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A New Reliability Allocation Method Based on FTA and AHP for Nuclear Power Plant

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Contributed by FDS Team

Institute of Nuclear Energy Safety Technology (INEST)
Chinese Academy of Sciences

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  - Nuclear Safety Innovation Project for Scientific and Technological Development
- **10 Divisions**

~380 members

Major Research Areas：

1. **Nuclear reactor safety**
   （reactor design, nuclear detect & experiments, safety analysis, …）
2. **Radiation safety and environmental impact**
   （radiation protection & shielding, chemistry safety of nuclear energy, …）
3. **Nuclear emergency and public safety**
   （nuclear safety culture, nuclear accident emergency, nuclear power economics, …）

The major professional/fundamental research basis for nuclear energy safety technology in China to promote the efficient and safe application of nuclear energy.

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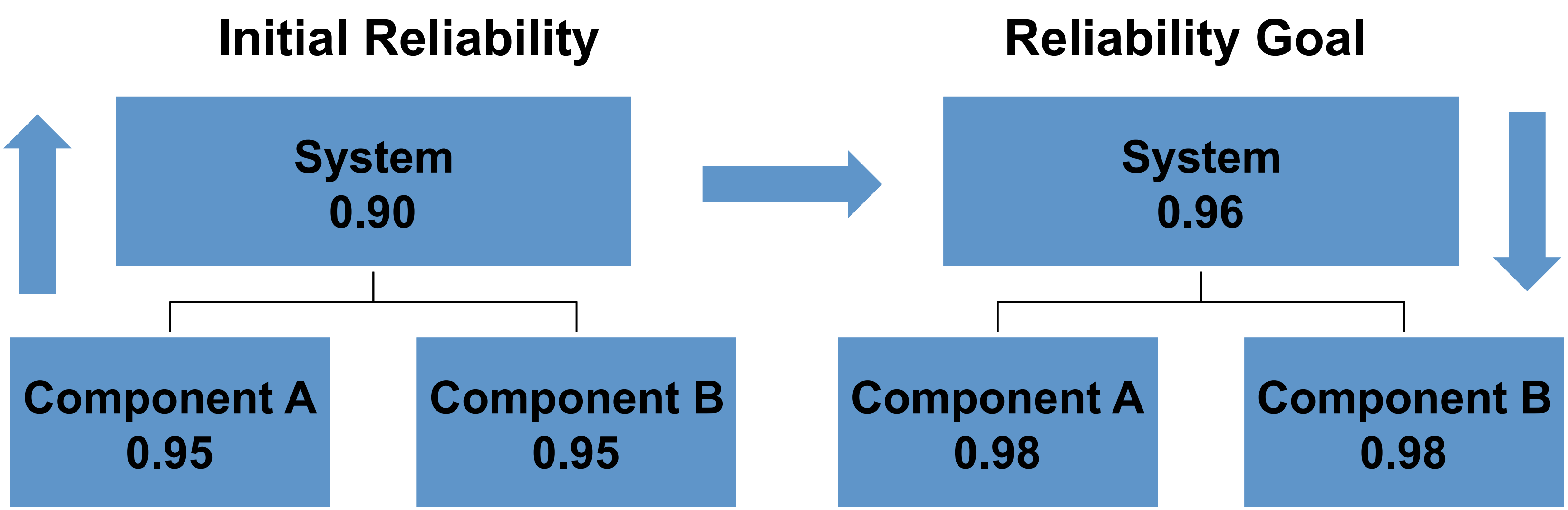
Background

- Reliability is the ability of a system to work correctly during operation
  - Measured by survival probability
- Reliability allocation determines the reliability characteristics of subsystems and components
  - Consider a set of top-level optimization objectives
- Most approaches have limitations in satisfying all optimization objectives
  - Equal reliability allocation method
- Important external factors
  - Impact of environment
  - Severity of the consequences

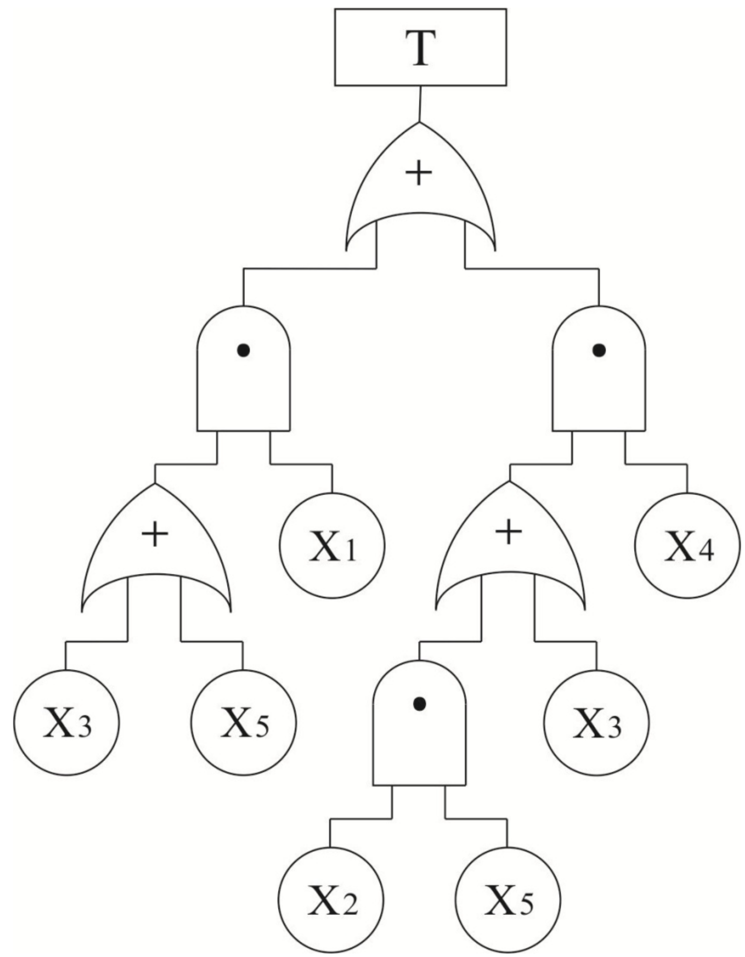
Basic concepts

- **Basic concepts**
  - Initial Reliability
  - Reliability Goal
- **Simple Example**



Fault Tree Analysis (FTA)

- **Elements**
  - Top Event (system)
  - Gates (subsystems)
  - Basic Events BE(components)
- **Cut set**
  - A set of basic events
  - Cause the system to fail
- **Minimum Cut-Set (MCS)**
  - Can not exclude any BE in it



Reliability Allocation Based on FTA

Allocation Criterion

- Importance of MCS and BE

Two Steps Allocation

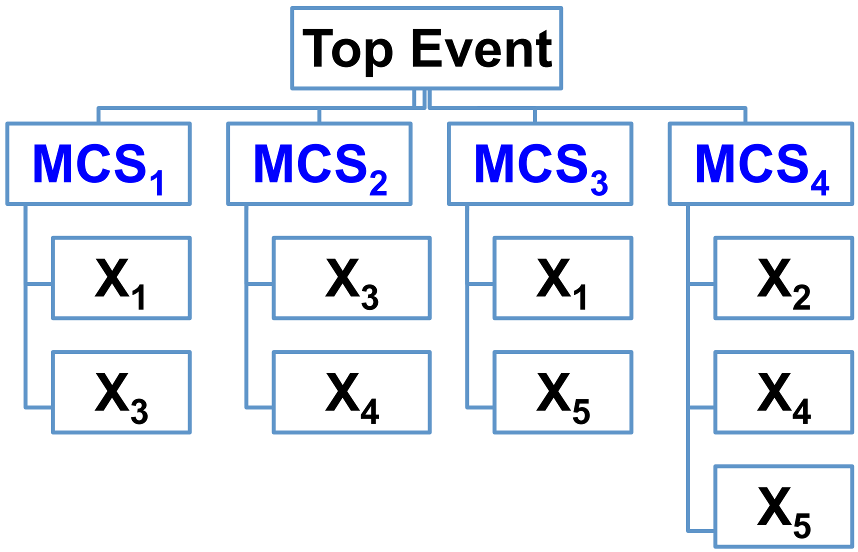
1. Top event to MCSs
2. MCS to BEs

Advantages

- Clear logic relationship
- Accurate quantitative analysis
- Mature and fast

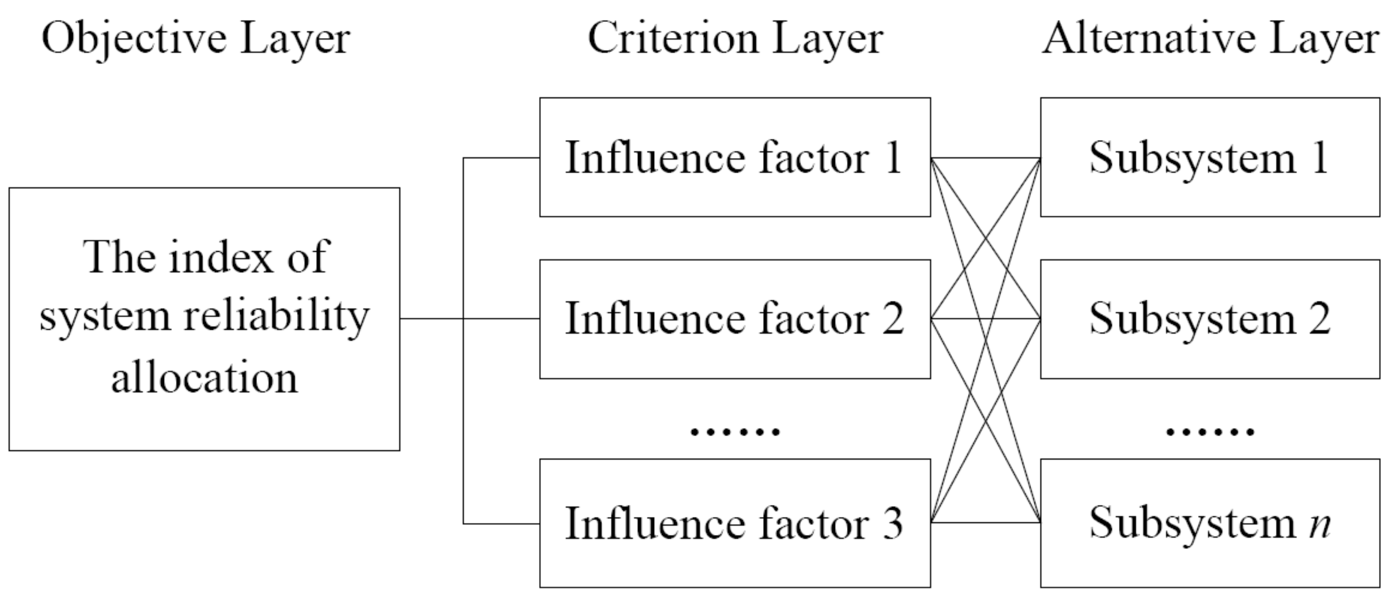
Defects

- Many ignored factors



Analytic Hierarchy Process (AHP)

Hierarchical Structure



Matrixes of Pairwise Comparison

- **Criterion Layer to Objective Layer**
- **Alternative Layer to Criterion Layer**

Reliability Allocation Based on AHP

Allocation Criterion

- Facts in Criterion layer

Four Steps:

1. Set up the hierarchical structure;
2. Collect pairwise comparisons at each level;
3. Compute relative weights at each level;
4. Aggregate the relative weights at lower levels to top level;

Advantages

- Integrate and quantify subjective views from experts

Defects

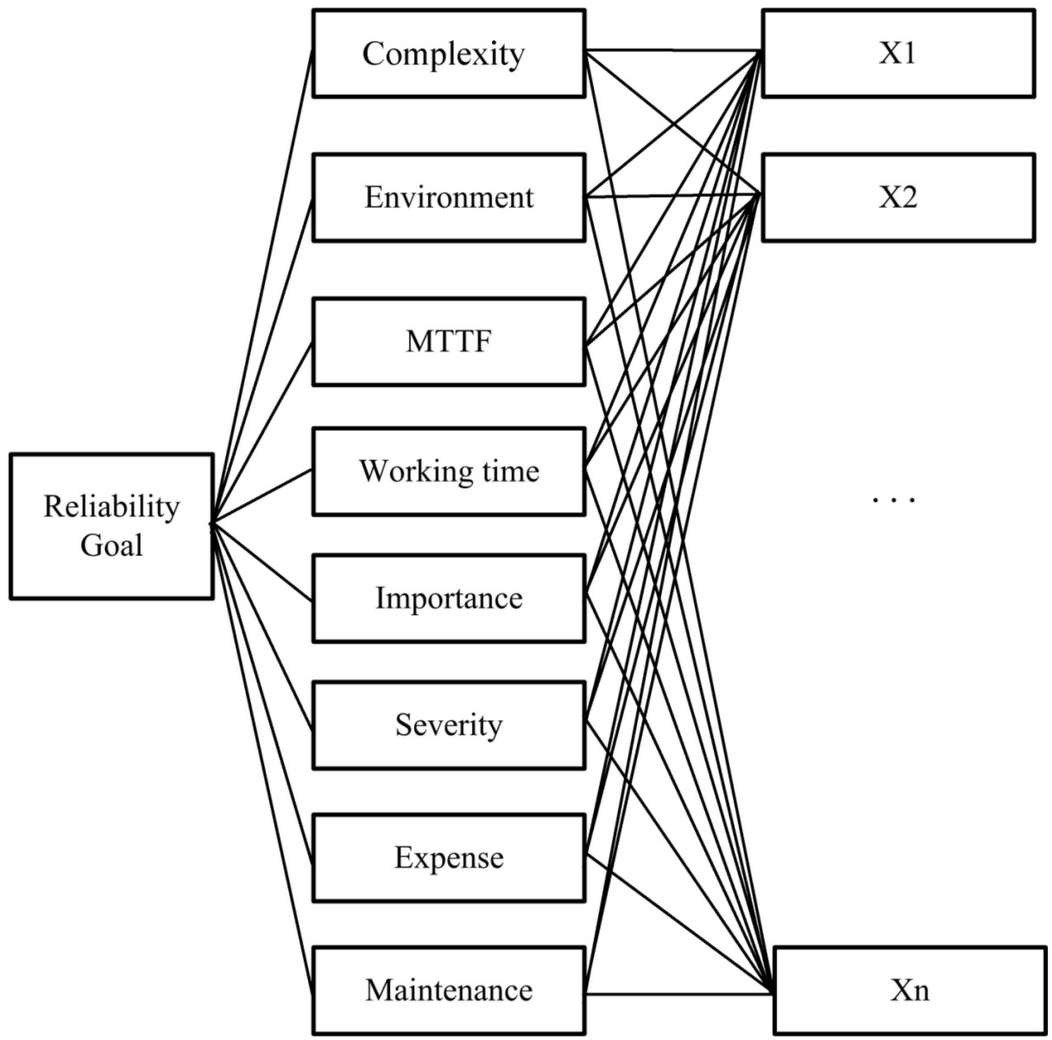
- Need much time for expert judgments
- Neglect available accurate data

Proposed Method

- **Combine FTA and AHP**
- **Two Steps Allocation**
  1. **Top event to MCSs**
  2. **MCS to BEs**
- **Advantages**
  - **Integrate subjective views and objective facts**
  - **Allocation process is efficient**
- **Defects**
  - **Still need time for expert judgments**

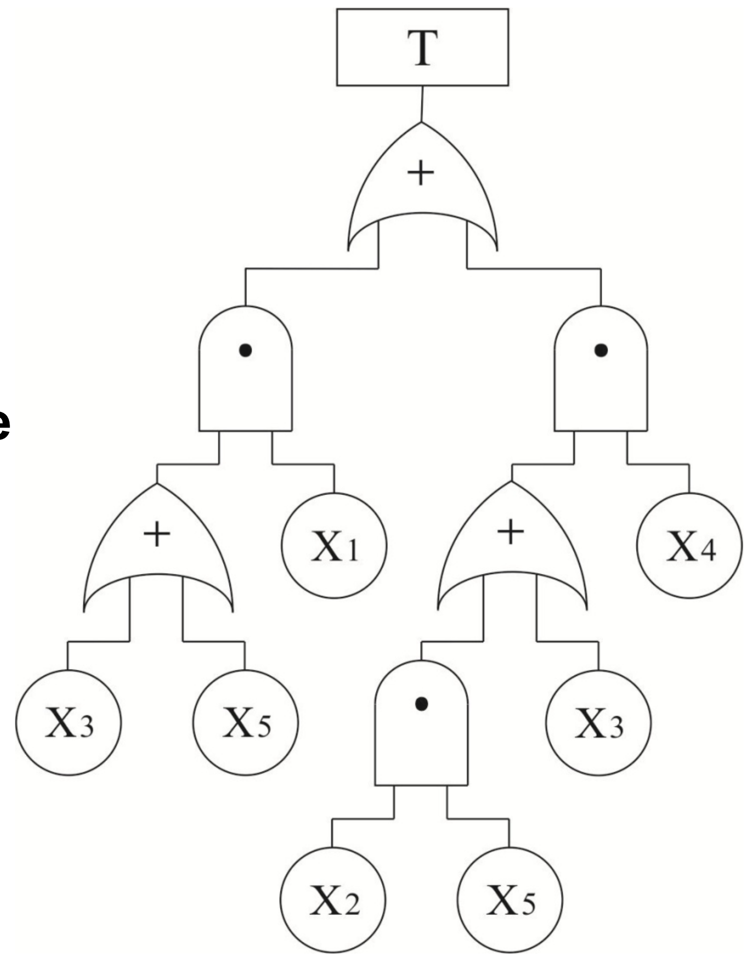
Second Step: MCS to Components

- **Importance**
  - From FTA
- **Working time**
- **MTTF**
  - From accurate data
- **The rest factors**
  - From the comparison matrixes filled by experts



Example

- **Simplified Passive Residual Heat Removal (PRHR) system**
- **Elements**
  - X_1: A complex subsystem working in harsh environment
  - X_2: A component that causes severe consequence if it fails
  - X_3: A component in bad working environment
  - X_4: A component in good working environment
  - X_5: An ordinary subsystem with low reliability



Results

❖ Table 1: Information of Basic Events

BE Name	Initial Reliability	Probabilistic Importance	MCS Included
X_1	0.98	0.0533	G_1,G_2
X_2	0.98	0.0007	G_4
X_3	0.97	0.0489	G_1,G_3
X_4	0.97	0.0298	G_3,G_4
X_5	0.75	0.0199	G_2,G_4

Results

- **Initial reliability of system: 0.993359**
- **Reliability goal of system: 0.998000**

- **Table 2: Information of Minimum Cut-sets**

MCS Name	Reliability Goal	BE Name
G_1	0.99500	X_1,X_3
G_2	0.99910	X_1,X_5
G_3	0.99940	X_3,X_4
G_4	0.99985	X_2,X_4,X_5

Results

❖ **Table 3: Allocation results**

BE Name	Initial Reliability	Reliability goal of FTA	Reliability goal of AHP	Reliability goal of the new method
X_1	0.98	0.9974	0.9895	0.9919
X_2	0.98	0.9800	0.9841	0.9885
X_3	0.97	0.9744	0.9801	0.9837
X_4	0.97	0.9754	0.9855	0.9834
X_5	0.75	0.7565	0.8149	0.8158

❖ **Reliability goal of X_1 is too high to reach**

- Complex subsystem working in harsh environment

❖ **Reliability goal of X_2 does not change**

- Although the consequence of X_2 failure is very severe

Discussion and Conclusions

- Same rationality as AHP method
  - Consider more factors than FTA
  - Even improve the accuracy of results of AHP method based on importance from quantitative analysis of FTA
- The allocation process is more efficient than AHP
  - Information from FTA and accurate data
  - Less time for expert judgments
- This method has been implemented in RiskA
  - Probabilistic Safety & Reliability Analysis Program

RiskA: Probabilistic Safety & Reliability Analysis Program from INEST,CAS

Main Functionalities

- Reliability Data Management
- Failure Mode and Effect Analysis (FMEA)
- Fault Tree Analysis (FTA)
- Event Tree Analysis (ETA)
- Importance Analysis
- Sensitivity Analysis
- Uncertainty Analysis

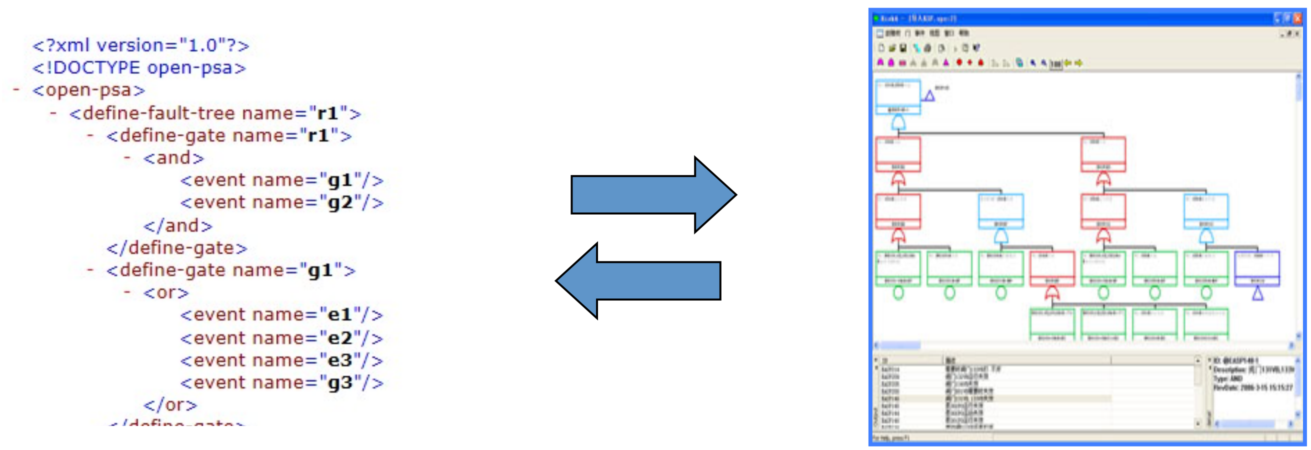
Advanced Functionalities

- Reliability Allocation
- Fault Diagnosis

Model Recognition and Sharing

❖ **FT and ET models can be imported and exported**

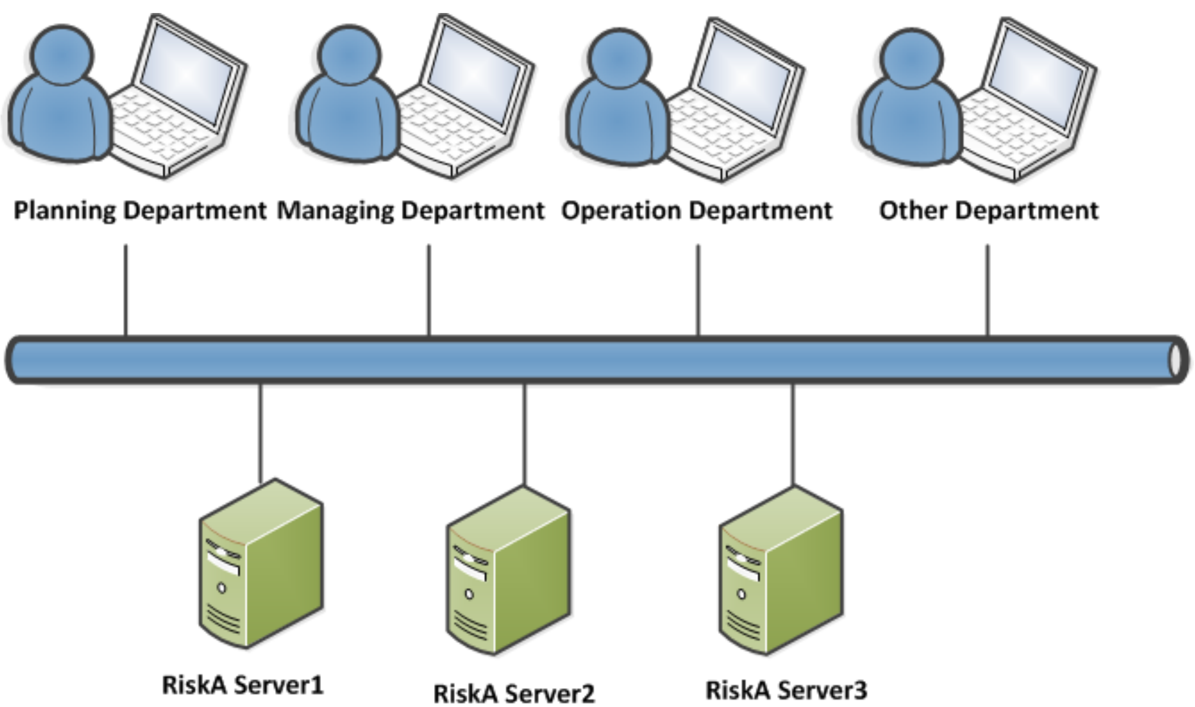
- **FTP**
- **XML**
- **RSA**
- **Format of RiskA**



Open Formats **Format of RiskA**

Co-modeling

- Standalone Version and Online Version
- Version Control and User Permission



Analysis

- **Fault tree Analysis**
  - **Improved Zero-suppressed Binary Decision Diagram (ZBDD)**
- **Uncertainty Analysis**
  - **Optimized Latin hypercube sampling**
- **Parallel Computing**
  - **Simultaneous multiple cases calculation**
  - **Can be deployed on computer cluster**

Applications

- **Computing Engine**
  - The Third Qinshan Nuclear Power Plant Risk Monitor (TQRM)
- **Probabilistic Safety Analysis**
  - International Thermonuclear Experimental Reactor (ITER)
  - Experimental Advanced Superconducting Tokamak (EAST)
- **Reliability Analysis**
  - Accelerator Driven Nuclear Waste Transmuter (ADS)
  - FDS series fusion reactors
  - Laser Radar System

Contact Information

- Institute of Nuclear Energy Safety Technology (INEST), Chinese Academy of Sciences (CAS)
- Website
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- Software Service
  - software@fds.org.cn
- We provide
  - Demo Version
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Thanks for Your Attention！

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First step: Top to Minimum Cut-Sets (MCSs)

- **Allocate reliability from Top (system) to Minimum Cut-Sets (MCSs)**
- **The procedure includes:**
  1. **Order all MCSs, and choose *k* low reliability MCSs**
  2. **Use the importance of each MCS as relative weight to calculate the reliability goal of each MCS**
- **Notices**
  - ***k* low reliability MCSs should cover all basic events**
  - ***k* should not be too large for efficiency**

Second Step: MCS to Components

- **Allocate reliability from MCSs to components (basic events)**
- **The procedure includes:**
  1. **Order all basic events, and choose / low reliability basic events**
  2. **Set up the hierarchical structure, 9 factors**
  3. **Construct the input matrixes of pairwise comparisons (IMPC)**
  4. **Examine the consistency of the IMPC**
  5. **Compute global relative weights**
  6. **Compute reliability goal of basic events based on global relative weights**

Results Optimization

- Get reliability goal of all basic events
  - Intersections of different MCSs
  - Reliability goal of one basic event may have different values
- Each component should have one value
- The maximum value is selected
  - Guarantee the reliability goal of the system