# Quantification of initiating events probability based on fragility functions and Bayesian network applied for multi-hazard

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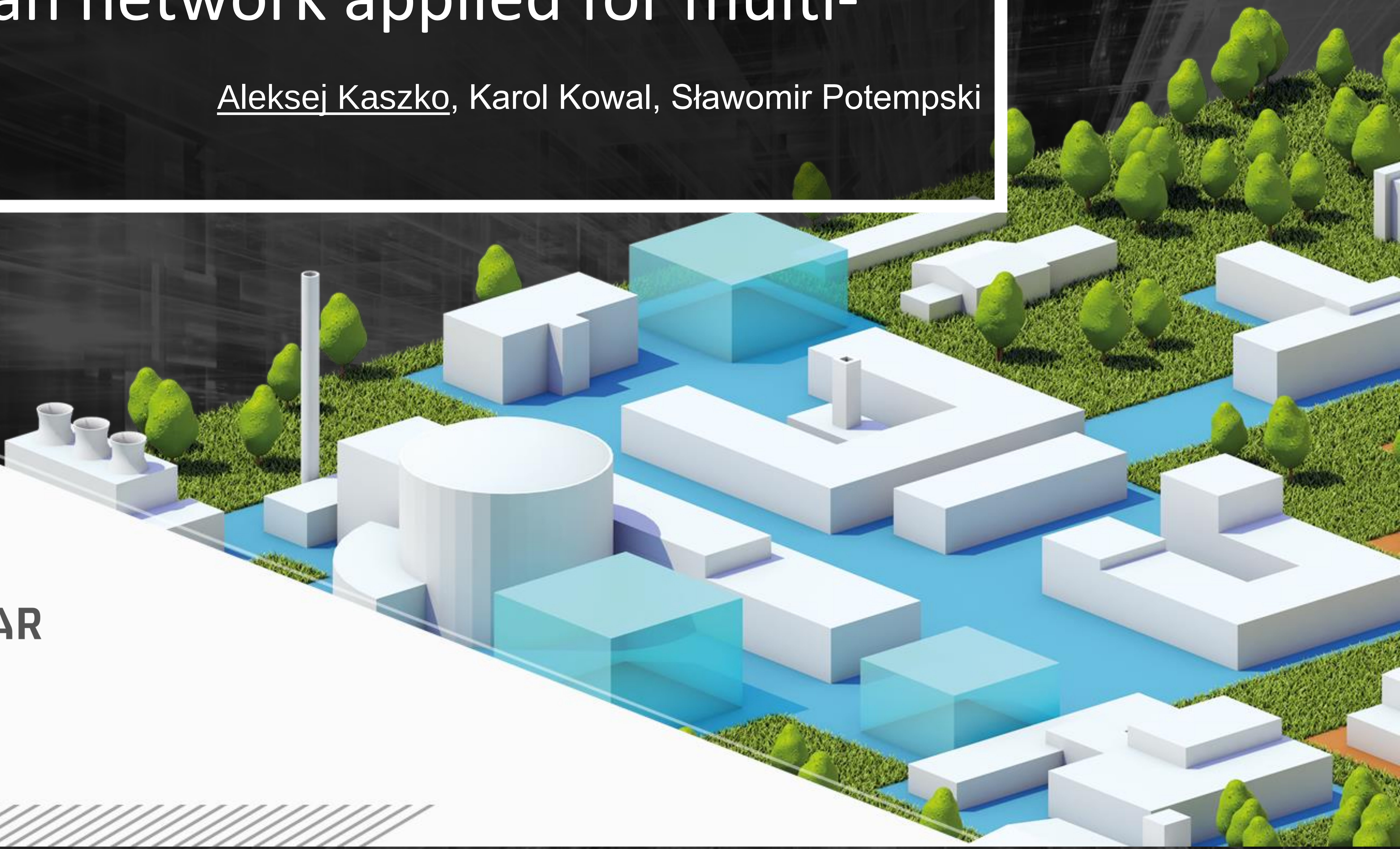

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1. Introduction
2. Fragility Functions
3. Bayesian Network
4. Integration of Fragility Functions and Bayesian Network
5. Example of integrated method
6. Advantages of integrated method

# Introduction

IAEA in „Defining initiating events for purposes of probabilistic safety assessment” describe seven methods for evaluation of IE:

a) Engineering Evaluation or technical study of plant
b) Reference to previous PRAs
c) EPRI list of IEs
d) Logical classification
e) Plant energy balance fault tree
f) Analysis of operating experience for actual plant
g) Failure mode and effect analysis
h) Other methods

Currently after Fukushima accident one of the major concern for the PSA  is to evaluate multi-hazards and initiating events that are caused by multi-hazards.

Multi-hazard in PSA is considering more than one hazard in a given place/facility and their interrelations such as correlation, time dependence or cumulative occurrence and potential interactions.

# Introduction

An initiating event is an incident that requires an automatic or operator initiated action to bring the plant into a safe and steady-state condition, where in the absence of such action the core damage states of concern can result in severe core damage. Initiating events are usually categorized in divisions of internal and external initiators reflecting the origin of the events [1]

Initiating Events are divided into two groups:

- Internal

1. Fires
2. Internal Floods
3. Turbine Missiles
4. etc.

- External

1. Forest Fires
2. External Floods, high level waters
3. Seismic Events
4. Extreme Winds
5. Airplane crash

# External Natural Hazards /Initiating Events

1. Seismotectonic hazards

- Vibratory ground motion
- Vibratory ground motion indused or triggered by human activity
- Surface fauling
- Liquefaction, lateral spreading
- Dynamic compaction
- Permament ground displacement subsequent to earthquake

2. Flooding and hydrological hazards

- Tsunami
- Flash flood
- Floods resulting from snow melt
- High groundwater
- Flooding due to obstruction of a river channel
- Floods resulting from changes in a river channel
- Floods resulting from large waves in inland waters
- Flood and waves caused by failure of of water control structures and watercourse containment
- Seiche
- Bore
- Seawater level
- Wind generated waves
- Corrosion from salt water
- Instability of the coastal area due to errosion by strong water currents or sedimentation
- Underwater debrits

3. Meteorological events:

a) Extreme values of meteorological phenomena

- Precipitation, snow pack
- Extremes of air temperature
- Extremes of ground temperature
- Extremes of cooling water
- Humidity, extreme atmospheric moisture
- Extremes of air pressure
- Extreme drought
- Low ground water
- Low seawater level
- Icing, freezing fog
- White frost, hard rime, soft rime
- Hail
- Permafrost
- Recurring soil frost

# External Natural Hazards /Initiating Events cont.

b) Rare meteorological phenomena

- Lightning
- High wind, storm
- Tornado
- Watersprout
- Blizzard, snowstorm
- Sandstorm, dust storm
- Salt spray, salt storm
- Wind-blown debris
- Snow avalanche
- Surface ice on river, lake or sea
- Frazil ice
- Ice barriers
- Mist, fog
- Solar flares, solar storms, geomagnetic storms

## 4. Biological hazards / Infestation

- Marine/river/lake growth, biological fouling
- Crustacean or mollusc growth, biological fouling
- Fish, jellyfish
- Airborne swarms
- Infestation by rodents and other animals
- Biological flotsam
- Microbiological corrosion

## 5. Geological hazards

- Subarial slope instability
- Undervater landslide, gravity flow
- Debris flow, mud flow
- Ground settlement
- Ground heave
- Karst, leeching of solube rocks
- Sinkholes
- Unstable soils
- Volcanic hazards: near volcanic centre
- Volcanic hazards: effect extending to areas remote from volcanic centre
- Methane seep
- Natural radiation
- Meteorite fall

## 6. Forest Fire

- Forest fire,  wildfire, burning turf or peat

# Earthquake Fragility Function

**Fragility function** is a probability distribution that is used to indicate the probability that a component, element or system will be damaged to a given or more severe damage expressed in the form of function of parameter

$$F_i(D) = \Phi\left(\frac{ln(D/\theta_i)}{\beta_i}\right)$$

Where:
$F_i(D)$ - conditional probability that the component will be damaged to damage state "i" or a more severe damage state as a function of demand parameter, D
$\Phi$ - standard normal (Gaussian) cumulative distribution function
$\theta_i$ - median value of the distribution
$\beta_i$ - logarithmic standard deviation

Median $\theta$ and logaritmic standard deviation can be obtained with one of six ways:

A. Actual Failure Excitation
B. Bounding Failure Excitation
C. Capable Data
D. Derivation (analysis)
E. Expert opinion
F. Updating

# Tsunami Fragility Function

$$P(x) = \Phi\left(\frac{x-\mu}{\sigma}\right)$$

or

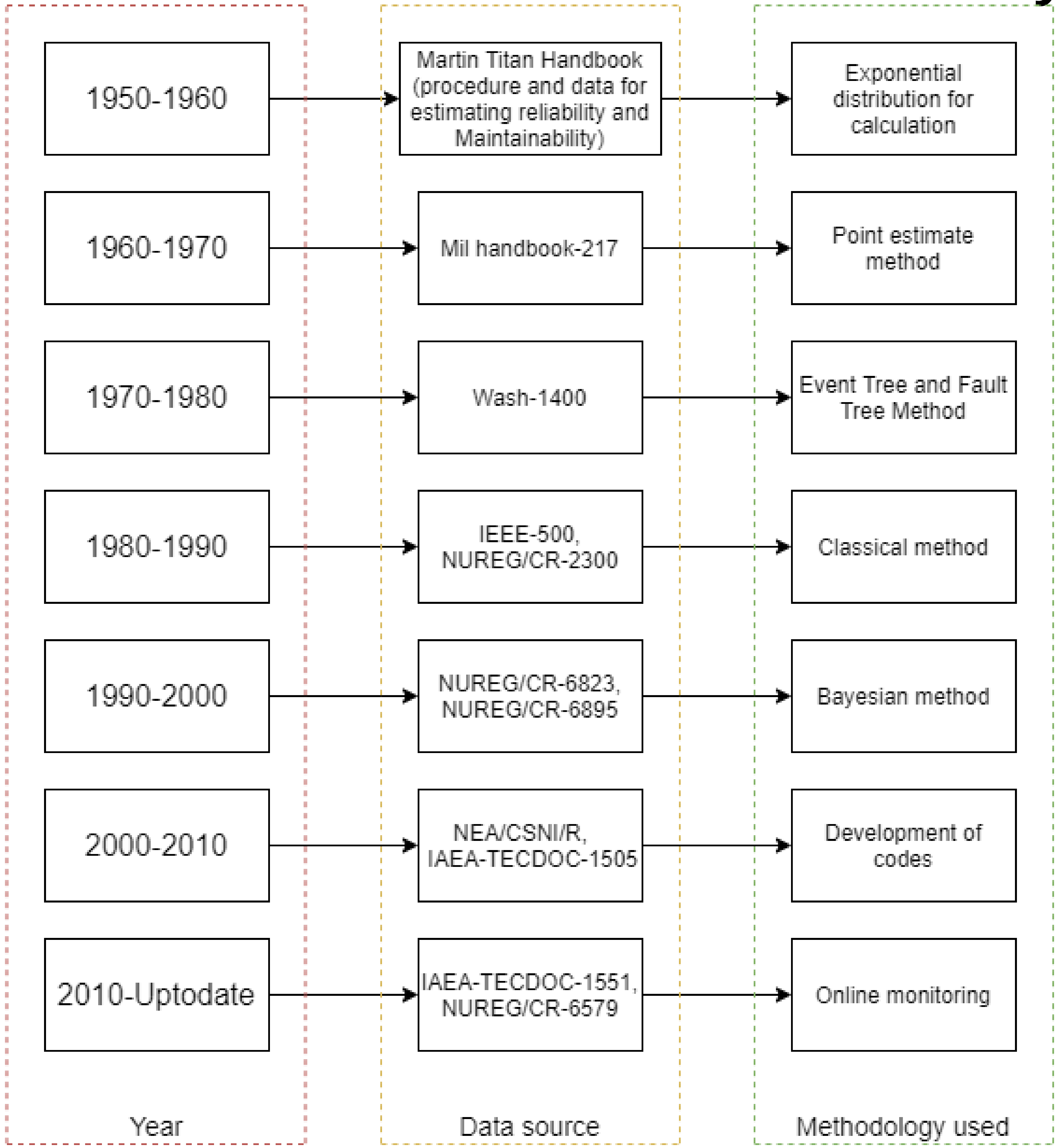
$$P(x) = \Phi\left(\frac{lnx-\mu'}{\sigma'}\right)$$

Where:
$P$ - cumulative probability of occurence of the damage
$\Phi$ - standarized normal distribution function
$x$ – hydrodynamic feature of tsunami
$\mu$ - mean deviation of $x$
$\sigma$ - standard deviation of $x$

The values of $\mu$ $(\mu')$ and $\sigma$ $(\sigma')$ are calculated by means of least-square fitting of $x$ $(lnx)$ and the inverse of $\Phi$, $(\Phi^{-1})$ on normal paper given by

$$x = \sigma\Phi^{-1} + \mu$$
$$lnx = \sigma'\Phi^{-1} + \mu'$$

# Calculation methods for reliability data

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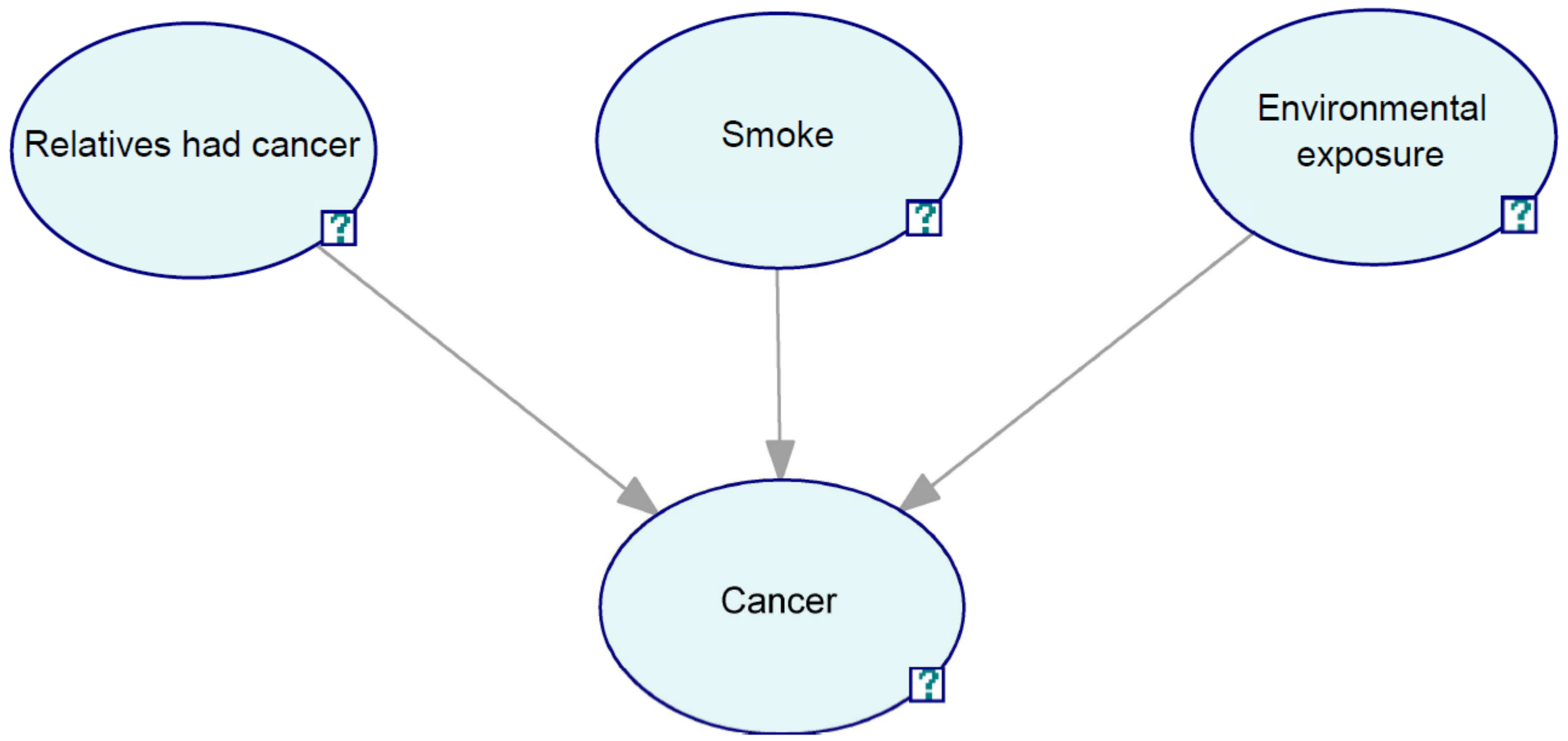
# Bayesian Network

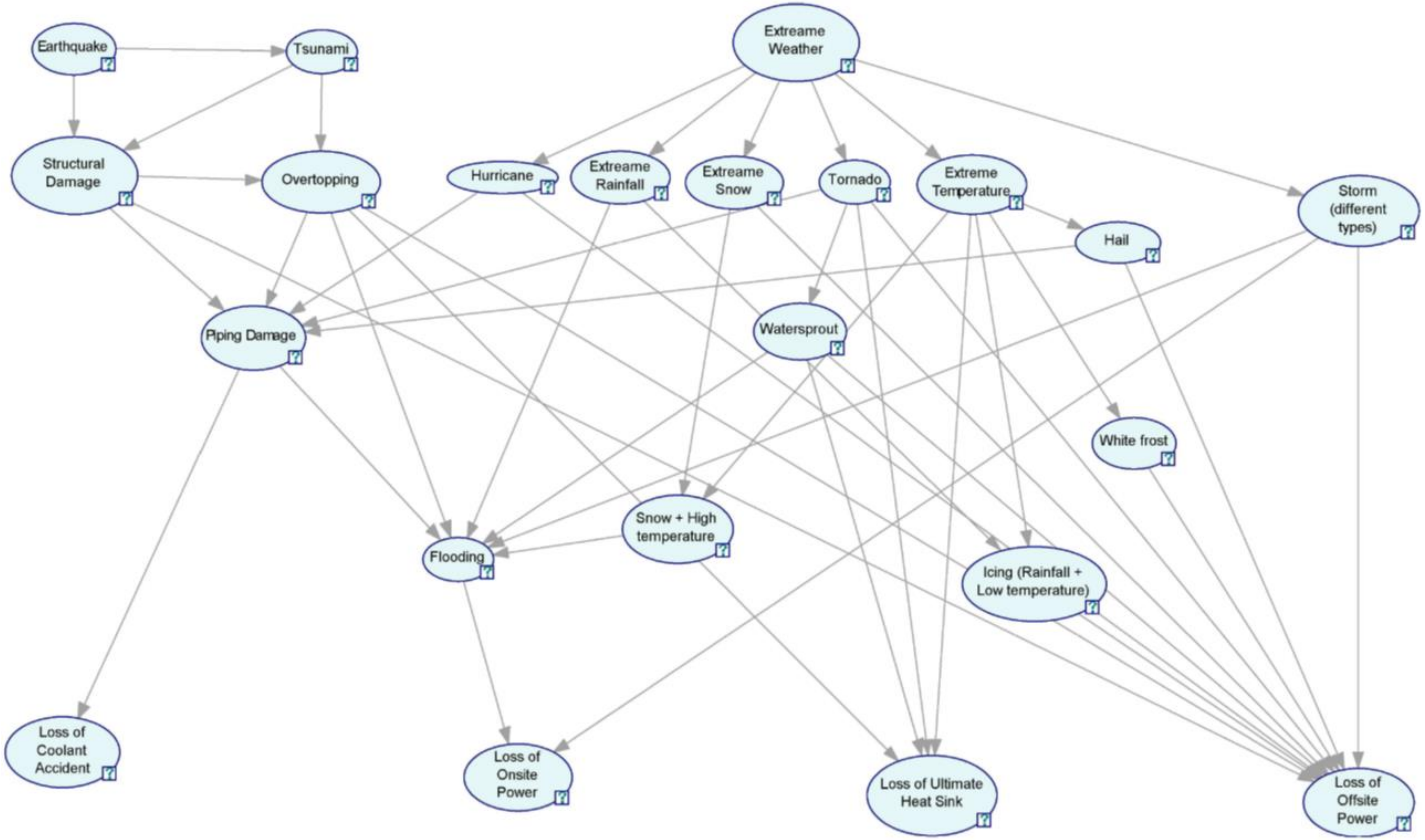
The Bayesian statistical approach facilitates the usual case in which part of the needed information is a priori available in measured data and functional relations or as expert knowledge, and part is uncertain and unknown. The unknown part can be updated a posteriori and the uncertainty reduced by later experience applying the basic laws (product and sum rule) of probability theory.

$$P(H|E) = \frac{P(E|H)P(H)}{P(E)}$$

Bayesian network (Bayesian Belief Network) is a type of probabilistic graphical model that uses Bayesian inference for probability computations. Bayesian network is aiming at modelling conditional dependence, and therefore causation, by representing conditional dependence by edges in a directed graph.



# Bayesian Network




Bayesian network representation of most cases of natural hazards and their correlations based on information from ASAMPSA_E project

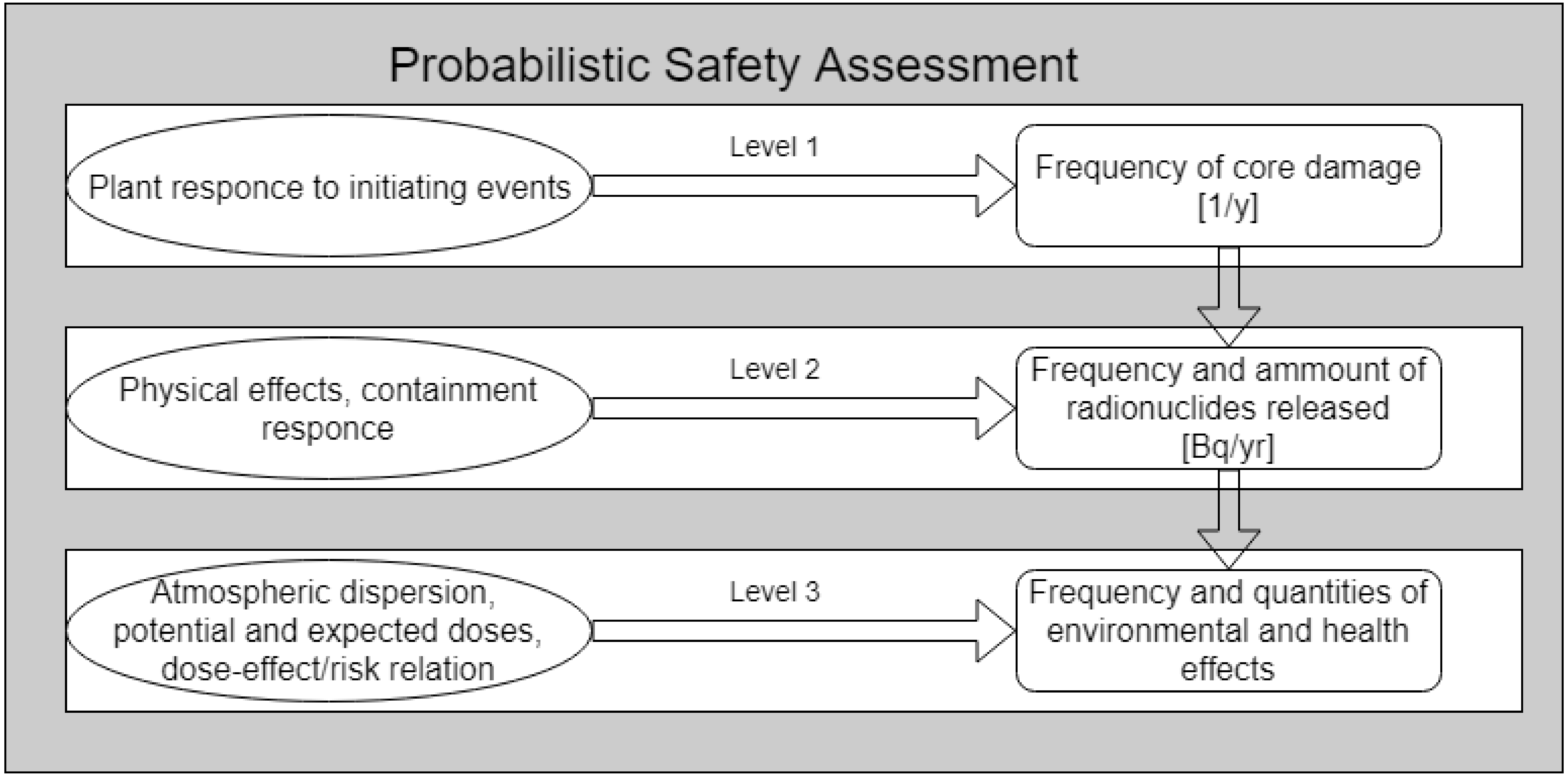
# Probabilistic Safety Assessment

PSA is systematic risk based analytical method that consists of Fault trees (systems) and Event trees - pathways that could lead to succes or failure (Core Damage). PSA is mostly used to calculate probability of hypothetical scenarios that could lead to severe core damage.

The results of PSA can show weaknesses and strengths of plant's safety, and helps in identification of most sensitive parts (for example systems, elements) with highest contribution to accident scenario. With identification operator or designers of a new facility can therefore improve safety by usage of redundancy or by replacement of elements for more reliable ones.

PSA consists of three levels and currently is used all over the world.

# Probabilistic Safety Assessment




Levels of PSA [5]

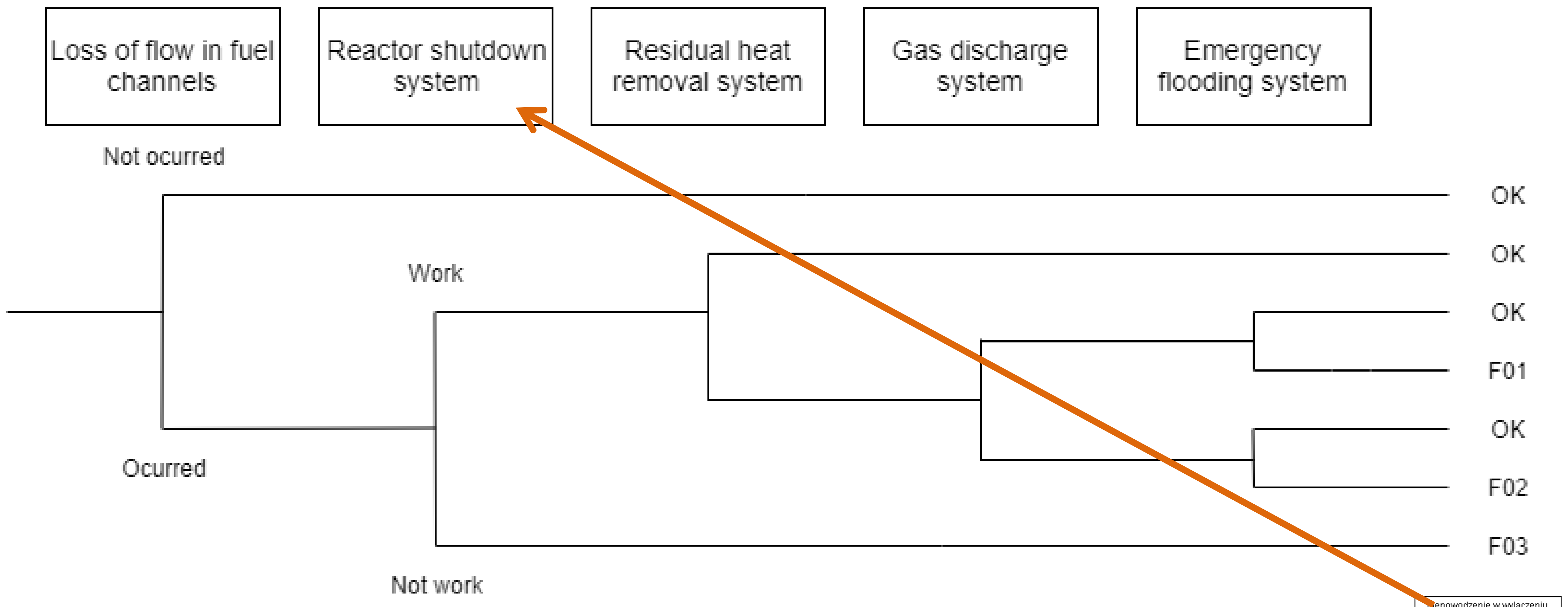
# Fault Tree / Event Tree Technique

The fault tree is a logic diagram based on the principle of multi-causality, which traces all branches of events which could contribute to an accident or failure. Fault tree analyse the systems using Boolean logic as a combination of basic events.

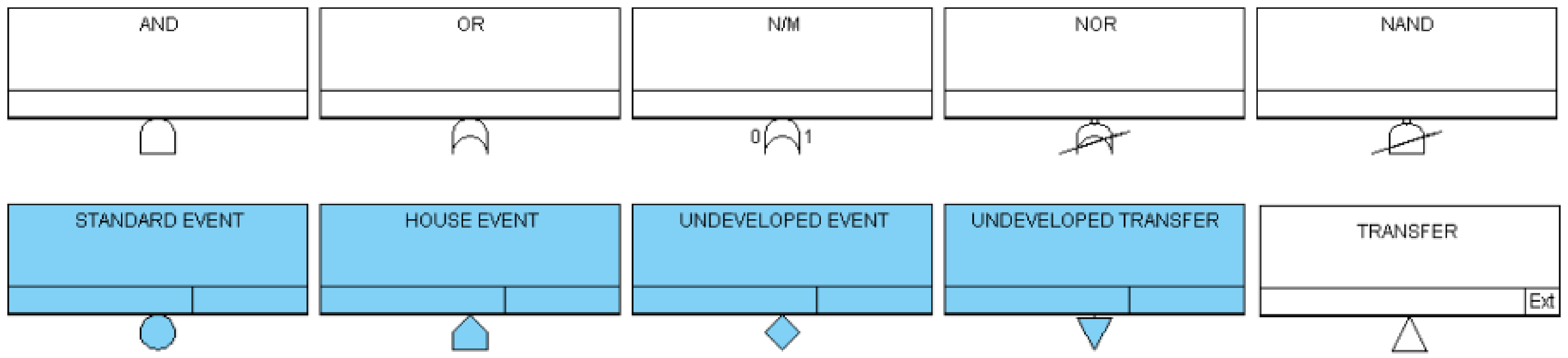
Fault tree technique is used in high-hazard industries such as nuclear, chemical, aerospace etc. starting from 1962.

Usually Fault Trees are used with Event Trees (so called bow tie method) to analyze sequence of failed or functioning systems and their effect. Event Tree was originally published in WASH-1400, although first introduction to this method was in 1968.

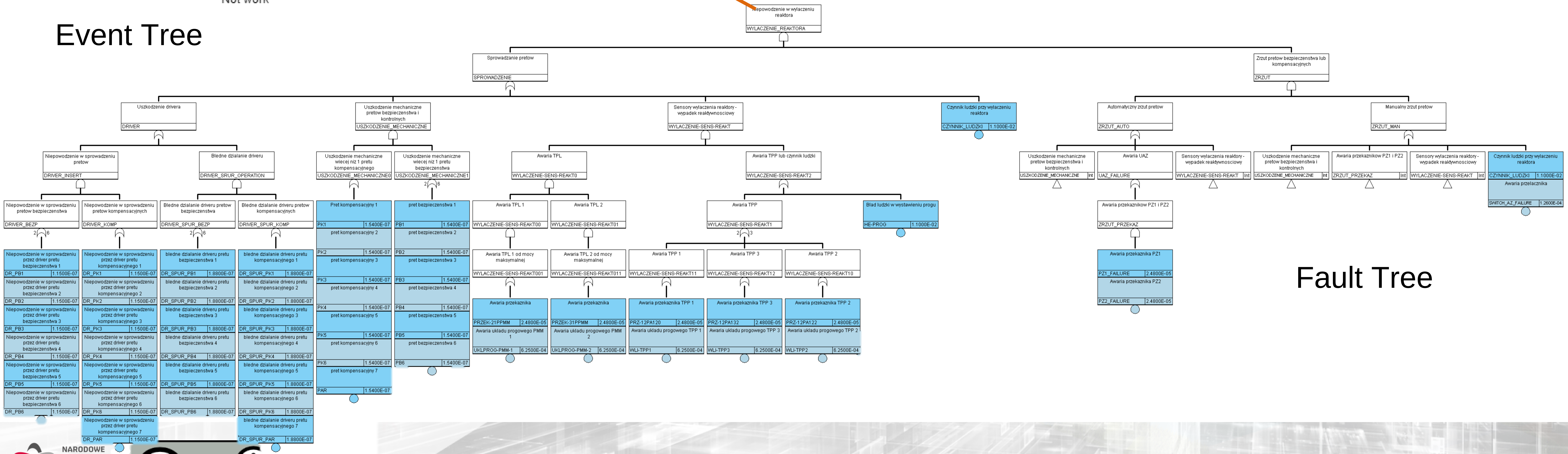
# Fault Tree / Event Tree Technique




Event Tree




Logic gates and basic events representation in SAPHIRE program




Fault Tree

# New approach to quantify initiating events

Each presented technique has its advantages and disadvantages. For example fragility functions are perfect for calculation of single hazard initiating events, bayesian networks have non linear structure and can help address multiple-hazards, FT/ET technique is well known and there is a lot of already developed models for nuclear facilities.

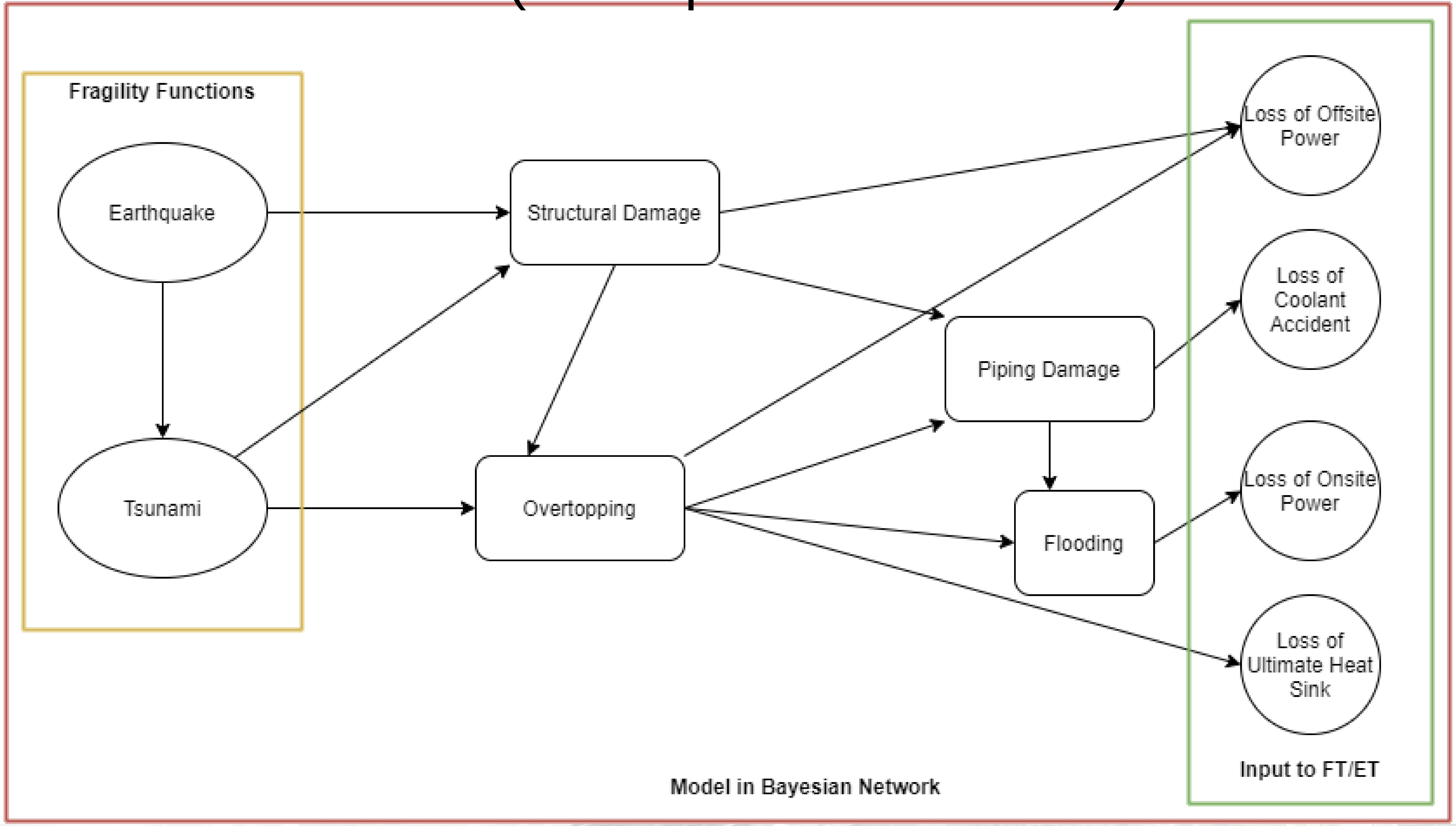
Combination of all these techniques into one model can help to address main issues in PSA that arised after Fukushima accident regarding multiple hazards

# New approach to quantify initiating events

Combination of three techniques:

- Fragility functions are used to evaluate impact on systems or components from considered natural or man induced hazards. Using of vector fragility function allows to take into account possible interactions.
- Bayesian network uses fragility functions and provides Initial Events probability in a more accurate way, taking into account multiple hazards, and their mutual dependencies.
- Well known and widely used from seventies of last century Event Trees and Fault Trees Techniques calculate Core Damage Frequency based on Initial Events probability received from Bayesian Network.

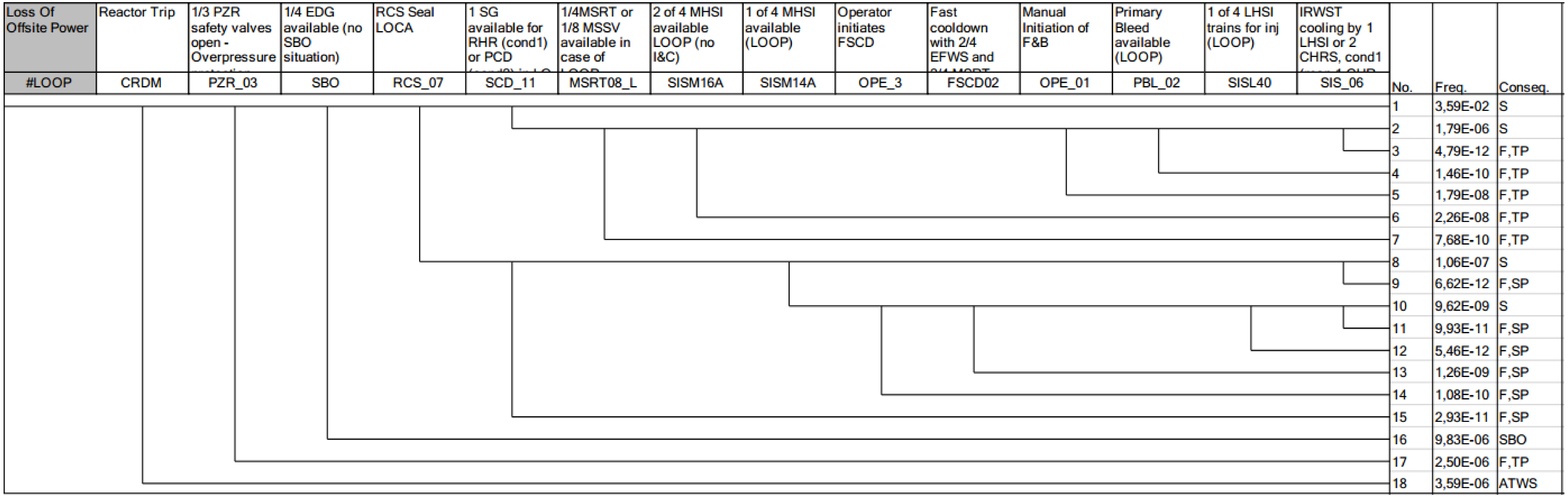
# Ideological scheme of new approach (Earthquake + Tsunami)

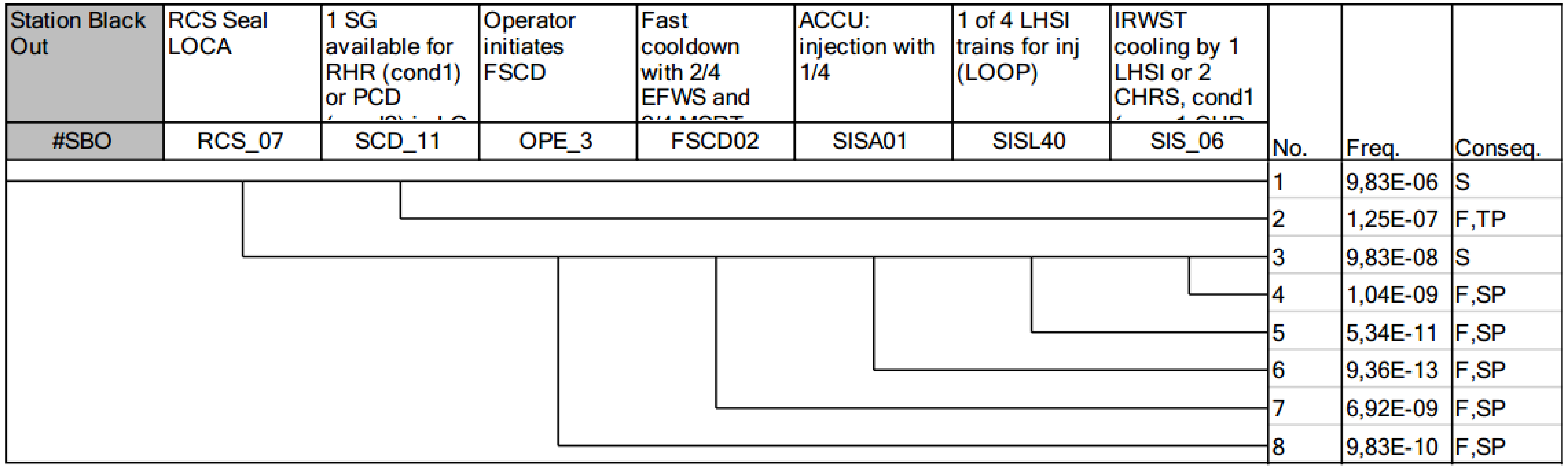



Ideological scheme of new approach that can represent similar case to Fukushima accident that happend in 2011.

This scheme can be extended to scheme similar to represented in slide 11 to adress most cases of natural hazards.

# Event Tree for LOOP scenario




Event tree for Loss of Offsite Power for reference Nuclear Power Plant that consist of 14 Main Fault Trees. Each Fault Tree represents safety system.

# Fault Trees for LOOP scenario

| Name | Basic Events | Sub Fault Trees | Probability |
|---|---|---|---|
| CRDM | 1 | 0 | 1.00E-04 |
| PZR_03 | 6 | 0 | 6.95E-05 |
| SBO | 13 | 4 | 2.74E-04 |
| RCS_07 | 62 | 43 | 5.87E-06 |
| SCD_11 | 192 | 97 | 5.34E-05 |
| MSRT08_L | 145 | 67 | 3.36E-10 |
| SISM16A | 103 | 54 | 1.91E-03 |
| SISM14A | 131 | 76 | 3.65E-04 |
| OPE_3 | 1 | 0 | 1.00E-02 |
| OPE_01 | 60 | 38 | 1.00E-02 |
| PBL_02 | 66 | 30 | 3.39E-05 |
| SISL40 | 224 | 110 | 3.17E-05 |
| SIS_06 | 236 | 111 | 1.05E-06 |
| SISA01 | 8 | 4 | 9.71E-06 |

This Table represents information regarding Fault Trees for LOOP Event Tree. As one can see creation of such fault trees is quite complex and can take alot of time because of reliability data gathering, fault trees creation time etc.

# Advantages of new proposed model

Currently this model is purely theoretical, and soon there are plans to make some calculations and comparison with pure PSA model. But in summary:

- Combination of three well developed techniques
- No need to create everything from the scratch (will use already developed PSA models)
    - Less time consuming to build the whole model
    - Less costs to create
    - Less human resources needed

- More accurate calculation of IE for PSA models
- Can address multiple-hazards for single IE
- Biggest part of the model (PSA) is well accepted by regulatory bodies
- Can be applied for preventive actions during natural hazards – by model adjustment using current data on occuring hazards (e.g. earthquake, tsunami)

# References

[1] IAEA-TECDOC-719 „Defining initiating events for purposes of probabilistic safety assessment”

[2] Porter, K., 2020. *A Beginner’s Guide to Fragility, Vulnerability, and Risk*. University of Colorado Boulder, 136 pp., https://www.sparisk.com/pubs/Porter-beginners-guide.pdf.

[3] Aránguiz, R., Urra, L., Okuwaki, R., and Yagi, Y.: Development and application of a tsunami fragility curve of the 2015 tsunami in Coquimbo, Chile, Nat. Hazards Earth Syst. Sci., 18, 2143–2160, https://doi.org/10.5194/nhess-18-2143-2018, 2018.

[4] Koshimura, Shunichi & Yanagisawa, Hideaki & Imamura, Fumihiko. (2009). Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia. Coastal Engineering Journal. 51. 984-51. 10.1142/S0578563409002004.

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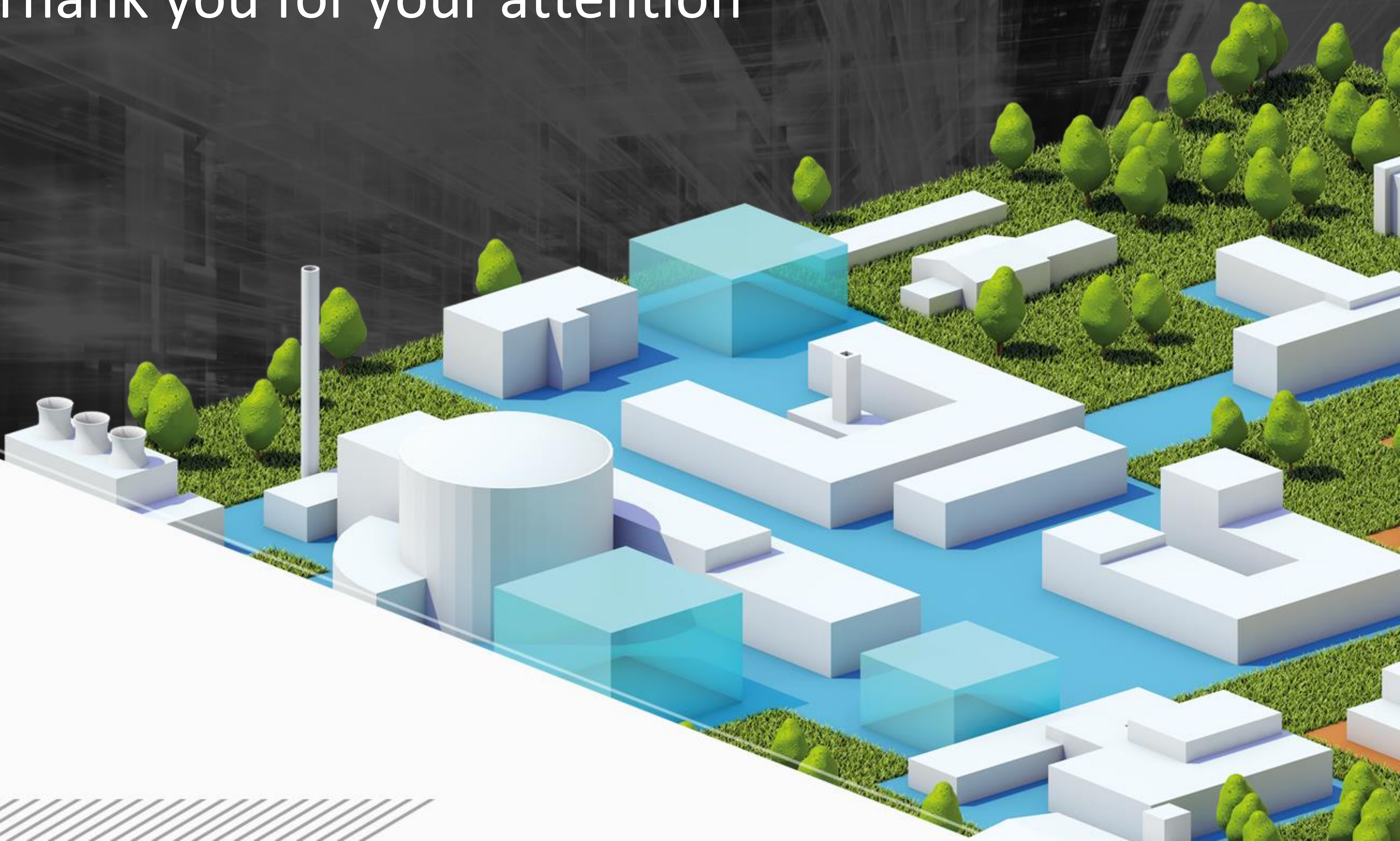
[5] Nusbaumer O., Introduction to Probabilistic Safety Assessments (PSA).

[6] Kelly D., et al.: *Bayesian inference in probabilistic risk assessment—The current state of the art.* Reliability Engineering and System Safety 94/2009, 628–643.

[7] Kwag S., et al.: *Probabilistic risk assessment framework for structural systems under multiple hazards using Bayesian statistics.* Nuclear Engineering and Design 315/2017, 20–34.

[8] Zubair M., et al.: *Advancement in living probabilistic safety assessment to increase safety of nuclear power plants*. Journal of Risk and Reliability 227(5)/2013, 534-539

# Thank you for your attention



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