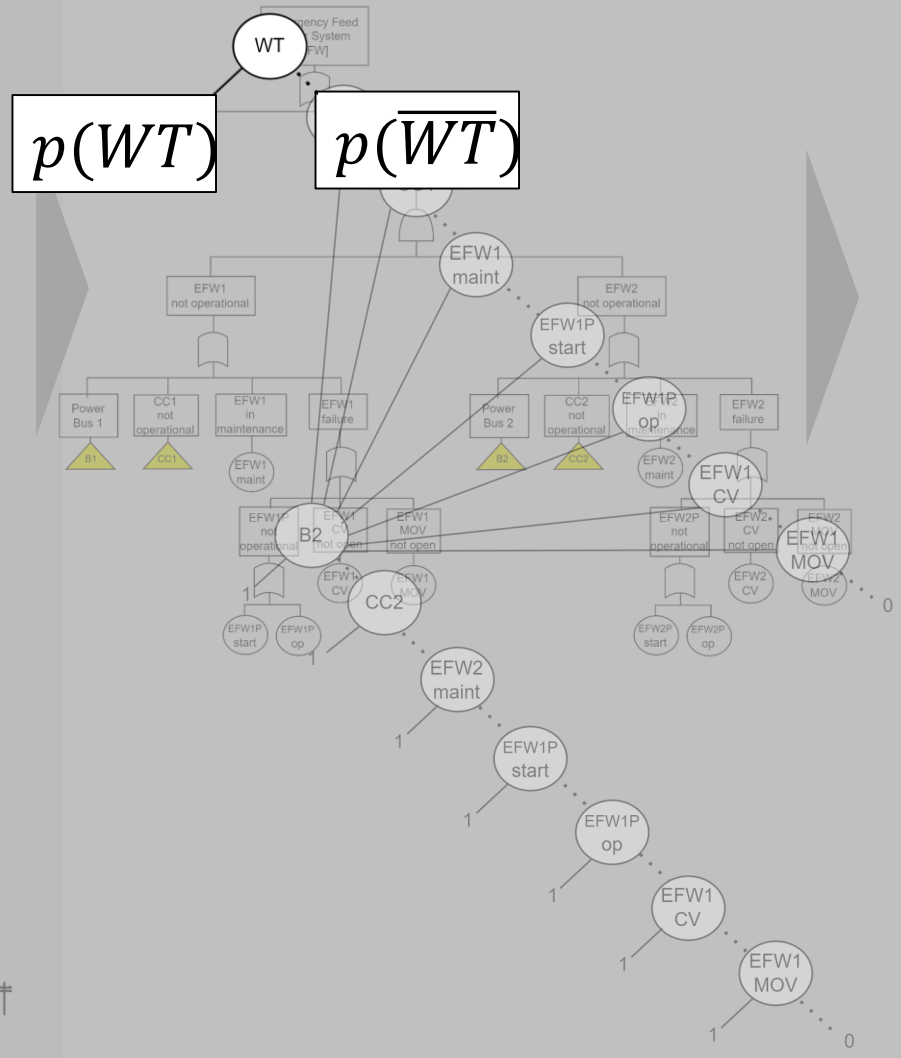

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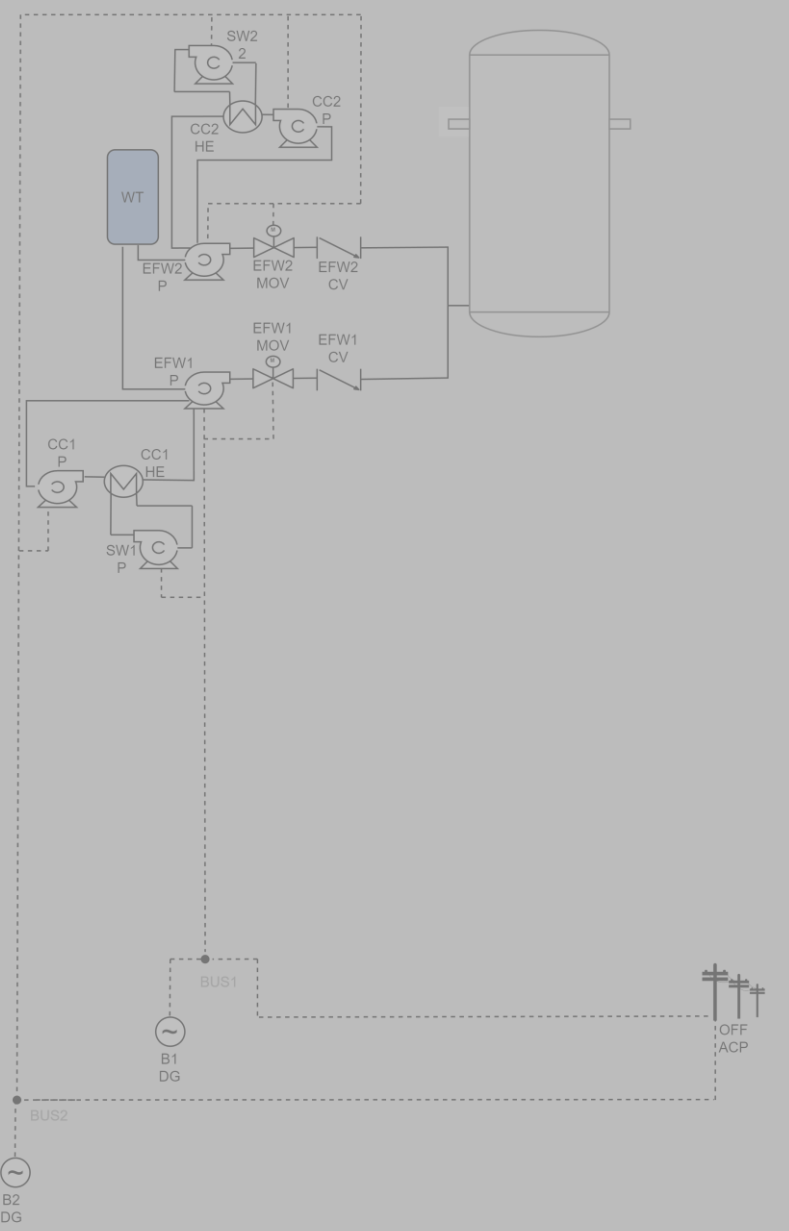

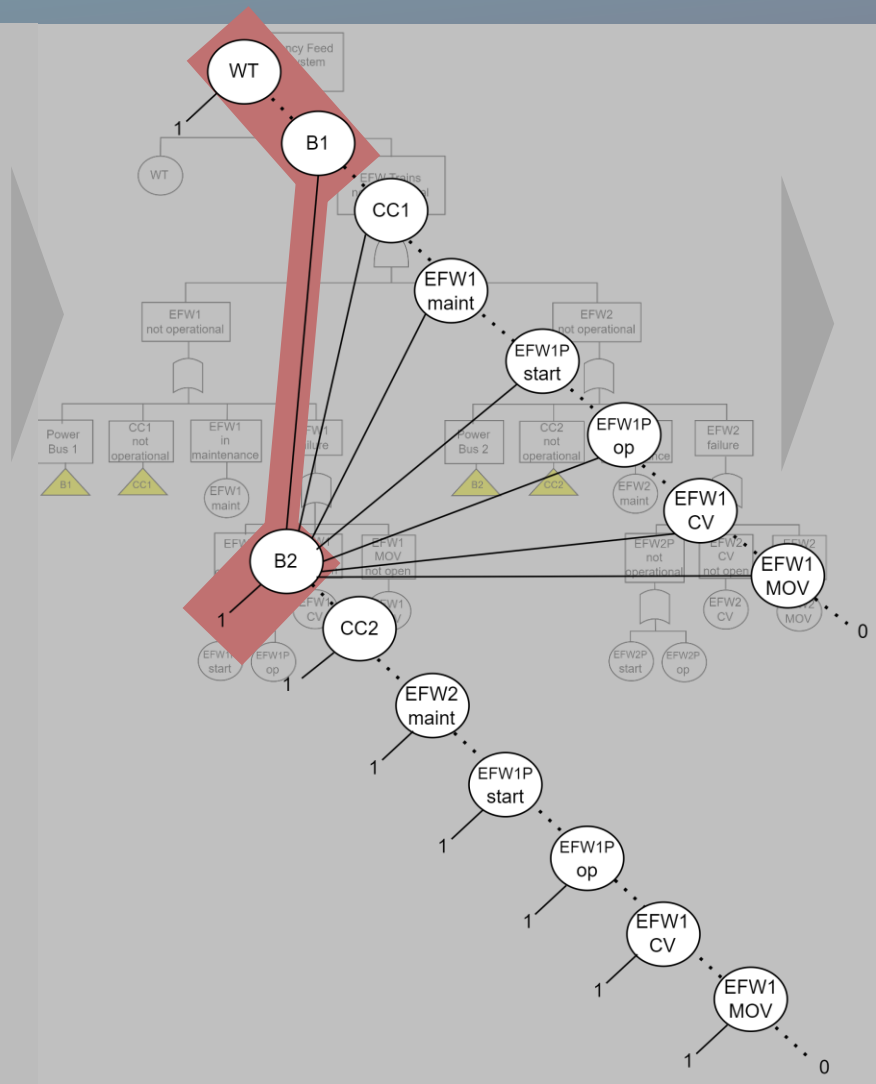

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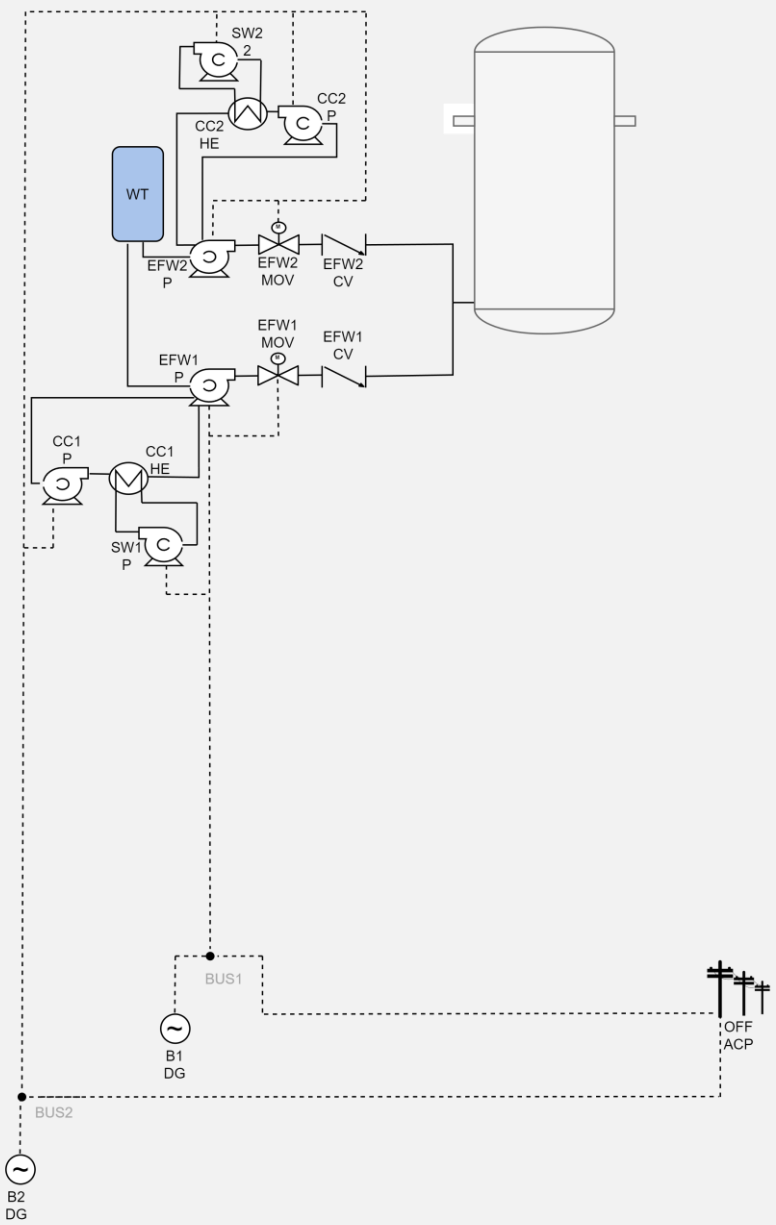

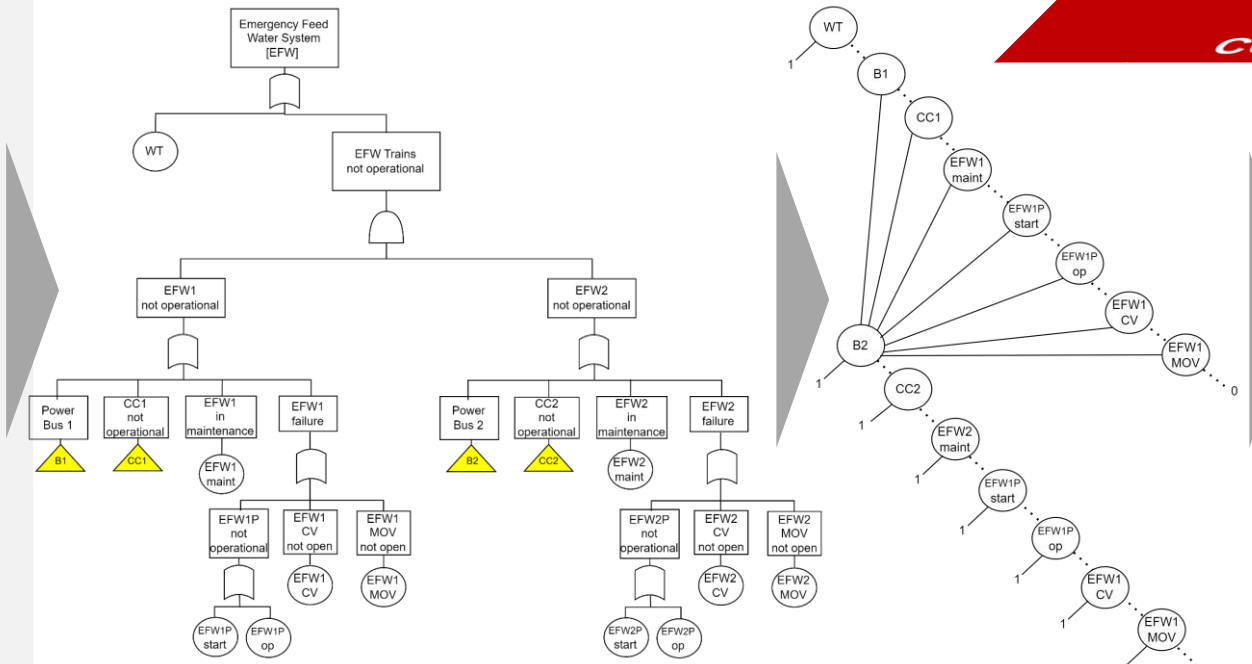

TOP EVENT PROBABILITY = 0.003701

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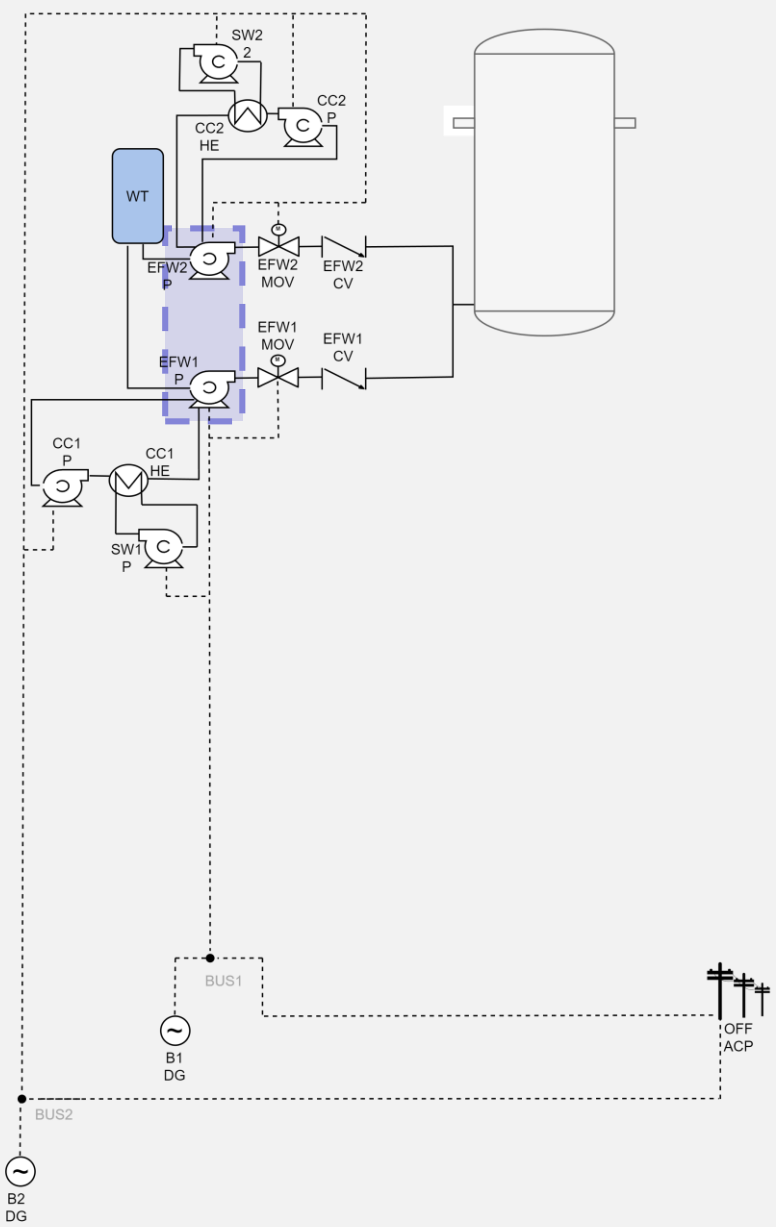
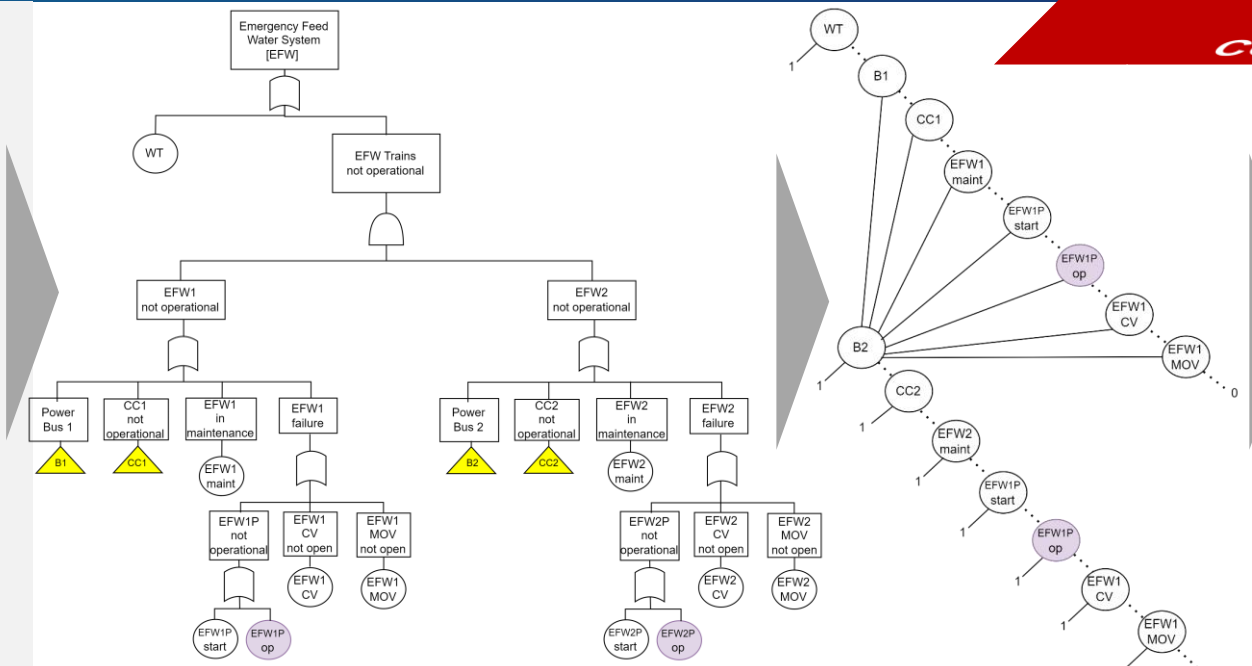
D²T²: Components Dependency

COMPONENTS





TOP EVENT PROBABILITY = ?

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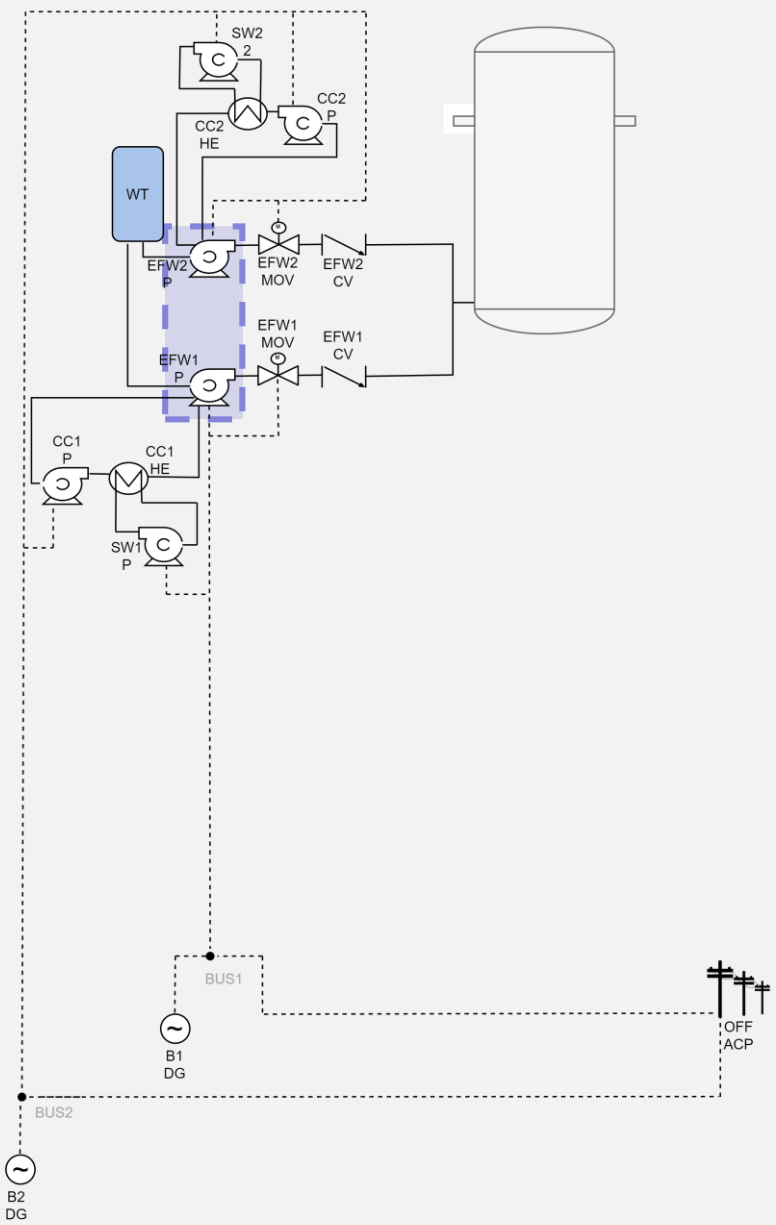
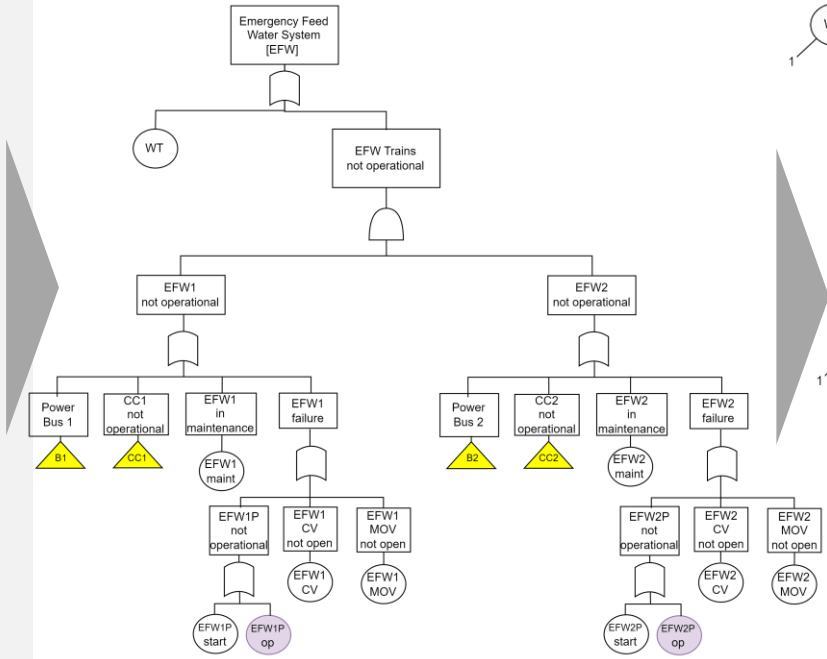
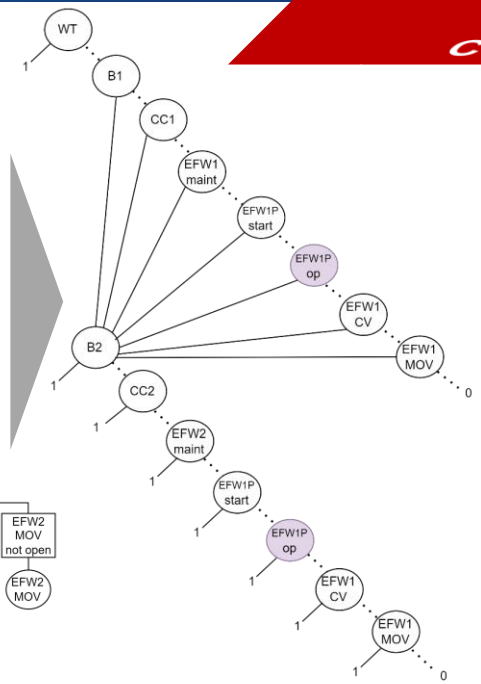
D^2T^2: Components Dependency

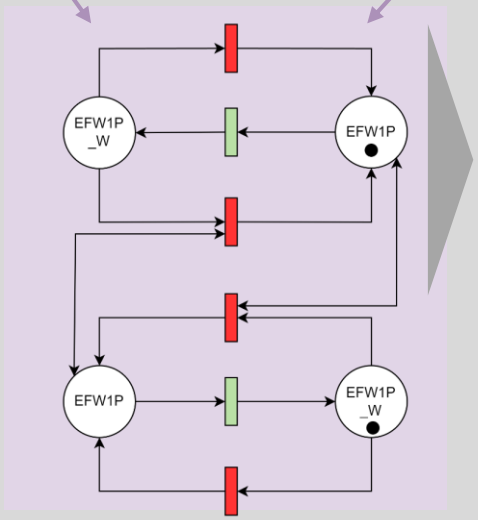
COMPONENTS







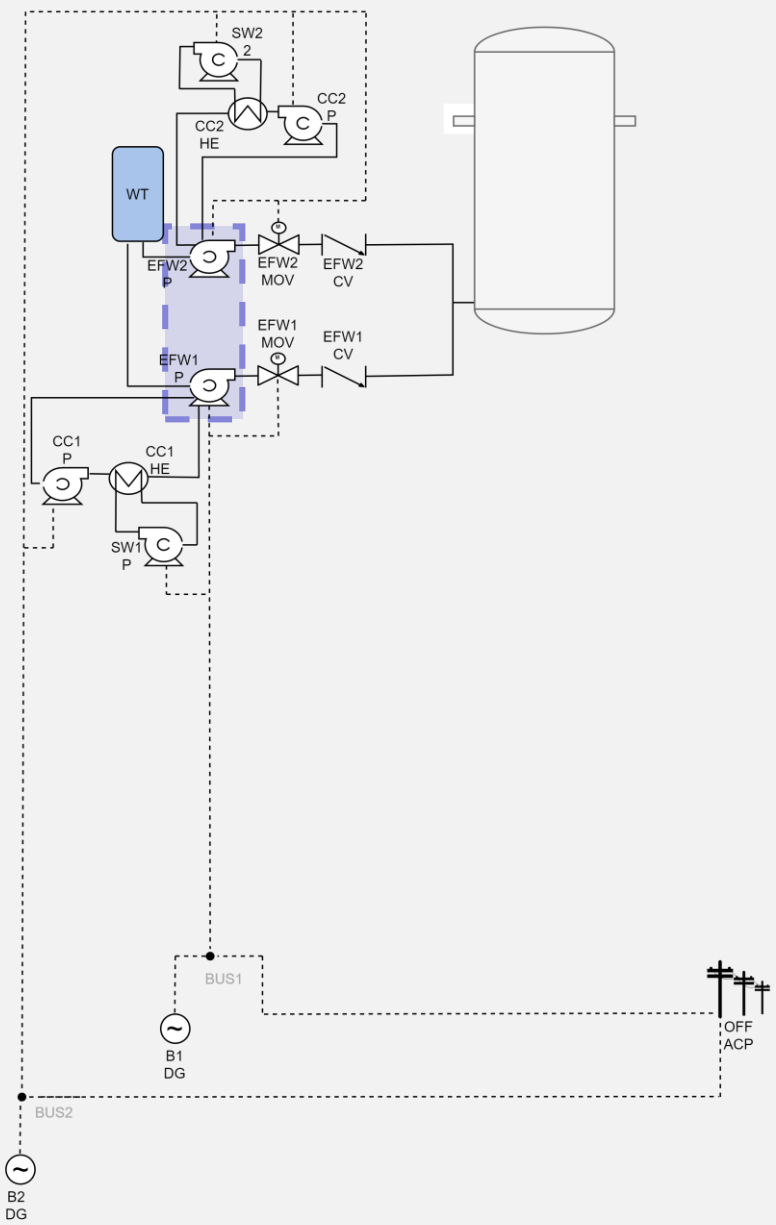
TOP EVENT PROBABILITY = ?

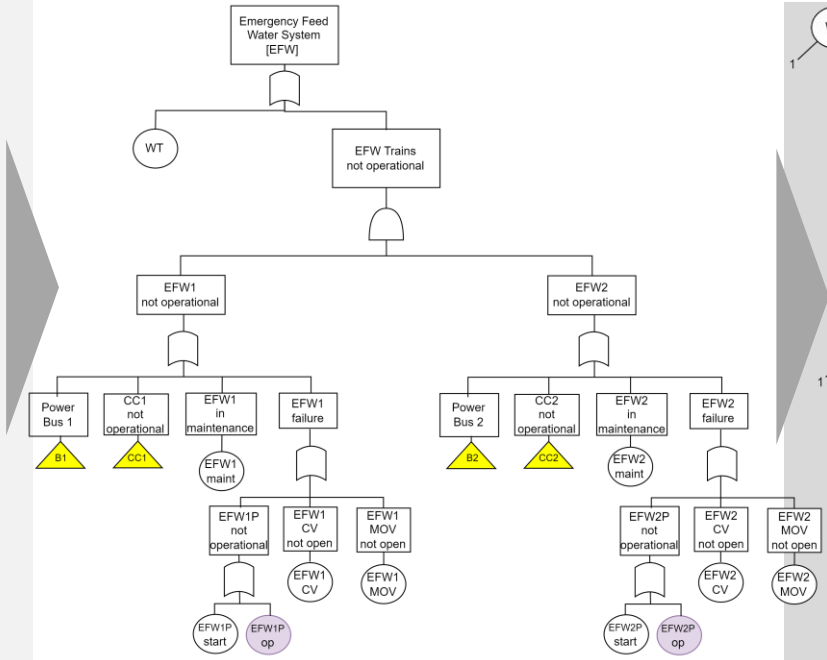


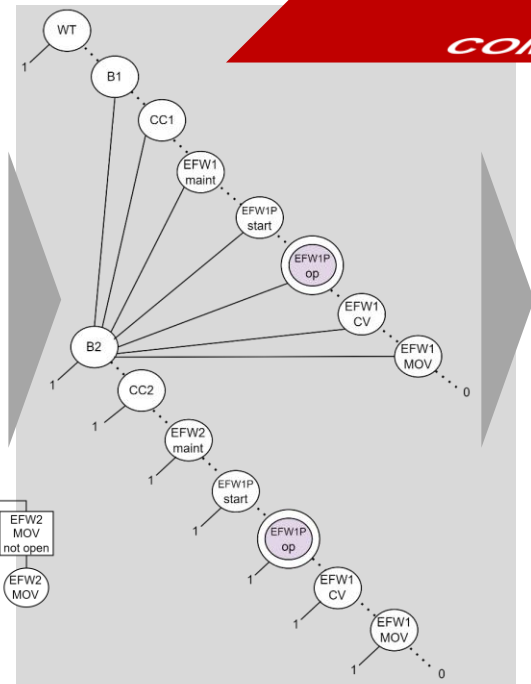
Joint Event	Probability
$\overline{EFW1Pop}, \overline{EFW2Pop}$	$9.9 \cdot 10^{-1}$
$\overline{EFW1Pop}, EFW2Pop$	$1.80 \cdot 10^{-4}$
$EFW1Pop, \overline{EFW2Pop}$	$1.79 \cdot 10^{-4}$
$EFW1Pop, EFW2Pop$	$2.96 \cdot 10^{-8}$

D^2T^2

D²T²: Components Dependency

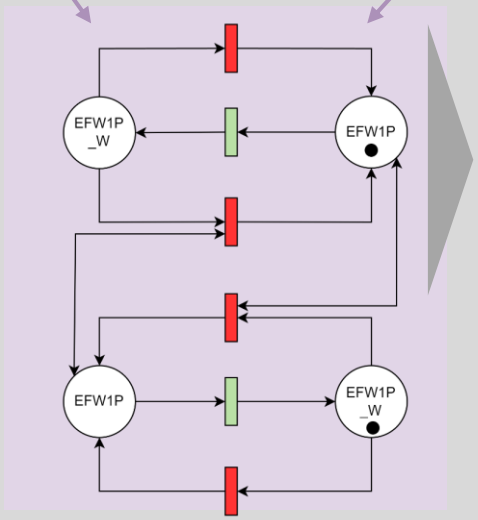






COMPONENTS

TOP EVENT PROBABILITY = 0.0040



Joint Event	Probability
$\overline{EFW1Pop}, \overline{EFW2Pop}$	$9.9 \cdot 10^{-1}$
$\overline{EFW1Pop}, EFW2Pop$	$1.80 \cdot 10^{-4}$
$EFW1Pop, \overline{EFW2Pop}$	$1.79 \cdot 10^{-4}$
$EFW1Pop, EFW2Pop$	$2.96 \cdot 10^{-8}$

D²T²

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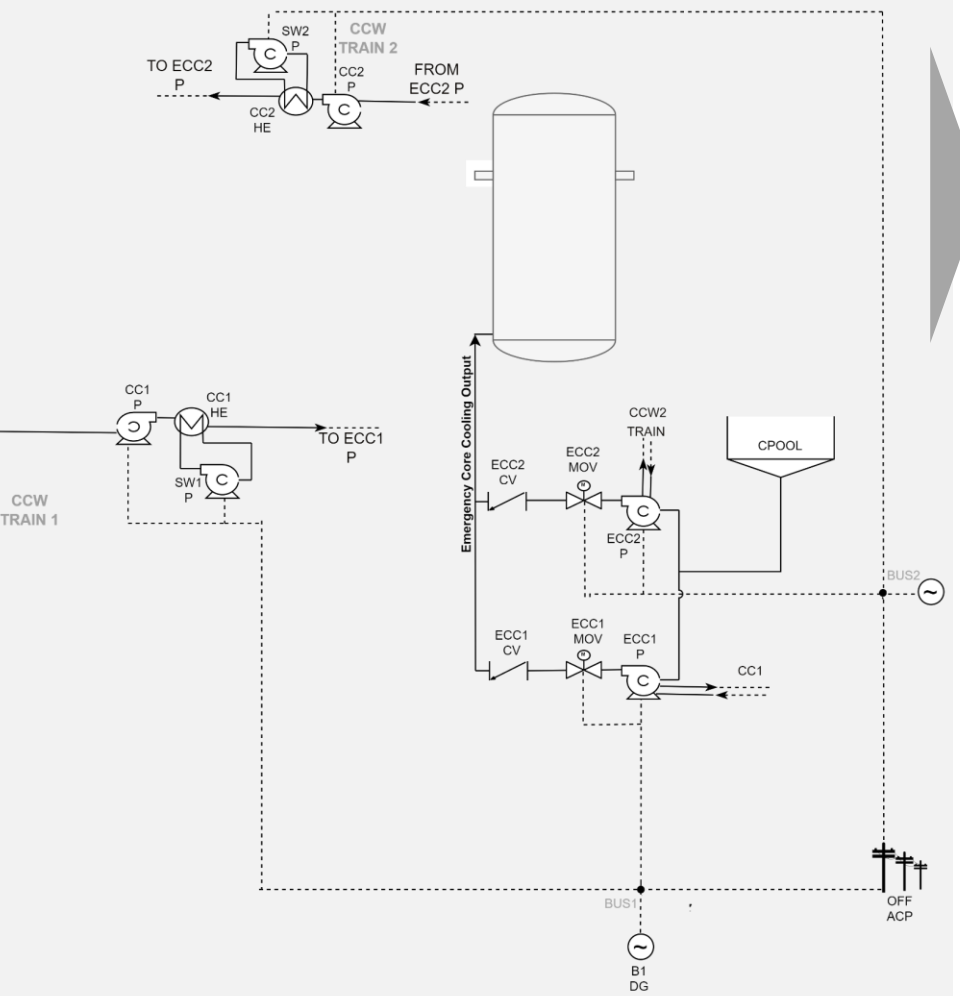
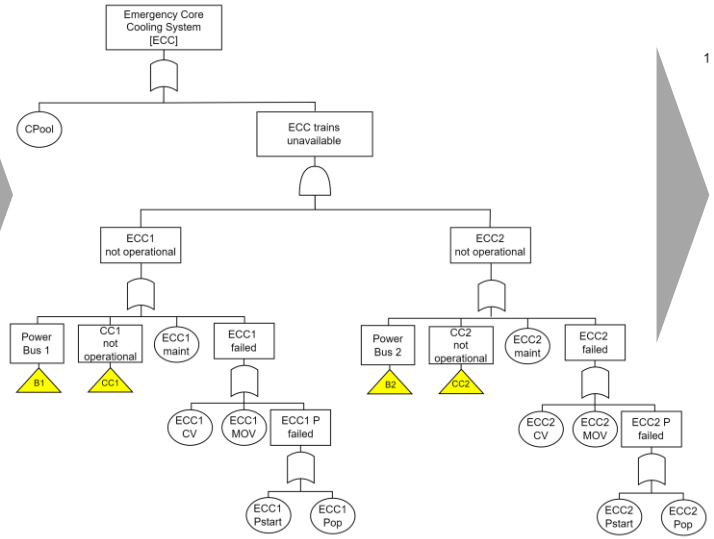
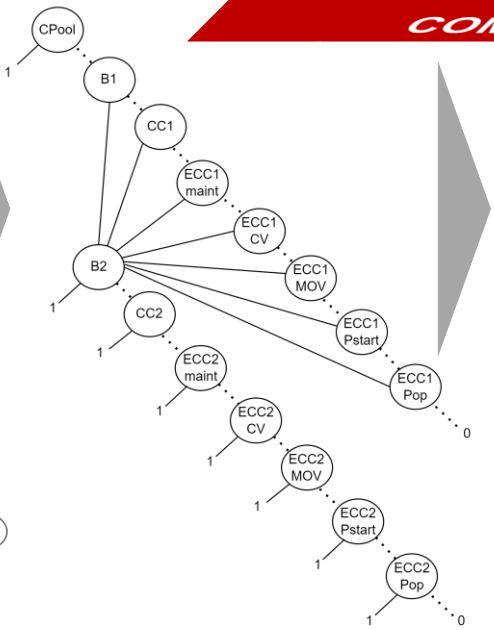
D²T²: Trains Dependency

TRAINS

COMPONENTS



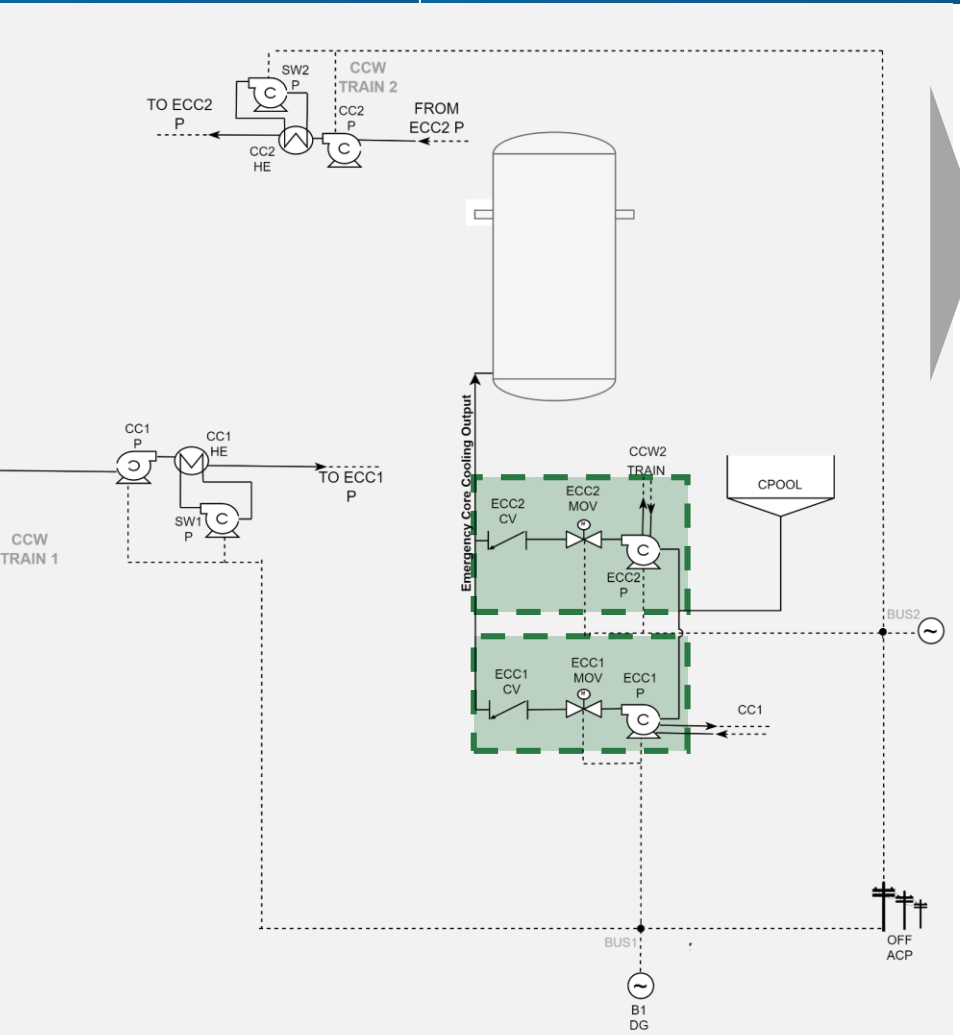


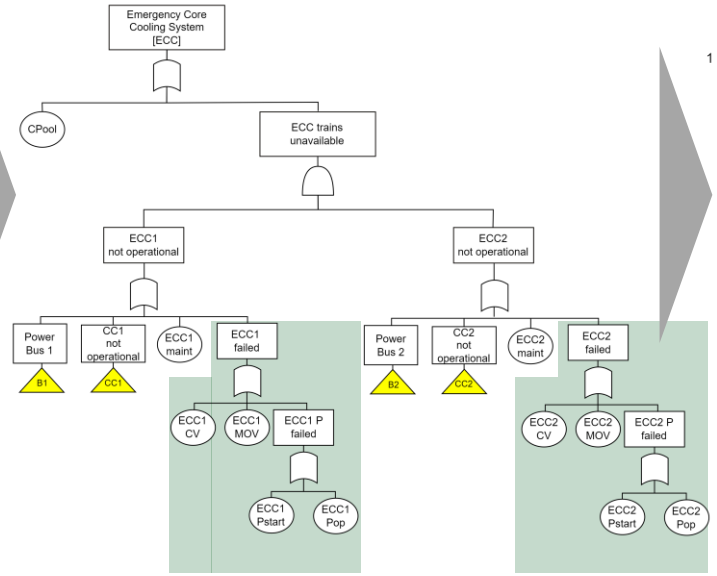


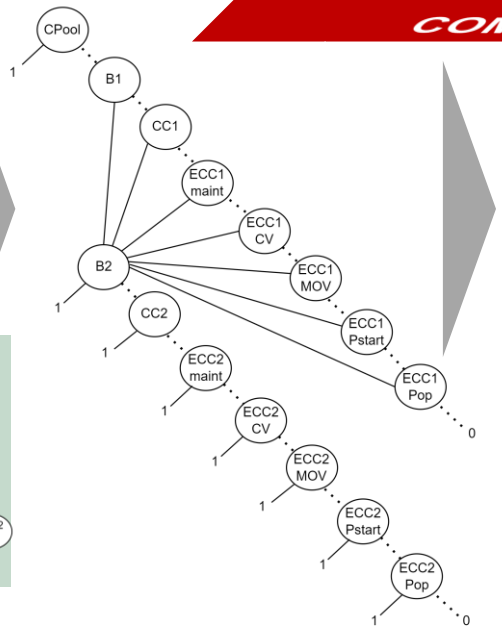
TOP EVENT PROBABILITY = 0.00541457

D²T²: Trains Dependency

TRAINS
COMPONENTS







TOP EVENT PROBABILITY = ?

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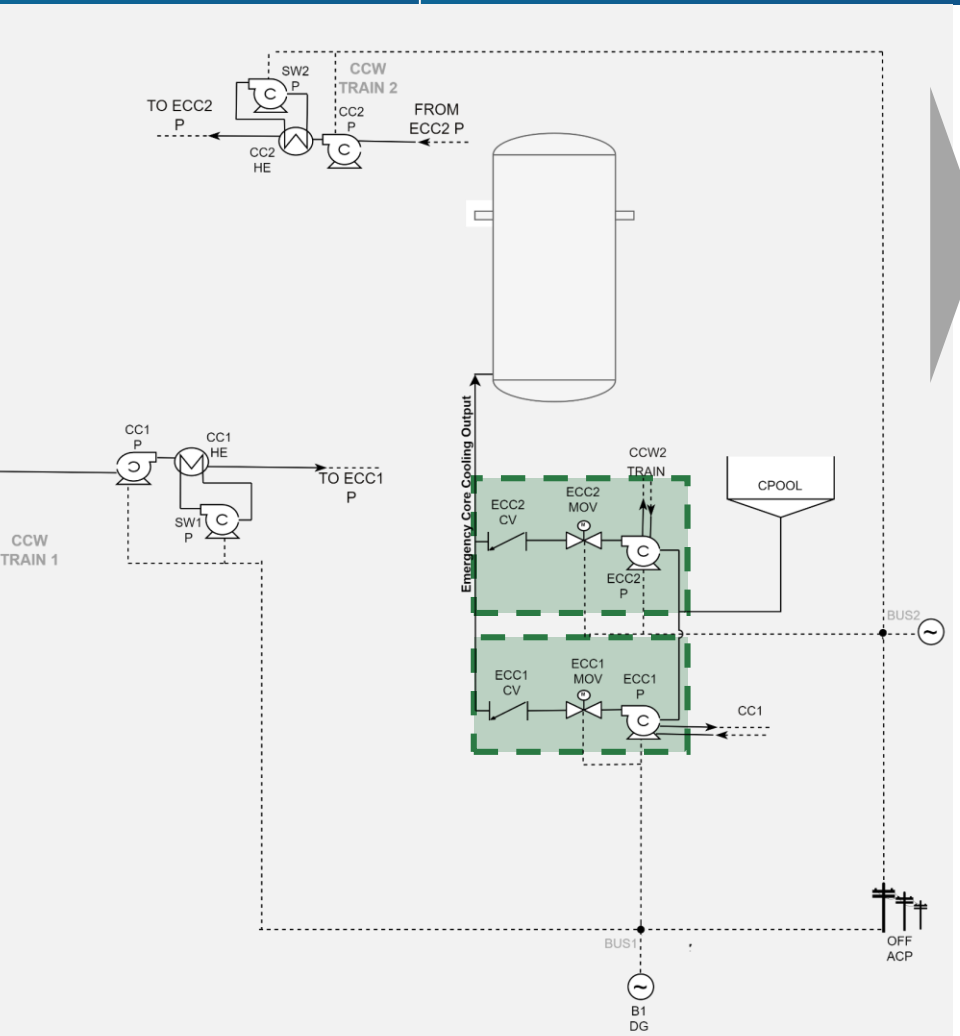
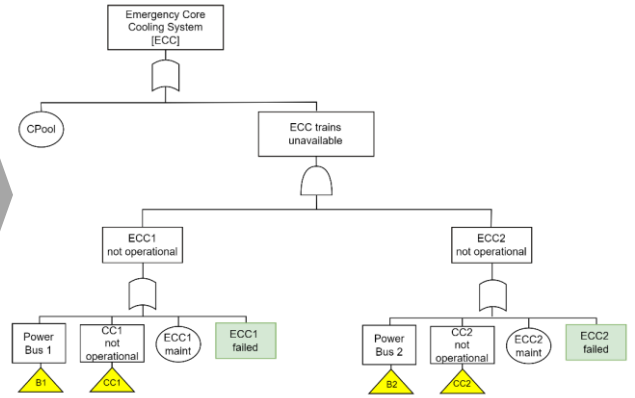
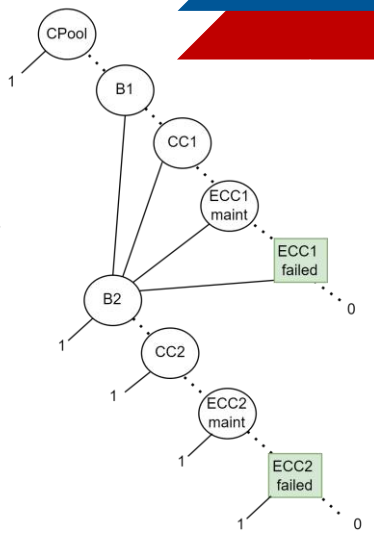
D²T²: Trains Dependency

TRAINS
COMPONENTS







TOP EVENT PROBABILITY = ?

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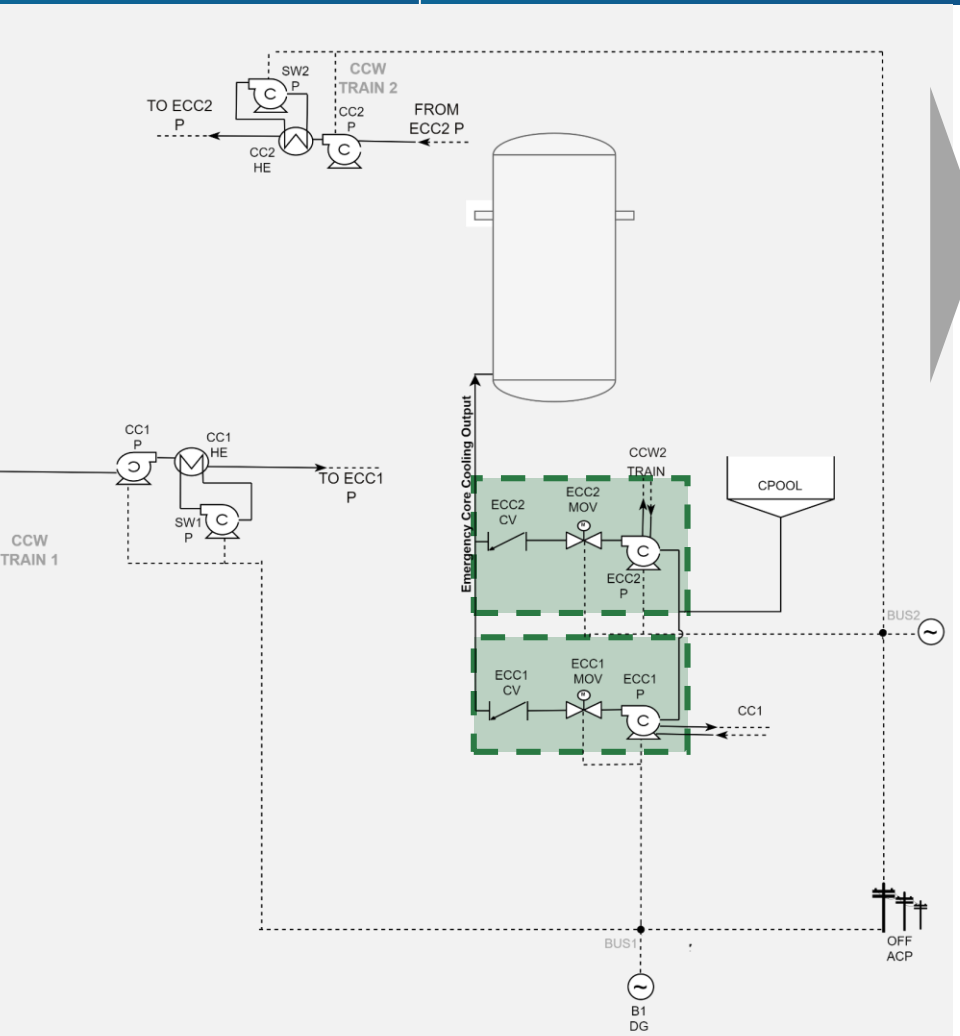
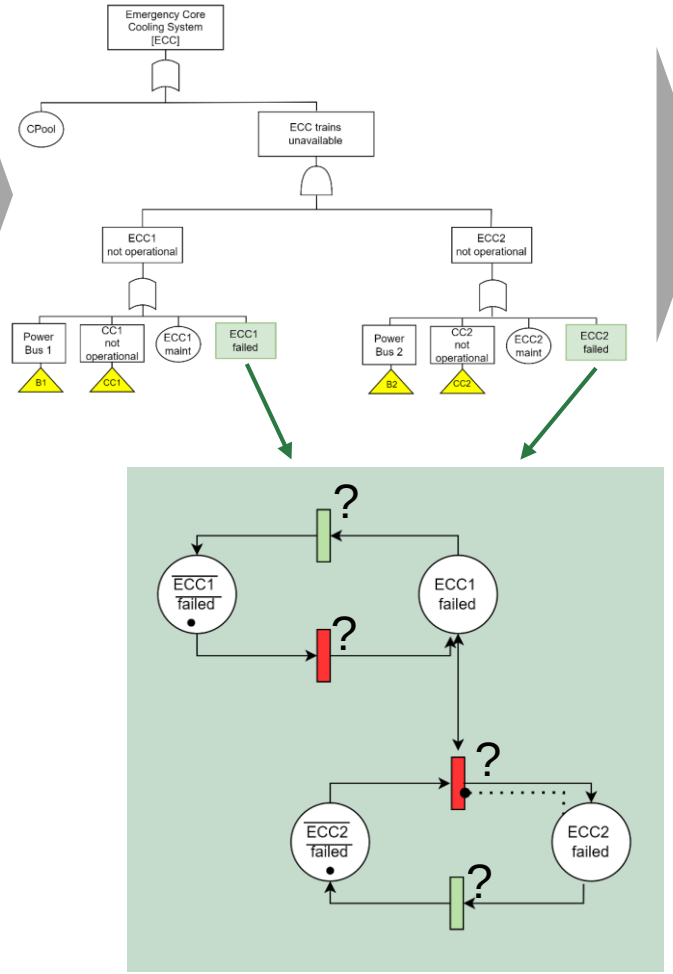
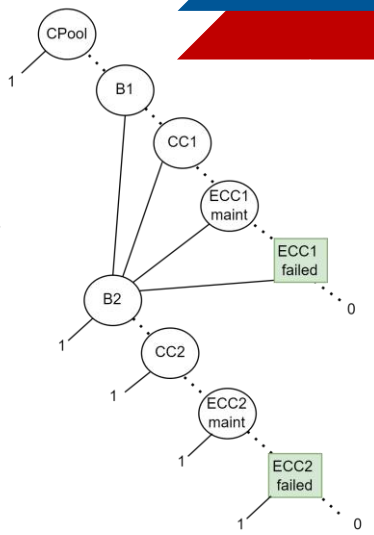
D²T²: Trains Dependency

TRAINS
COMPONENTS







TOP EVENT PROBABILITY = ?

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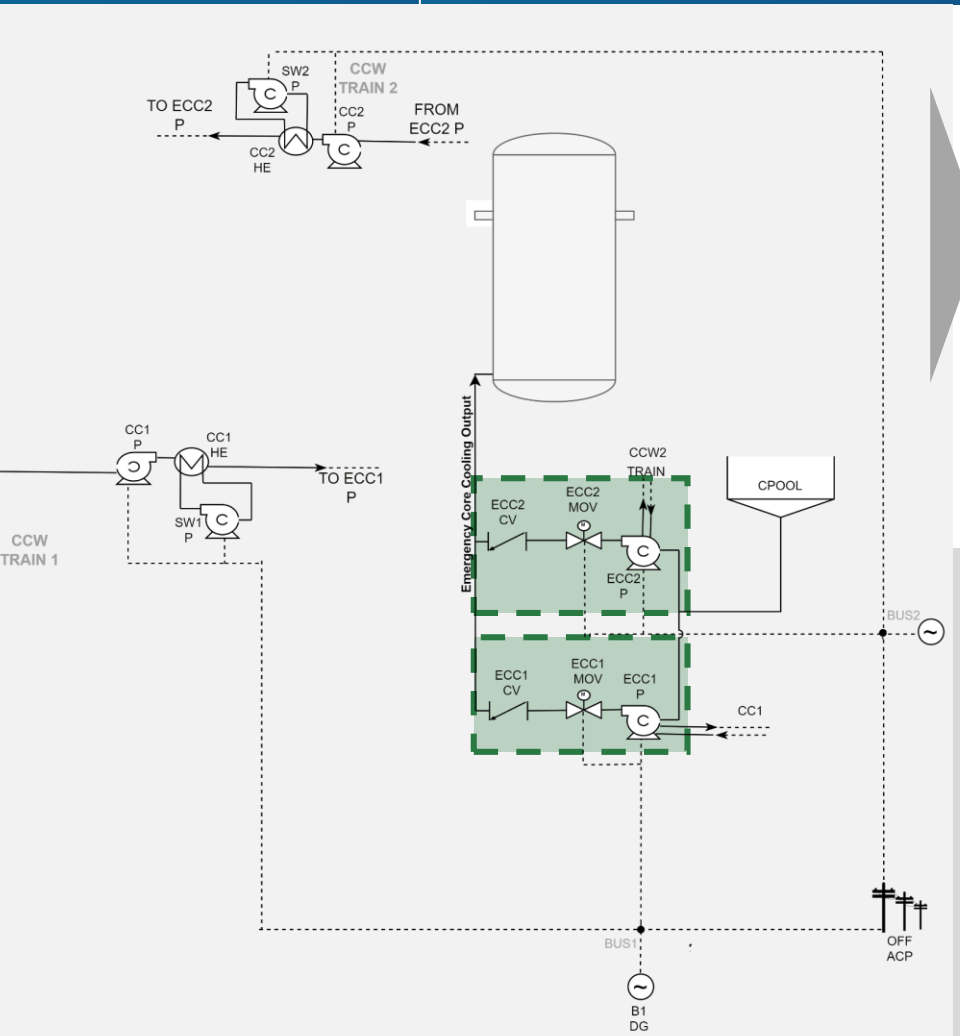
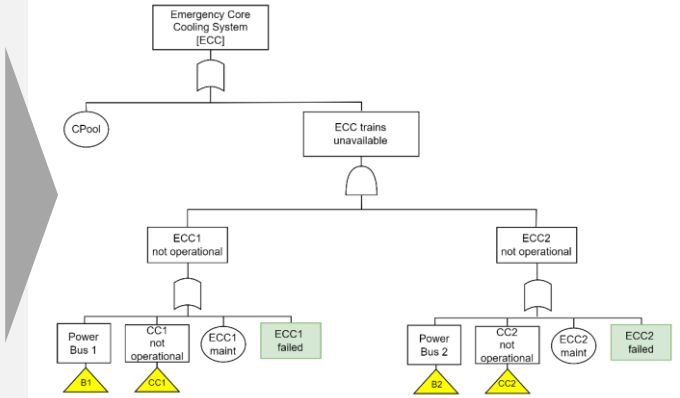
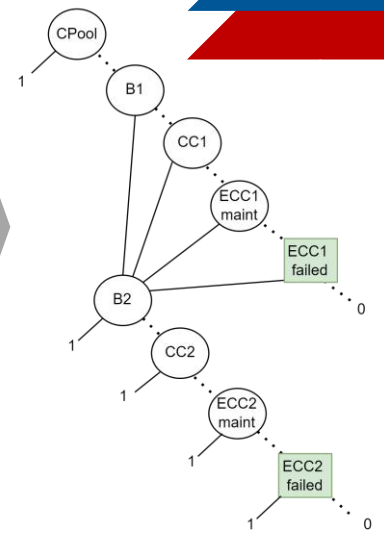
D²T²: Trains Dependency

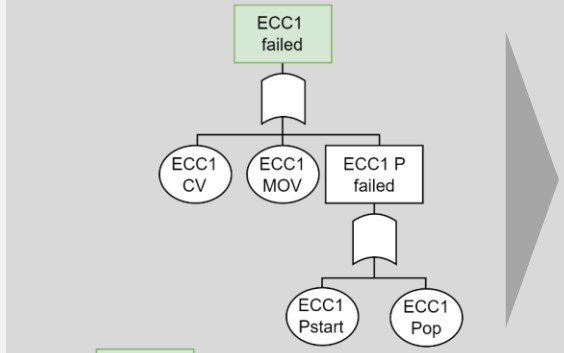
TRAINS
COMPONENTS

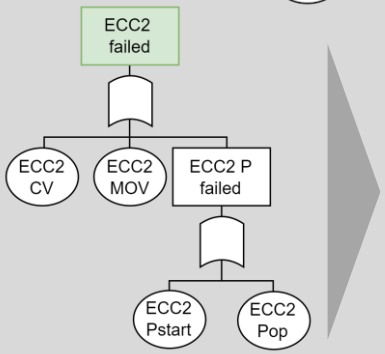


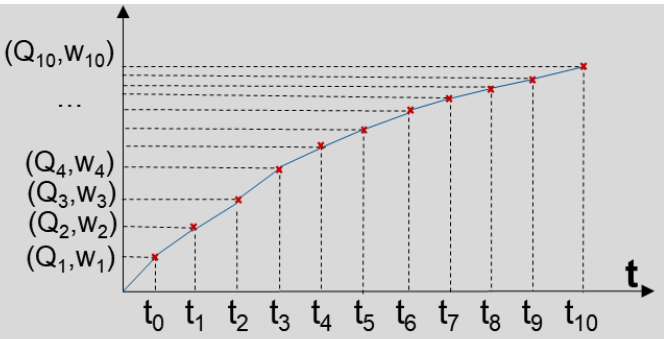


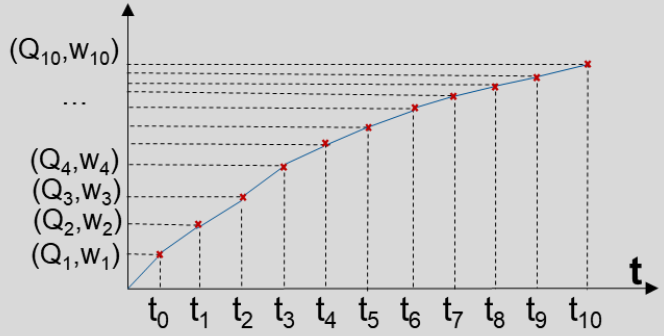


TOP EVENT PROBABILITY = ?









D²T²

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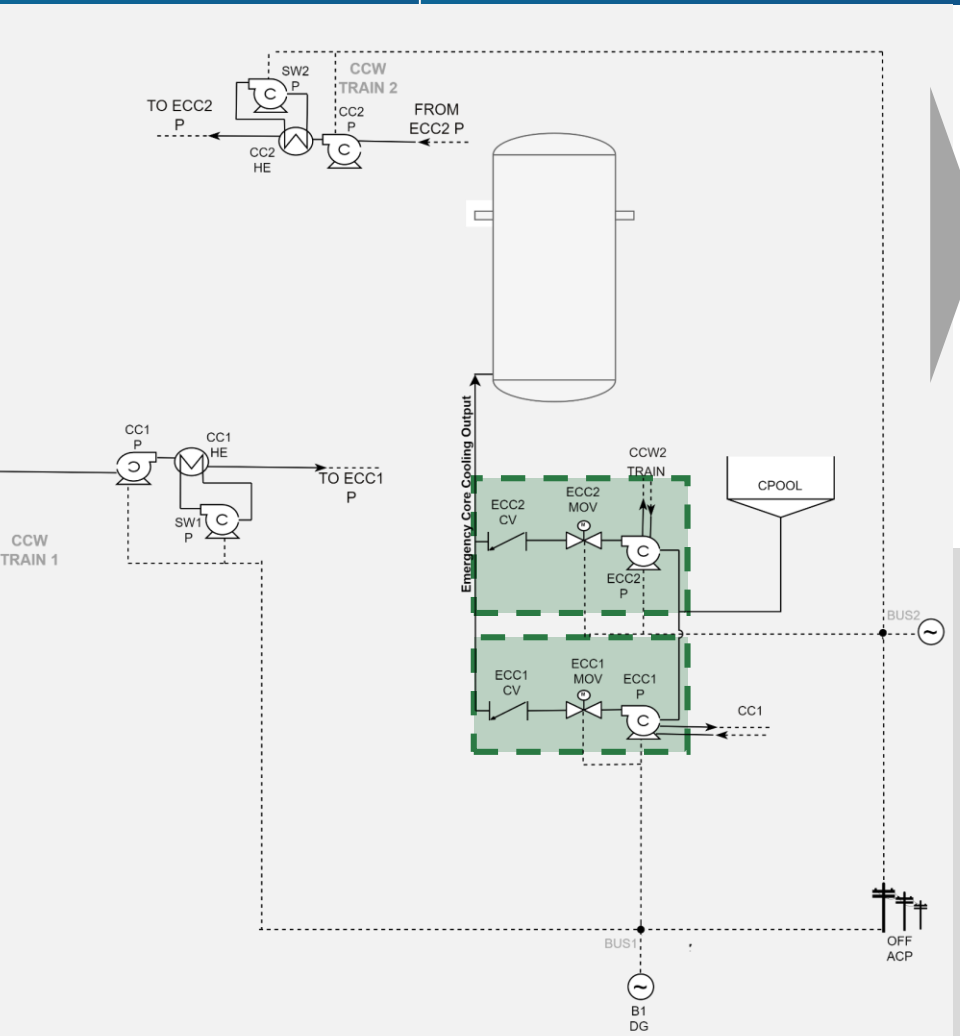
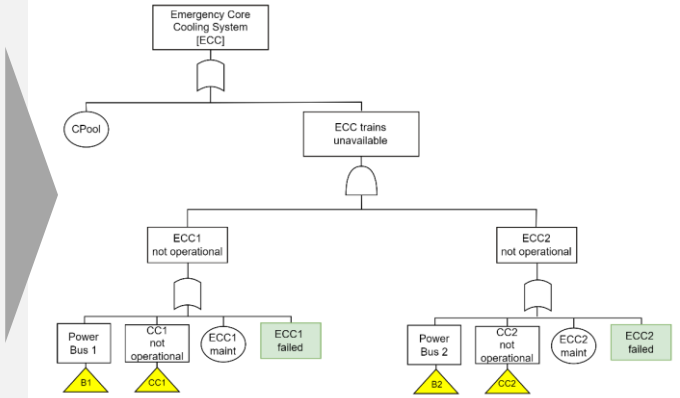
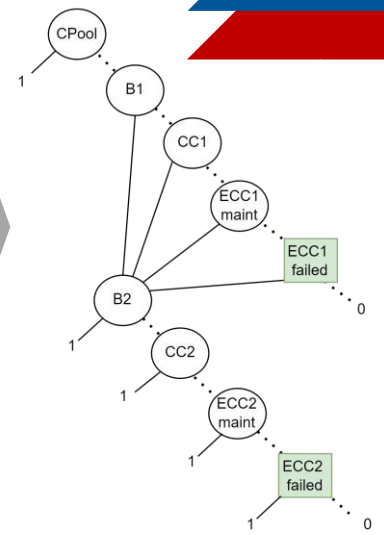
D²T²: Trains Dependency

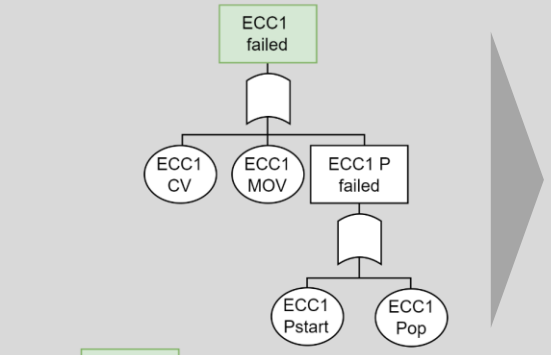
TRAINS
COMPONENTS

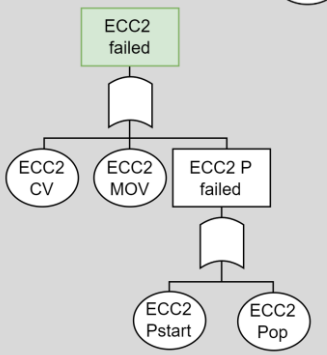






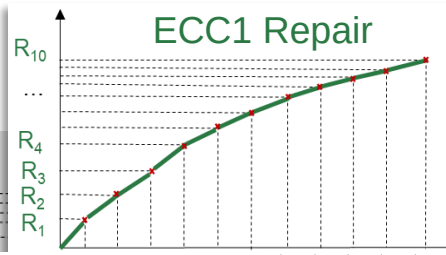
TOP EVENT PROBABILITY = ?

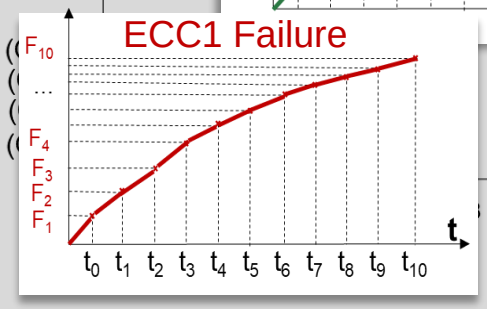


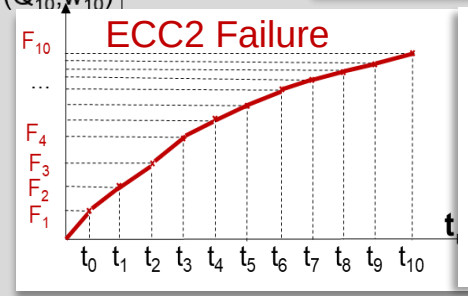


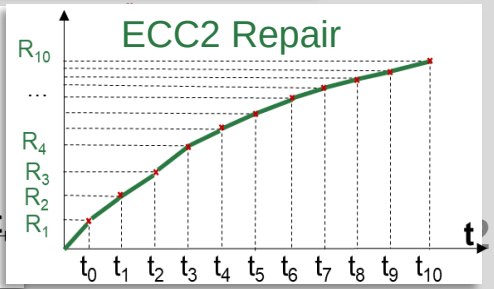
$(F_{10},R_{10}) \leftarrow (Q_{10},w_{10})$

(F_4,R_4)
(F_3,R_3)
(F_2,R_2)
(F_1,R_1)









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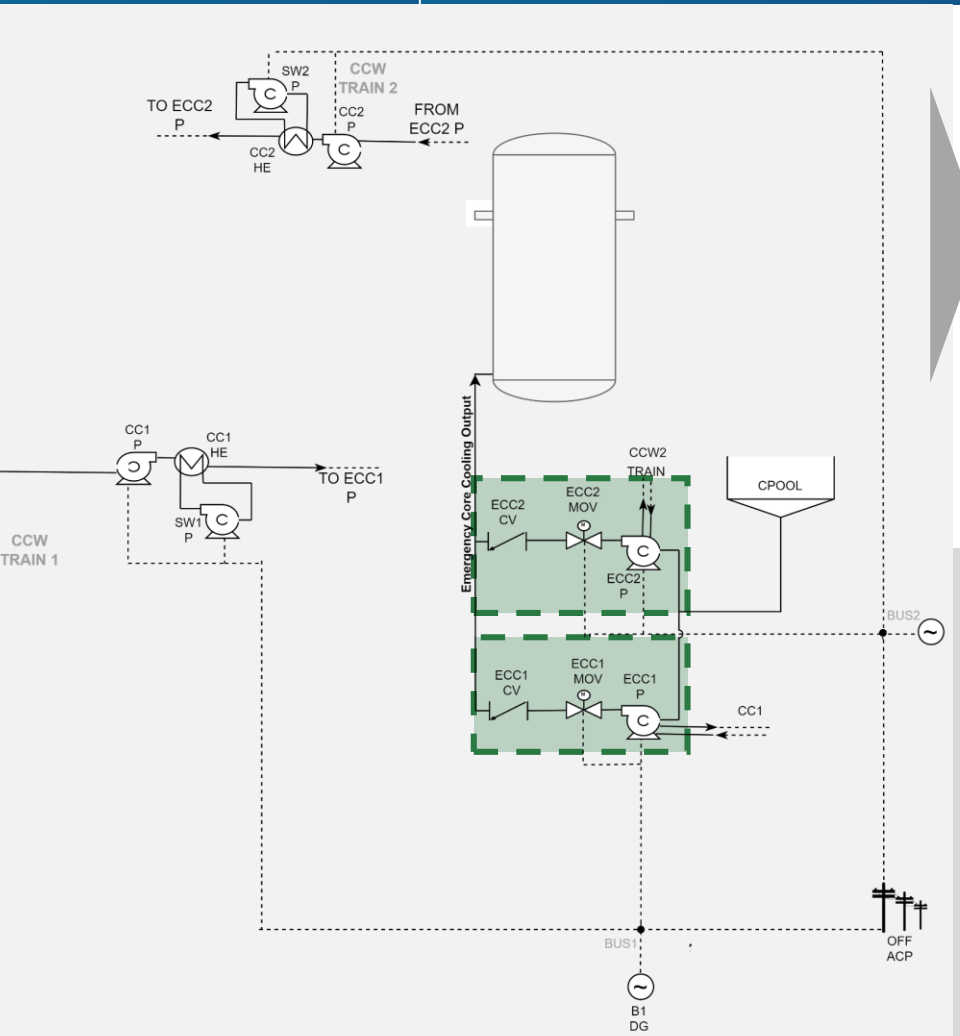
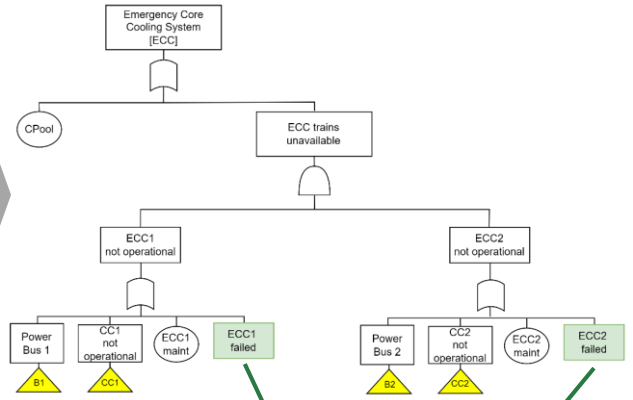
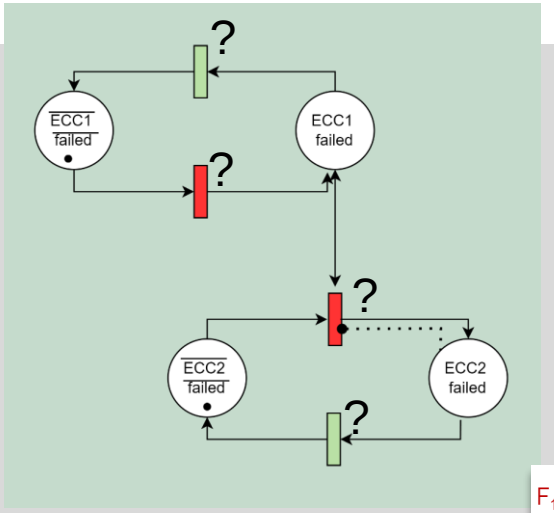
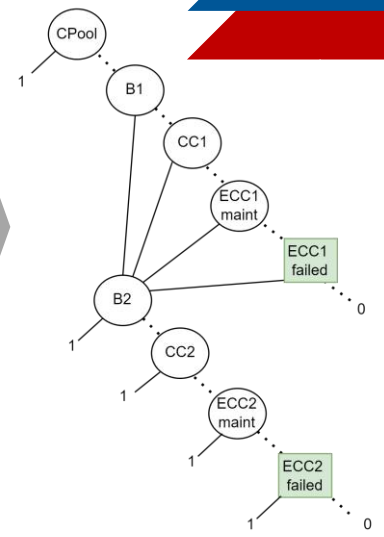
D^2T^2: Trains Dependency

TRAINS
COMPONENTS

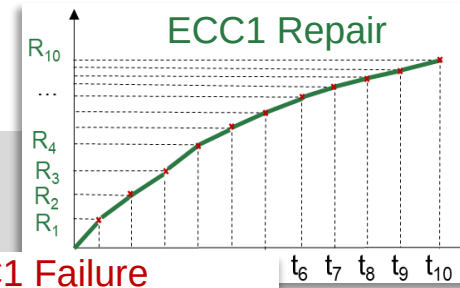


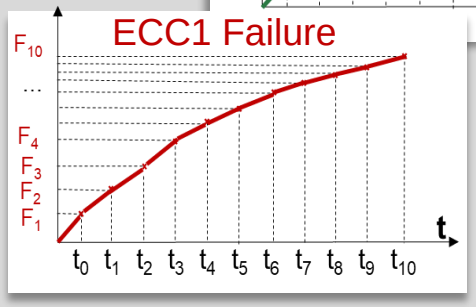


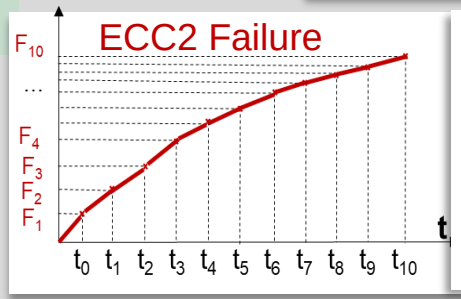


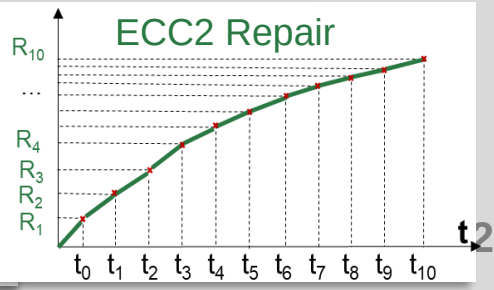


TOP EVENT PROBABILITY = ?









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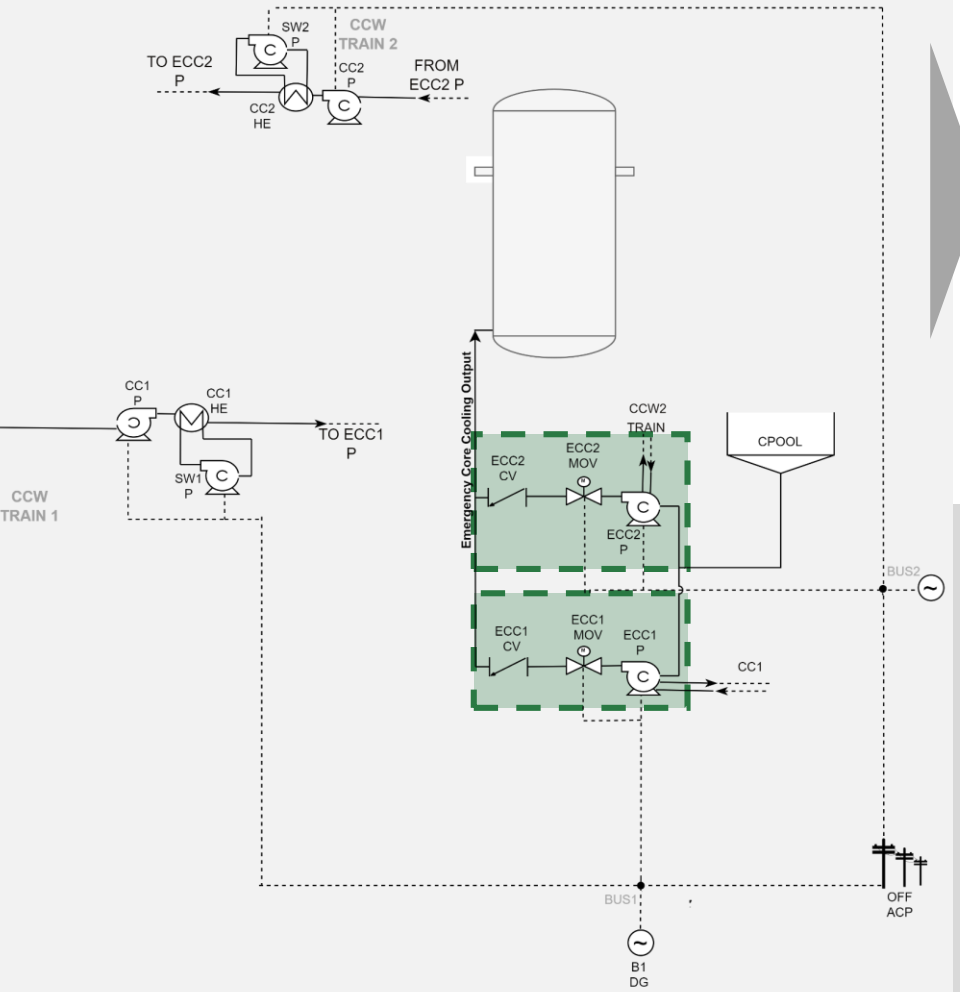
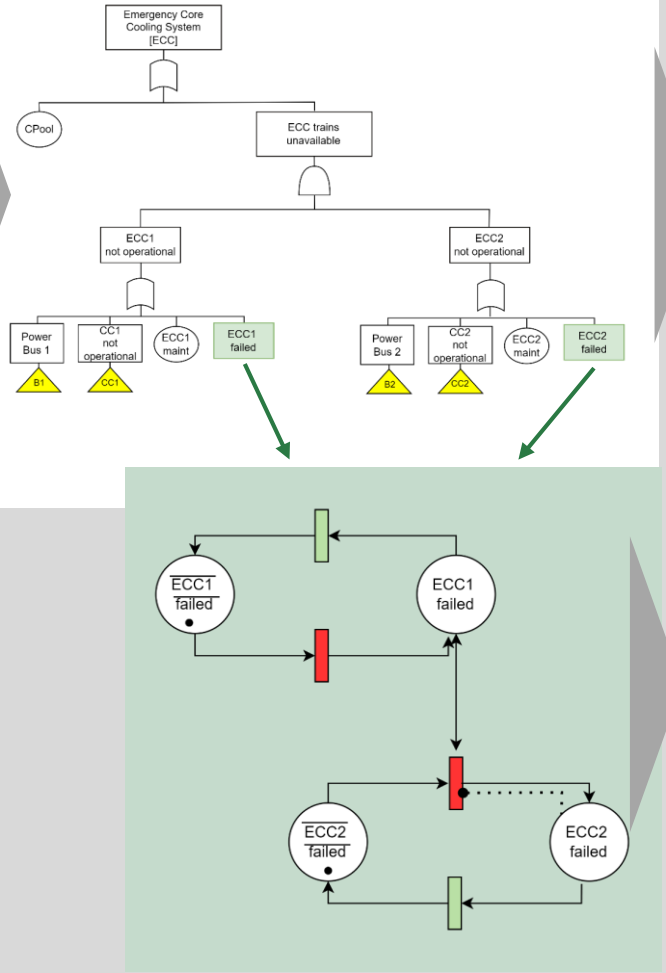
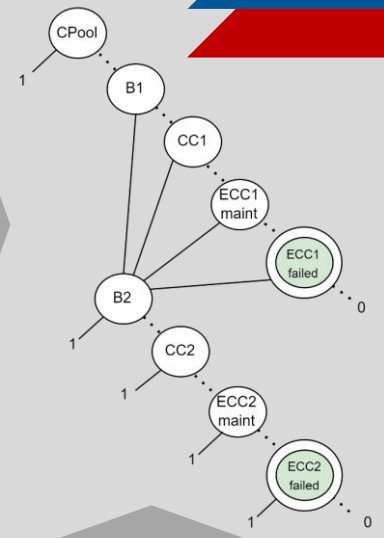
D²T²: Trains Dependency

TRAINS
COMPONENTS







TOP EVENT PROBABILITY = 0.0035

Joint Event	Probability
$\overline{ECC1fail}, \overline{ECC2fail}$	$9.996 \cdot 10^{-1}$
$\overline{ECC1fail}, ECC2fail$	$1.26 \cdot 10^{-5}$
$ECC1fail, \overline{ECC2fail}$	$5.20 \cdot 10^{-2}$
$ECC1fail, ECC2fail$	$1.39 \cdot 10^{-5}$

D²T²

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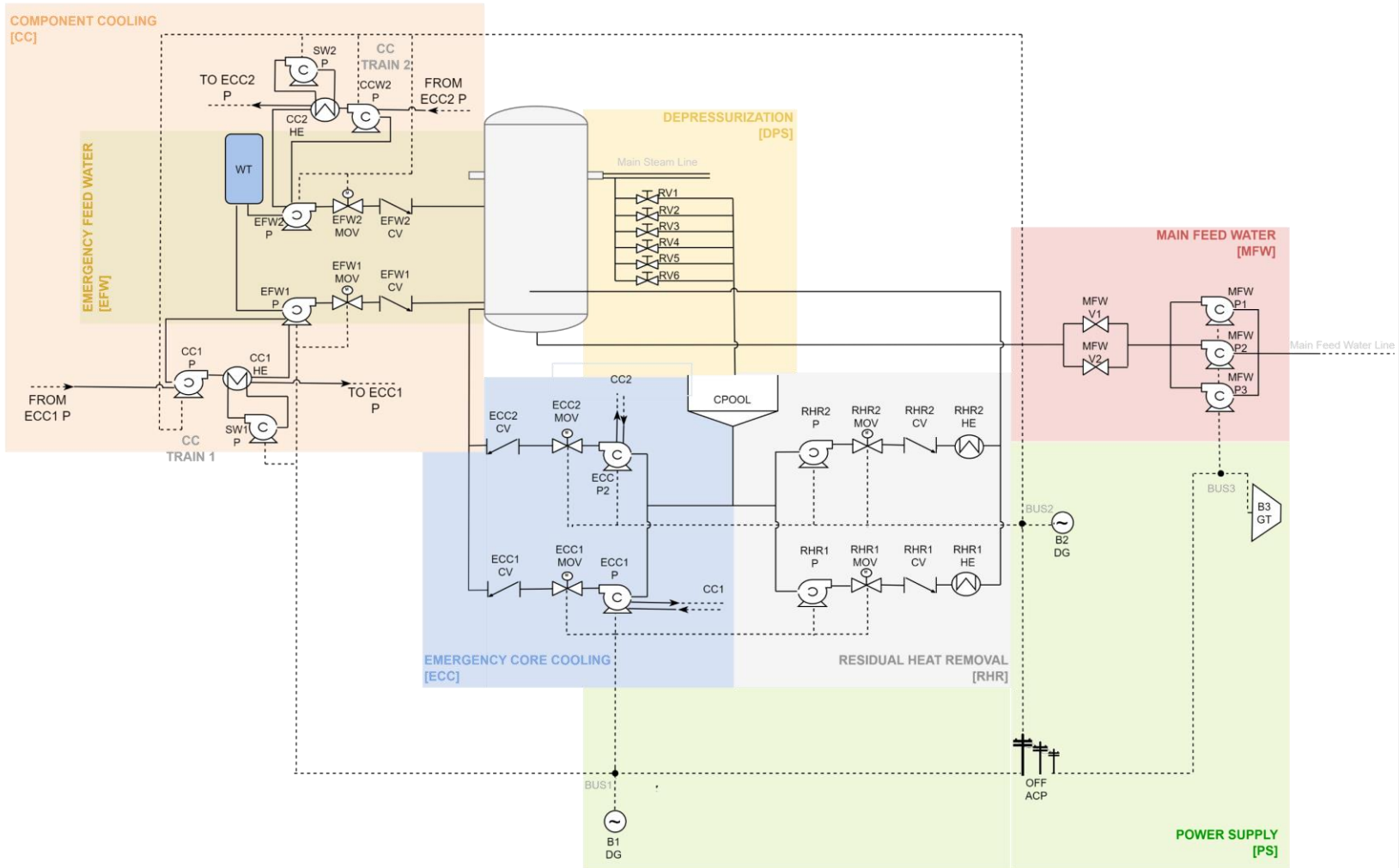
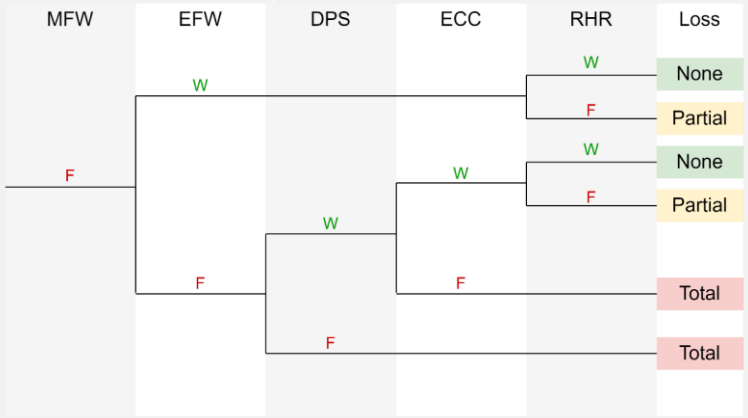
D²T²: Subsystems Dependency

SUBSYSTEMS
TRAINS
COMPONENTS





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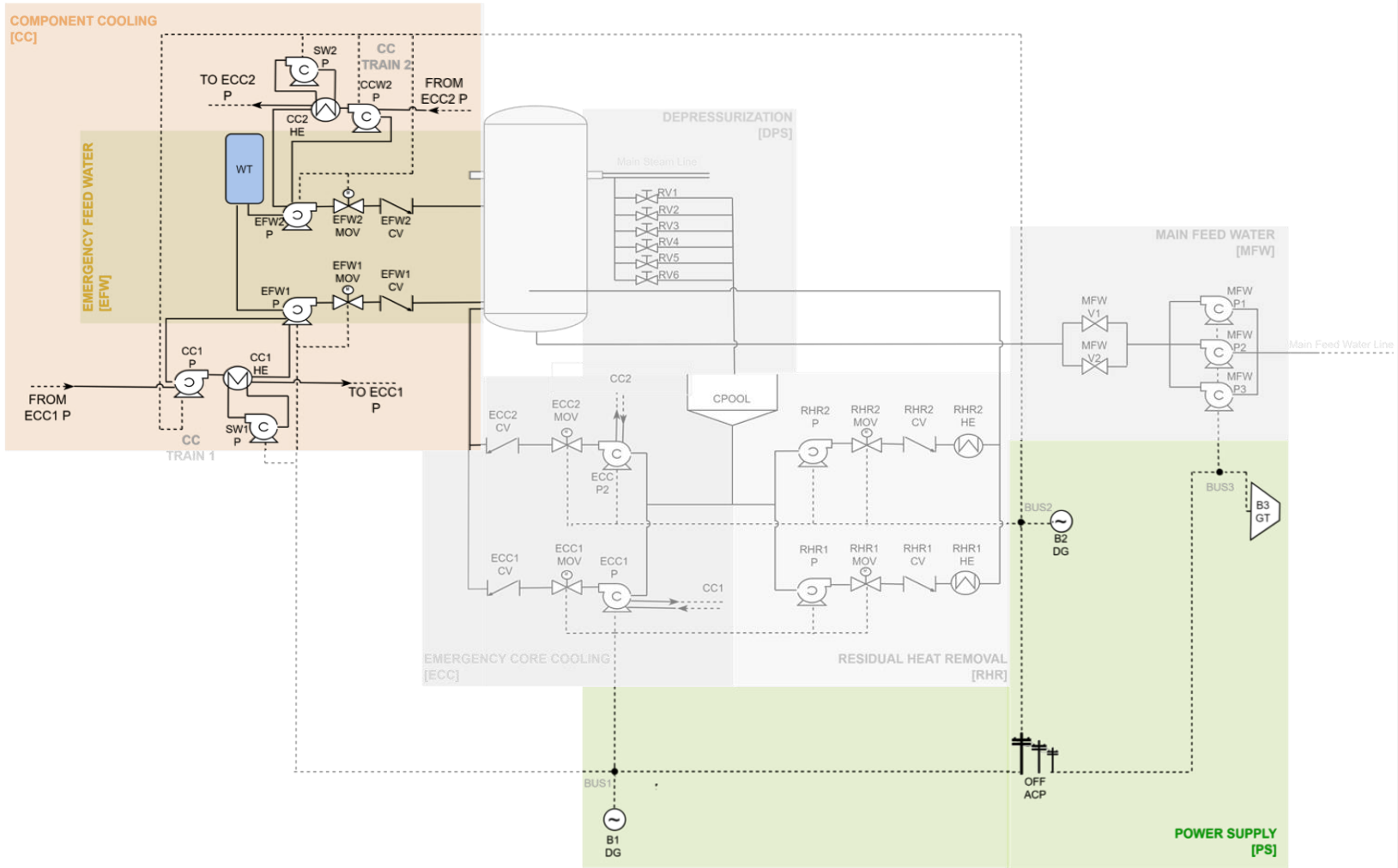
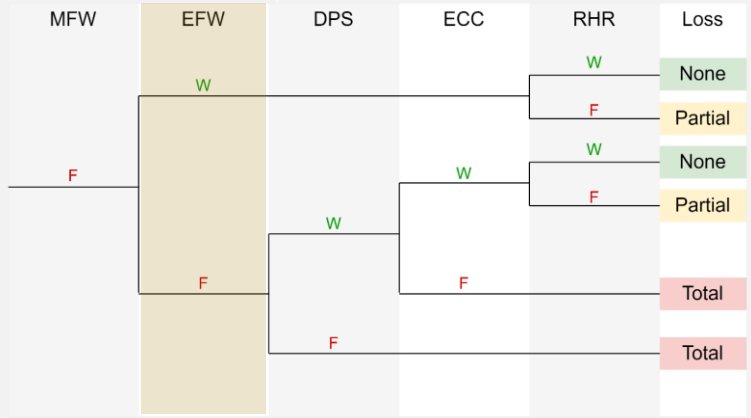
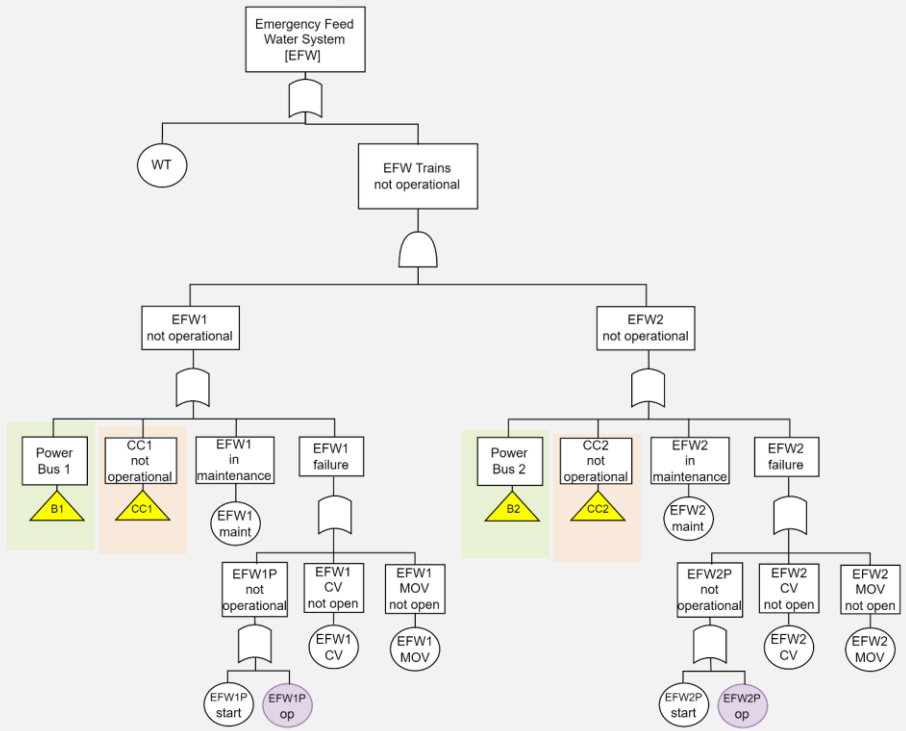
D²T²: Subsystems Dependency

SUBSYSTEMS
TRAINS
COMPONENTS







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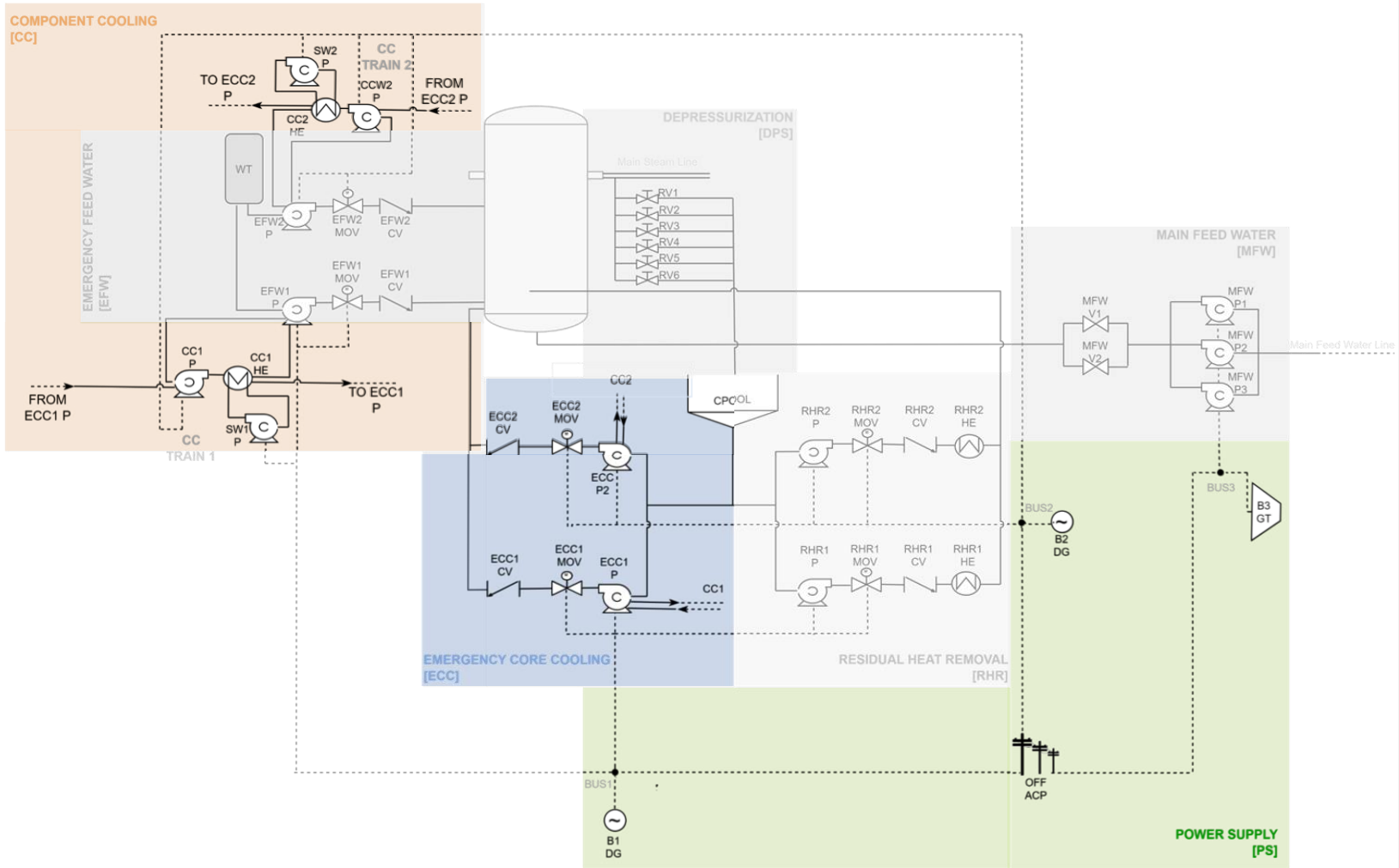
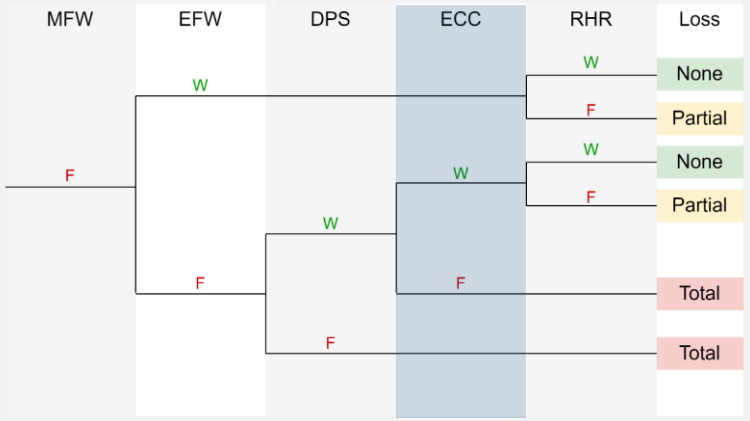
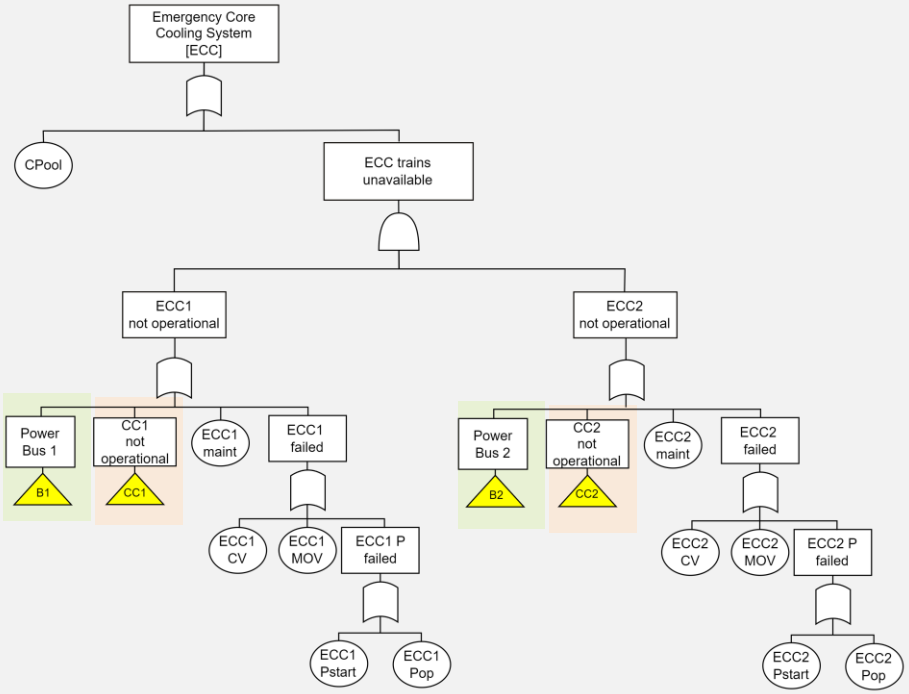
D^2T^2: Subsystems Dependency

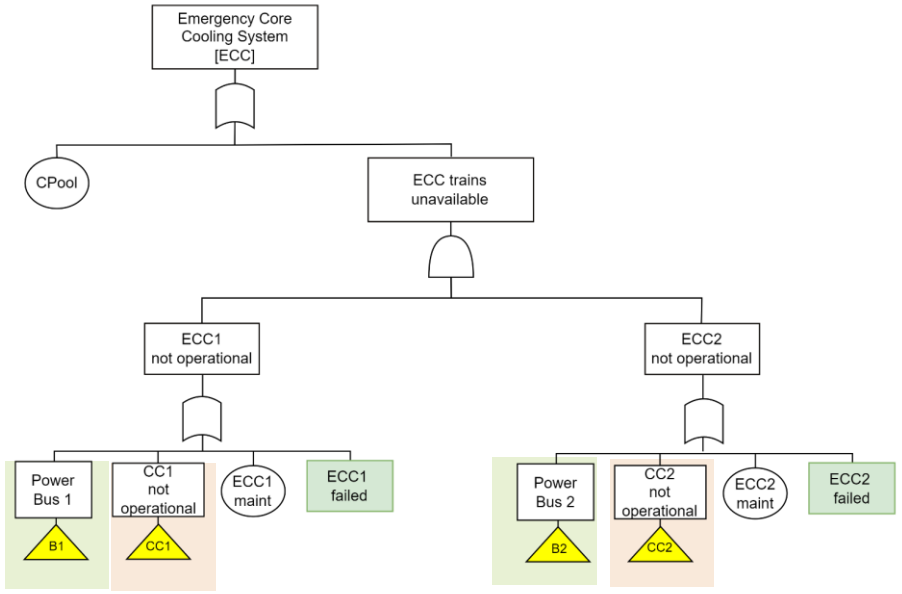
SUBSYSTEMS
TRAINS
COMPONENTS

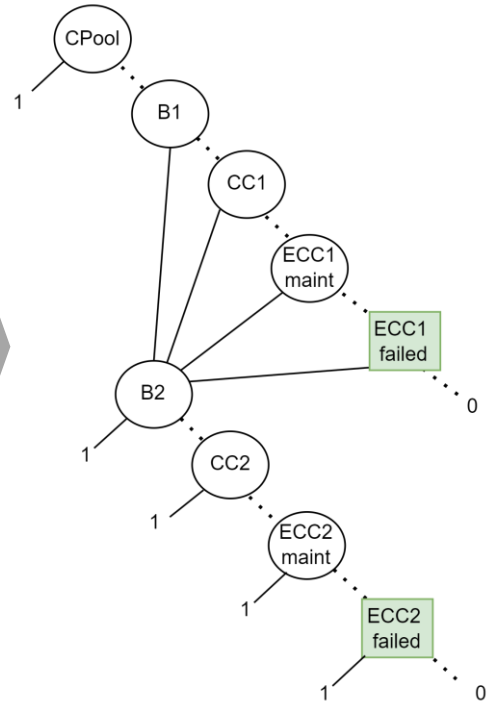






D²T²: Subsystems Dependency

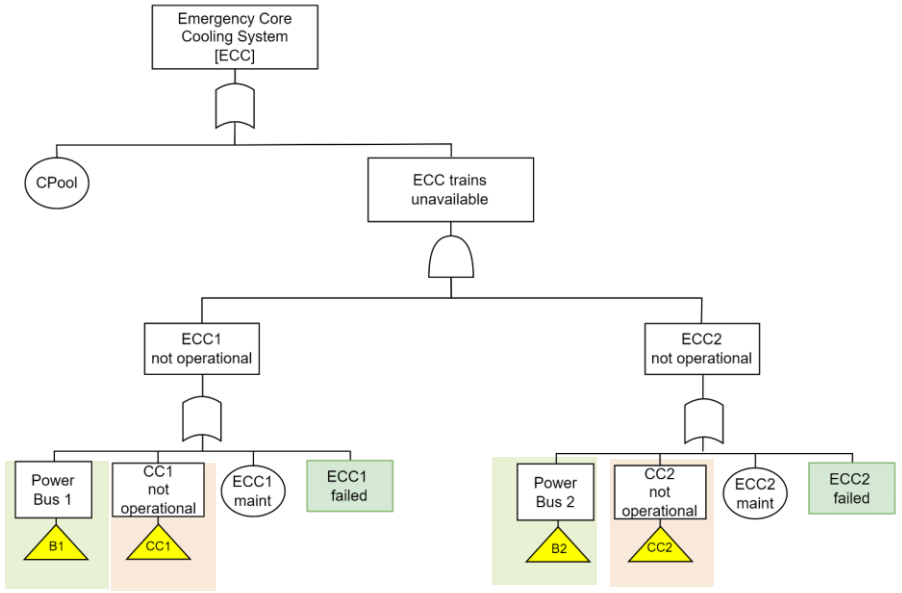


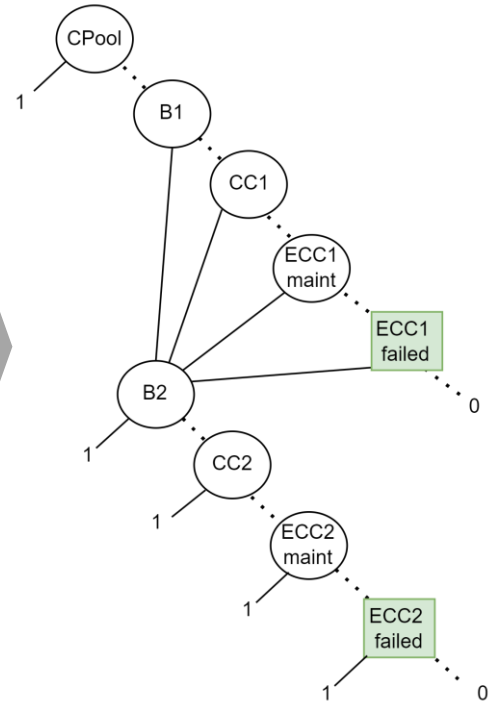


$$P_{top} = \sum_{i}^{n} path_i = 0.0035$$

$$\overrightarrow{P_{top}} = \{p_{ss0}, p_{ss1}, \ldots, p_{ssn}\}$$

D²T²: Subsystems Dependency





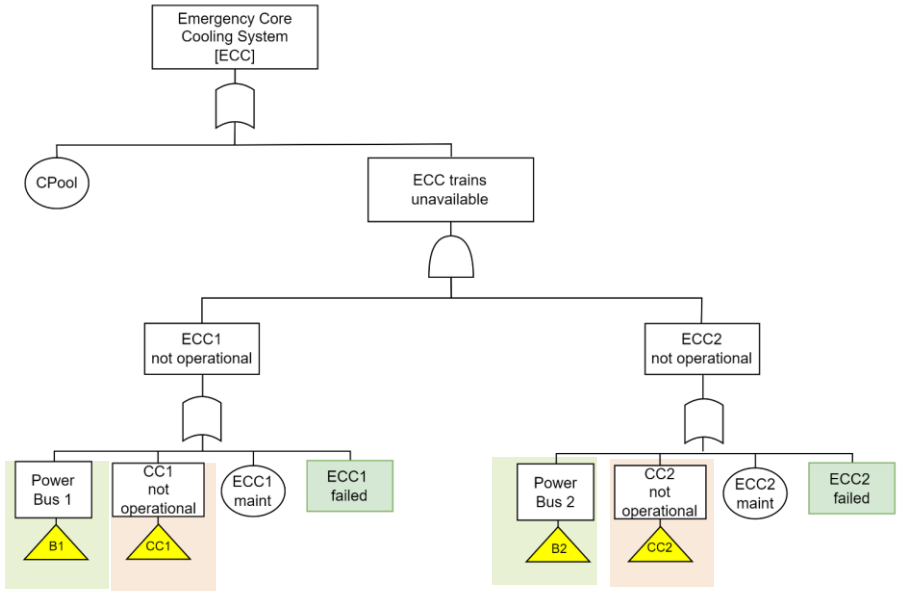
SUBSYSTEMS
TRAINS
COMPONENTS

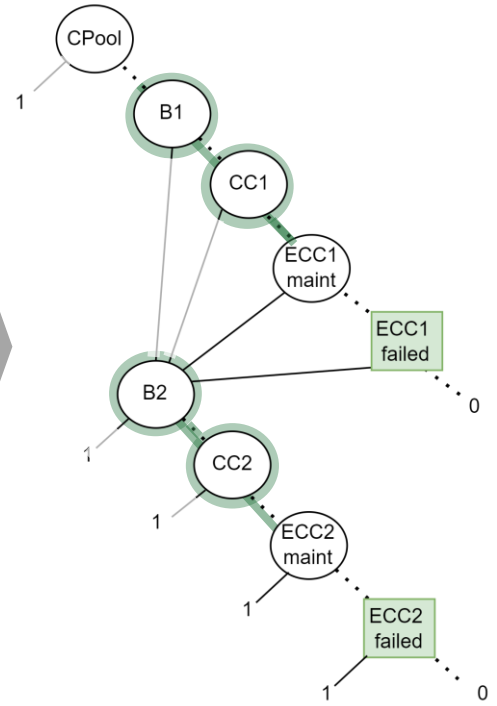
$B1, CC1, B2, CC2$
$B1, CC1, B2, \overline{CC2}$
$B1, CC1, \overline{B2}, CC2$
$B1, CC1, \overline{B2}, \overline{CC2}$
$B1, \overline{CC1}, B2, CC2$
$B1, \overline{CC1}, B2, \overline{CC2}$
$B1, \overline{CC1}, \overline{B2}, CC2$
$B1, \overline{CC1}, \overline{B2}, \overline{CC2}$
$\overline{B1}, CC1, B2, CC2$
$\overline{B1}, CC1, B2, \overline{CC2}$
$\overline{B1}, CC1, \overline{B2}, CC2$
$\overline{B1}, CC1, \overline{B2}, \overline{CC2}$
$\overline{B1}, \overline{CC1}, B2, CC2$
$\overline{B1}, \overline{CC1}, B2, \overline{CC2}$
$\overline{B1}, \overline{CC1}, \overline{B2}, CC2$
$\overline{B1}, \overline{CC1}, \overline{B2}, \overline{CC2}$

$\overrightarrow{P_{top}}$

D²T²: Subsystems Dependency

SUBSYSTEMS
TRAINS
COMPONENTS



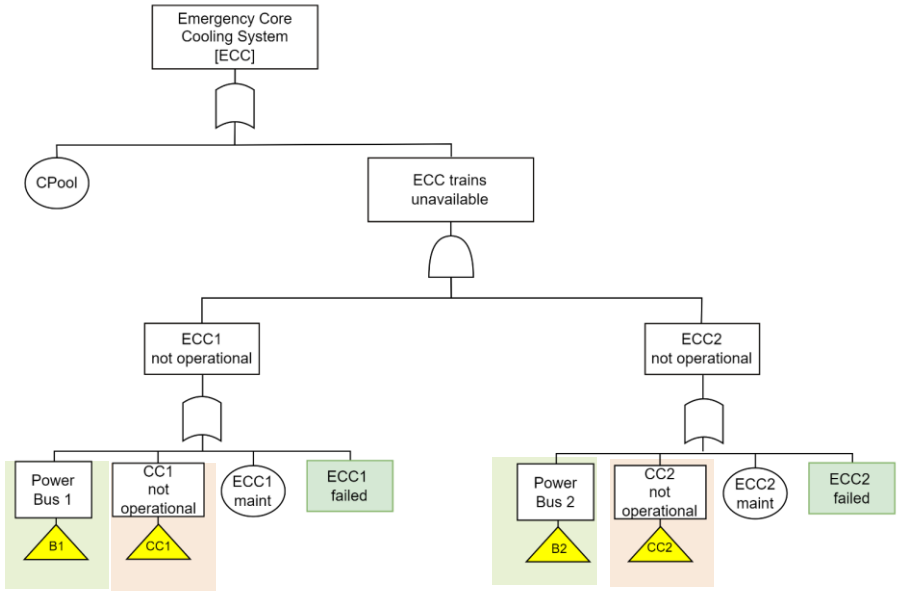


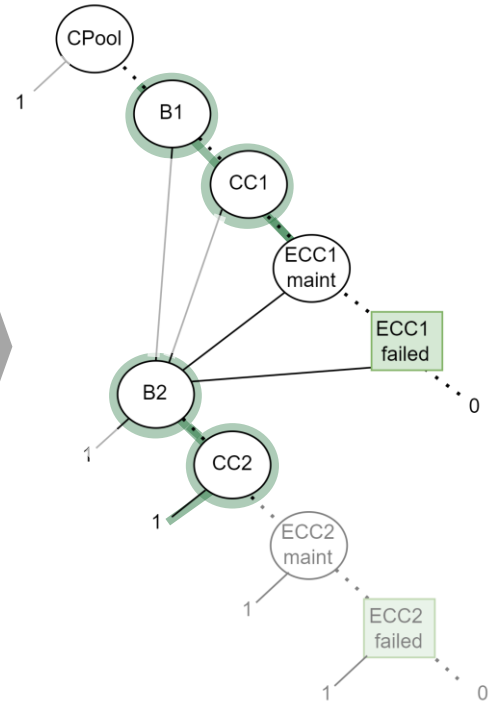
$B1, CC1, B2, CC2$	
$B1, CC1, B2, \overline{CC2}$	
$B1, CC1, \overline{B2}, CC2$	
$B1, CC1, \overline{B2}, \overline{CC2}$	
$B1, \overline{CC1}, B2, CC2$	
$B1, \overline{CC1}, B2, \overline{CC2}$	
$B1, \overline{CC1}, \overline{B2}, CC2$	
$B1, \overline{CC1}, \overline{B2}, \overline{CC2}$	
$\overline{B1}, CC1, B2, CC2$	
$\overline{B1}, CC1, B2, \overline{CC2}$	
$\overline{B1}, CC1, \overline{B2}, CC2$	
$\overline{B1}, CC1, \overline{B2}, \overline{CC2}$	
$\overline{B1}, \overline{CC1}, B2, CC2$	
$\overline{B1}, \overline{CC1}, B2, \overline{CC2}$	
$\overline{B1}, \overline{CC1}, \overline{B2}, CC2$	
$\overline{B1}, \overline{CC1}, \overline{B2}, \overline{CC2}$	$5.62 \cdot 10^{-04}$

$\overrightarrow{P_{top}}$

D²T²: Subsystems Dependency

SUBSYSTEMS
TRAINS
COMPONENTS





$B1, CC1, B2, CC2$	
$B1, CC1, B2, \overline{CC2}$	
$B1, CC1, \overline{B2}, CC2$	
$B1, CC1, \overline{B2}, \overline{CC2}$	
$B1, \overline{CC1}, B2, CC2$	
$B1, \overline{CC1}, B2, \overline{CC2}$	
$B1, \overline{CC1}, \overline{B2}, CC2$	
$B1, \overline{CC1}, \overline{B2}, \overline{CC2}$	
$\overline{B1}, CC1, B2, CC2$	
$\overline{B1}, CC1, B2, \overline{CC2}$	
$\overline{B1}, CC1, \overline{B2}, CC2$	
$\overline{B1}, CC1, \overline{B2}, \overline{CC2}$	
$\overline{B1}, \overline{CC1}, B2, CC2$	
$\overline{B1}, \overline{CC1}, B2, \overline{CC2}$	
$\overline{B1}, \overline{CC1}, \overline{B2}, CC2$	$3.30 \cdot 10^{-02}$
$B1, CC1, B2, CC2$	$5.62 \cdot 10^{-04}$

$\overrightarrow{P_{top}}$

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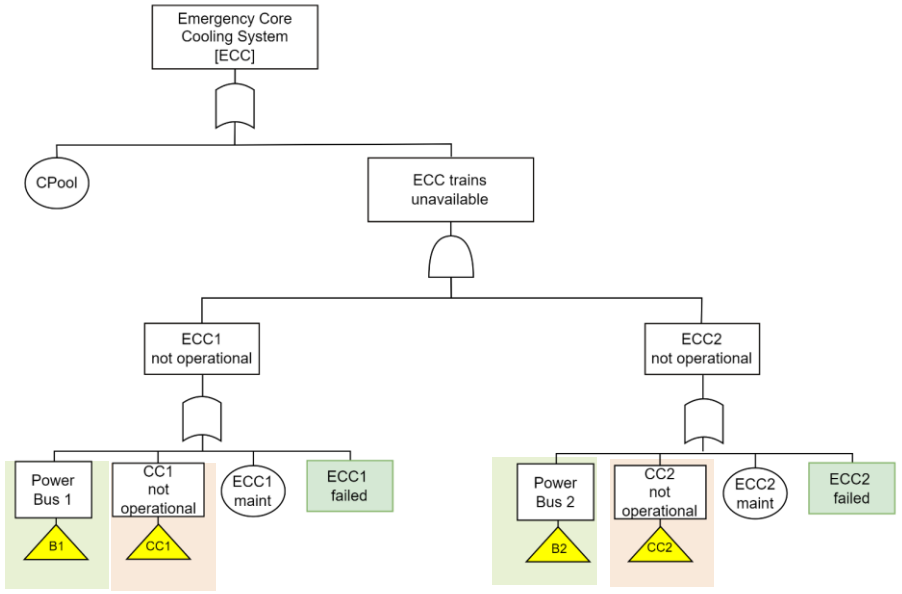
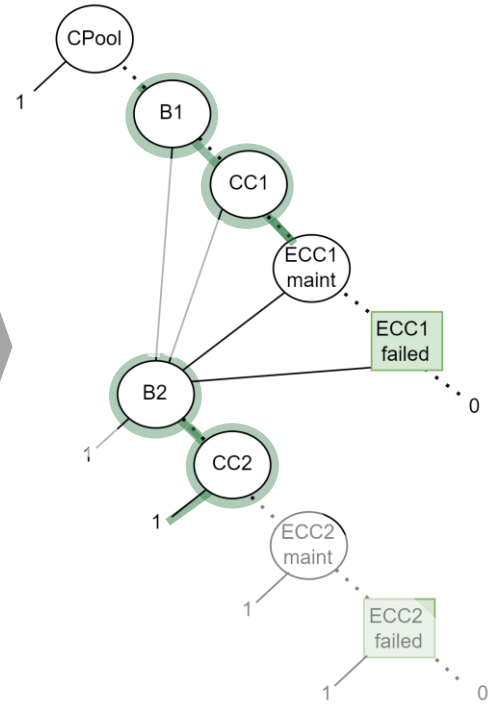
D²T²: Subsystems Dependency

SUBSYSTEMS
TRAINS
COMPONENTS

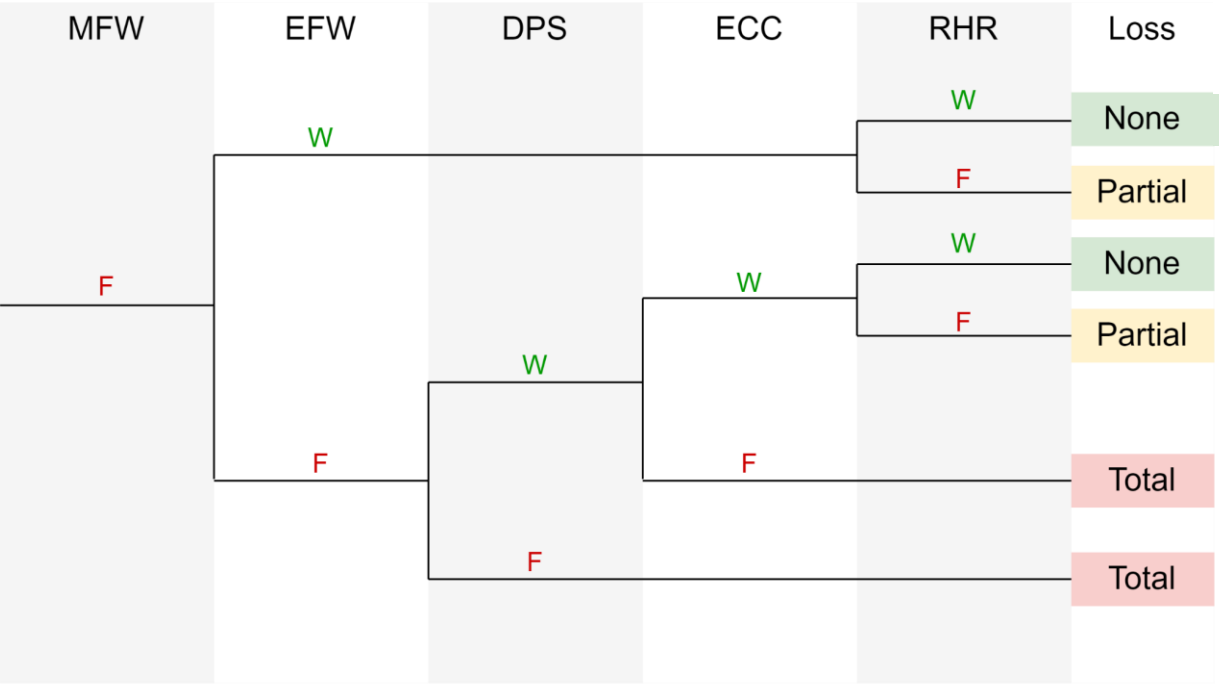




$B1, CC1, B2, CC2$		1
$B1, CC1, B2, \overline{CC2}$		0
$B1, CC1, \overline{B2}, CC2$		1
$B1, CC1, \overline{B2}, \overline{CC2}$	3.30	$\cdot 10^{-02}$
$B1, \overline{CC1}, B2, CC2$		0
$B1, \overline{CC1}, B2, \overline{CC2}$		0
$B1, \overline{CC1}, \overline{B2}, CC2$		0
$B1, \overline{CC1}, \overline{B2}, \overline{CC2}$		0
$\overline{B1}, CC1, B2, CC2$		1
$\overline{B1}, CC1, B2, \overline{CC2}$		0
$\overline{B1}, CC1, \overline{B2}, CC2$		1
$\overline{B1}, CC1, \overline{B2}, \overline{CC2}$	3.30	$\cdot 10^{-02}$
$\overline{B1}, \overline{CC1}, B2, CC2$	3.30	$\cdot 10^{-02}$
$\overline{B1}, \overline{CC1}, B2, \overline{CC2}$		0
$\overline{B1}, \overline{CC1}, \overline{B2}, CC2$	3.30	$\cdot 10^{-02}$
$B1, CC1, B2, CC2$	5.62	$\cdot 10^{-04}$

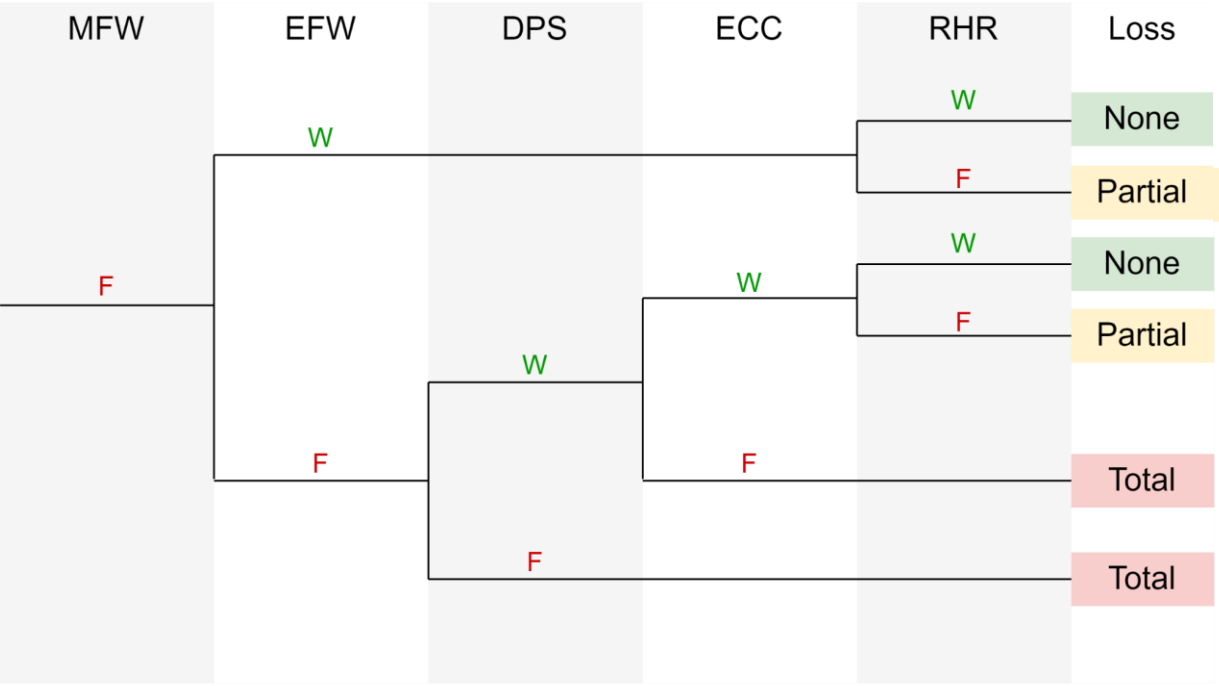
$\overrightarrow{P_{top}}$

D²T²: Subsystems Dependency



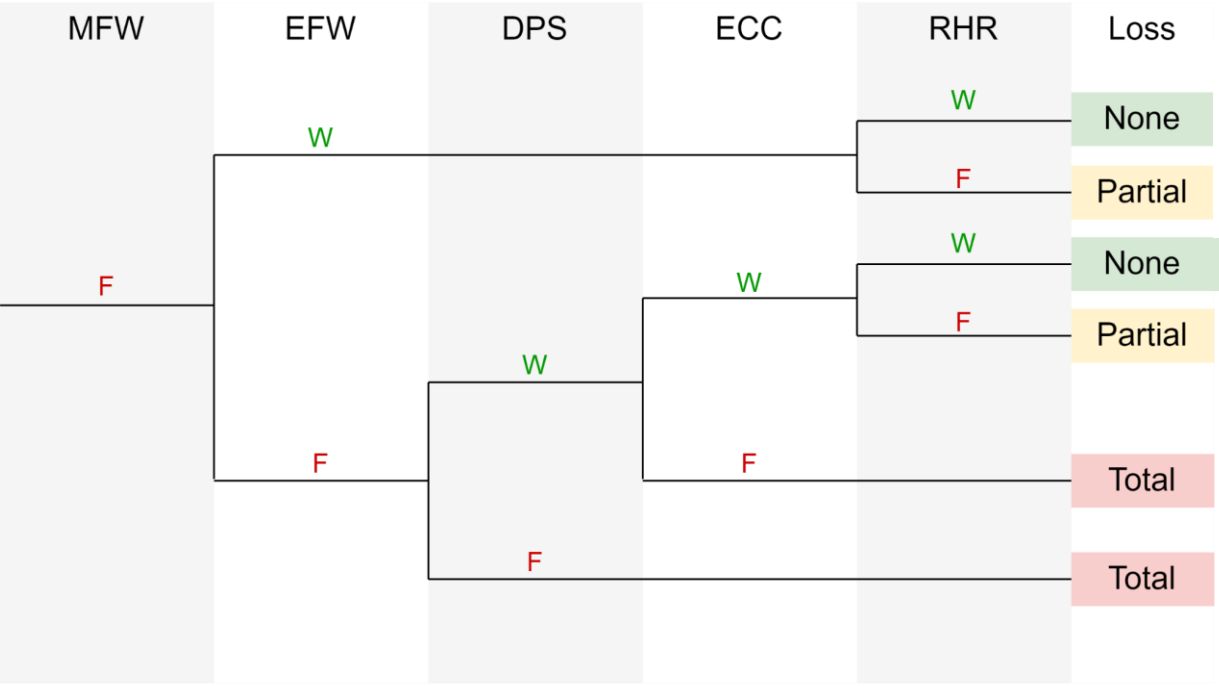
$$\vec{W}_{none1} = \vec{W}_{MFW} \cdot \vec{\vec{P}}_{EFW} \cdot \vec{\vec{P}}_{RHR} \cdot \vec{P}_{SS}$$

D²T²: Subsystems Dependency



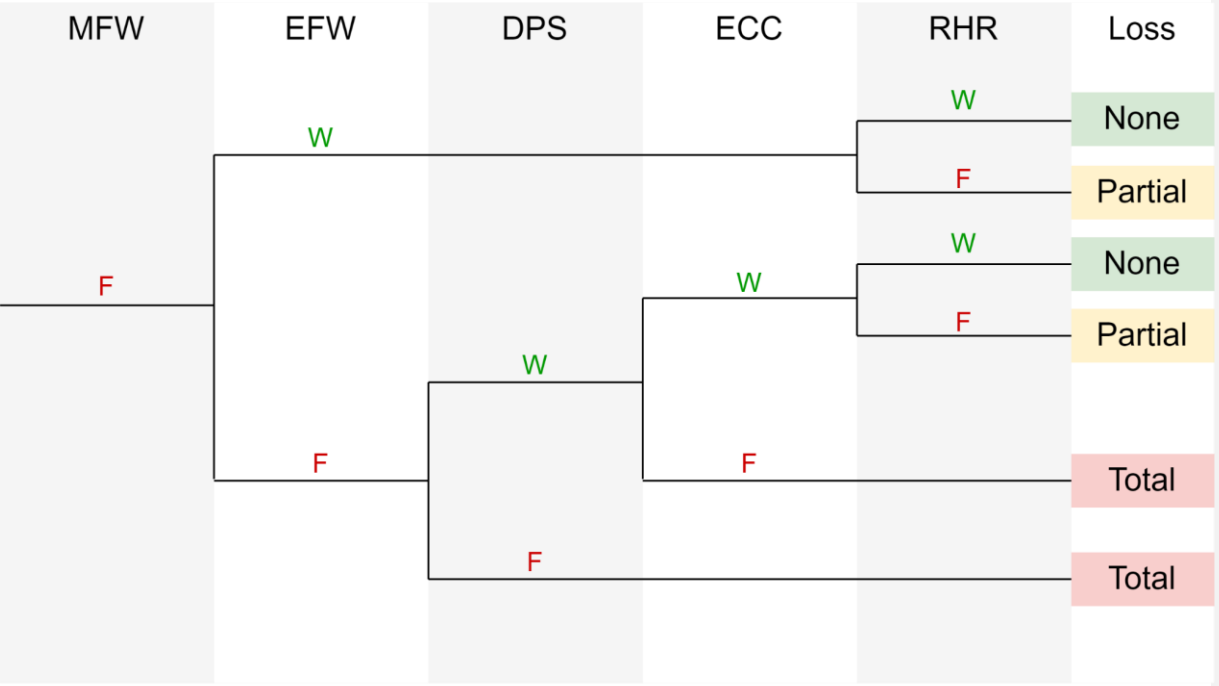
$$\vec{W}_{partial1} = \vec{W}_{MFW} \cdot \vec{\vec{P}}_{EFW} \cdot \vec{P}_{RHR} \cdot \vec{P}_{SS}$$

D²T²: Subsystems Dependency



$$\vec{W}_{none2} = \vec{W}_{MFW} \cdot \vec{P}_{EFW} \cdot \vec{\bar{P}}_{DPS} \cdot \vec{\bar{P}}_{ECC} \cdot \vec{\bar{P}}_{RHR} \cdot \vec{P}_{SS}$$

D^2T^2: Subsystems Dependency

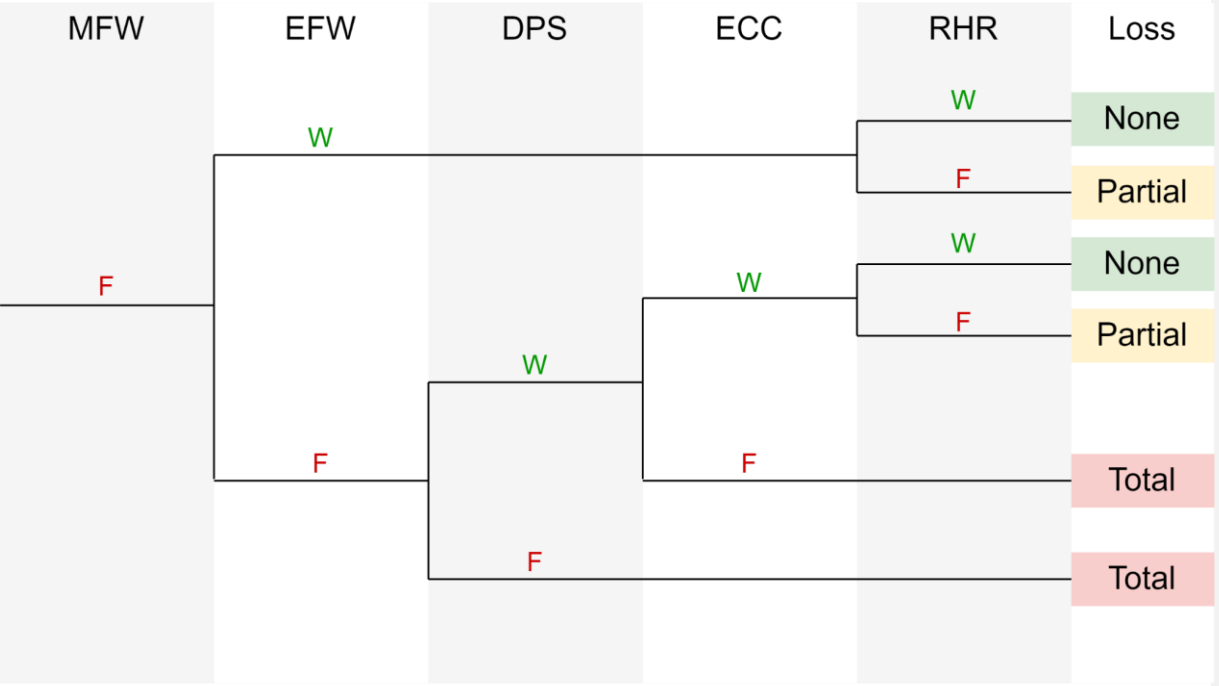


$$\vec{W}_{none} = \vec{W}_{none1} + \vec{W}_{none2}$$

$$\vec{W}_{partial} = \vec{W}_{partial1} + \vec{W}_{partial2}$$

$$\vec{W}_{total} = \vec{W}_{total1} + \vec{W}_{total2}$$

D²T²: Subsystems Dependency



$$W_{none} = \sum_i \overrightarrow{W^i}_{none} = 2.371 \cdot 10^{-6} \quad h^{-1}$$

$$W_{partial} = \sum_i \overrightarrow{W^i}_{partial} = 9.977 \cdot 10^{-9} \quad h^{-1}$$

$$W_{total} = \sum_i \overrightarrow{W^i}_{total} = 5.345 \cdot 10^{-9} \quad h^{-1}$$

Summing Up

Conclusions

Conclusions

- Umbrella methodology integrating flexible modelling techniques within traditional system safety methodologies
- Retains modelling framework familiarity, intuitivity and efficiency while enhancing accuracy
- High potential for modularization
- Dependencies included at any level of system safety modelling
- Algorithms and computational tools available (*NxGen Tool*)
- Removing hidden assumptions

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Thank you

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