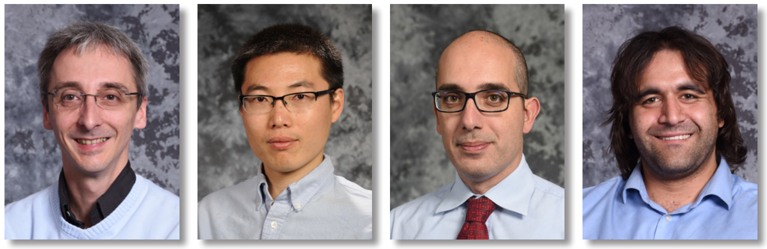
Integration of Classical PRA models into Dynamic PRA



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Risk-Informed Systems Analysis Pathway

Since the 1970s, the U.S. nuclear industry and the U.S. NRC have developed probabilistic risk assessment (PRA) models to evaluate the safety risk associated with nuclear power plants. These PRA models, termed "Classical PRA," are based on two classes of models: Fault-Trees (FTs) and Event-Trees (ETs). FTs are used to determine under which condition a plant system (e.g., low pressure injection system) can fail provided the status of its components (e.g., pumps and valves) through a series of logic gates (e.g., AND, OR). ETs are instead used to model accident progression provided the status of the plant systems for a specific initiating event (e.g., transient, loss-of-offsite power, loss-of-coolant-accident) using a tree structure. Traditionally, two outcomes are possible for each ET sequence: OK (i.e., reactor in a safe and stable state) or core damage.

Dynamic PRA models have been under development since the early 1990s as an evolution from Classical PRA models. Instead of employing ETs and FTs, they are based on two items: (1) a set of system simulator(s) to represent plant physical phenomena; and (2) a stochastic code to represent probabilistic variation found within off-normal scenarios. The stochastic codes are used to determine timing and sequencing of events that are either stochastically (through a Monte-Carlo sampling algorithm) or deterministically (because of something occurring in a scenario). System simulators are used to model accident progression provided the timing and sequencing of events generated by the stochastic results.

The Risk-Informed Systems Analysis (RISA) Pathway has developed methods to integrate important portions of Classical PRA models into a Dynamic PRA, thus creating a "hybrid" PRA. We have shown how this integration can be performed within the open source Risk Analysis Virtual ENvironment (RAVEN) statistical software that has been created by LWRS Program researchers. As part of this research, we developed unique capabilities including:

1. Implementing the ability to import Classical PRA models (e.g., ETs and FTs) into RAVEN.
2. Integrating the imported Classical PRA models to a system simulation code approach.
3. Comparing Classical and Dynamic PRA quantitative results for comparison and validation purposes.

Capability 1 allows RAVEN to read ET and FT structures from files in the OpenPSA format (a widely used format in the nuclear industry) and creates a RAVEN model that mimics such structures. In addition, RAVEN can import two other common Classical PRA models: Markov models and Reliability Block Diagrams (RBDs). In Dynamic PRA, time is explicitly considered in the analysis while Classical PRA is based on Boolean logic, not time. This implies that a Dynamic PRA considers not only if something has failed or not, but also when it fails.

Capability 2 uses RAVEN to identify input/output connections between different Classical PRA models in order to properly run these models. Note that proper execution of all the connected models is important because a model may be dependent on one of the outcomes of a previously executed model (e.g., an ET may depend on a FT).

Capability 3 creates a data-mining post-processor in RAVEN that can be used to match the ET or FT output to the data generated by a Dynamic PRA. This data classifier associates a label to each simulation generated by the Dynamic PRA – this label is created by understanding what systems have failed or are successful as a part of the simulation.

Representative Test Case

In order to test the methods proposed here, several simple analytical test cases based on classical reliability configurations were generated. For all these simple cases, the results matched the predicted analytical results.
In addition, a more thorough benchmark testing was developed between our approach (using RAVEN/RELAP5-3D)

and the Classical PRA approach. The more relevant test case was for a large break loss-of-coolant accident (LB-LOCA) where depressurization of the reactor occurs very quickly (due to the large break) and a large amount of water inventory is lost. In this situation, several systems are called upon to respond to the LOCA, including the accumulator (ACC), the low-pressure injection (LPI), and the low pressure recirculation (LPR) system.

The overall LB-LOCA model (see the right portion of Figure 3) was created by: (1) importing the three FTs into RAVEN; (2) developing the RELAP5-3D models for LB-LOCA cases (4", 8", 10", and double guillotine break); and (3) creating a RAVEN model that links the three FT models to the RELAP5-3D model. Then, 10,000 simulation runs were generated using RAVEN/RELAP5-3D on high-performance computing system. The scope of this exercise is not only to show how FTs can be effectively linked to a simulation run, but also to perform a comparison between the outcome prediction of the ET sequences and the set of RELAP5-3D simulation runs as shown in Figure 3. This comparison was performed by associating each transient simulated by RELAP5-3D to a specific branch of the ET.

From Figure 4, Classical and Dynamic PRA results match for Branches 1 through 3 while the simulations contained in Branch 4 saw outcomes that resulted in OK part of the time and core damage part of the time. This inconsistency was observed for all four LB-LOCA cases (6", 8", 10", and 2A), which implied that the classical PRA model was, in this case, conservative. The successful outcome of this research has shown how to take the investment in classical PRA models and integrate them into Dynamic PRA in order to reduce conservatisms found in the traditional models. Further, by integrating the Classical PRA models using RAVEN, we can bring in a large body of engineering knowledge found in those models (e.g., how systems operate under off-normal conditions) into our risk analysis approaches.

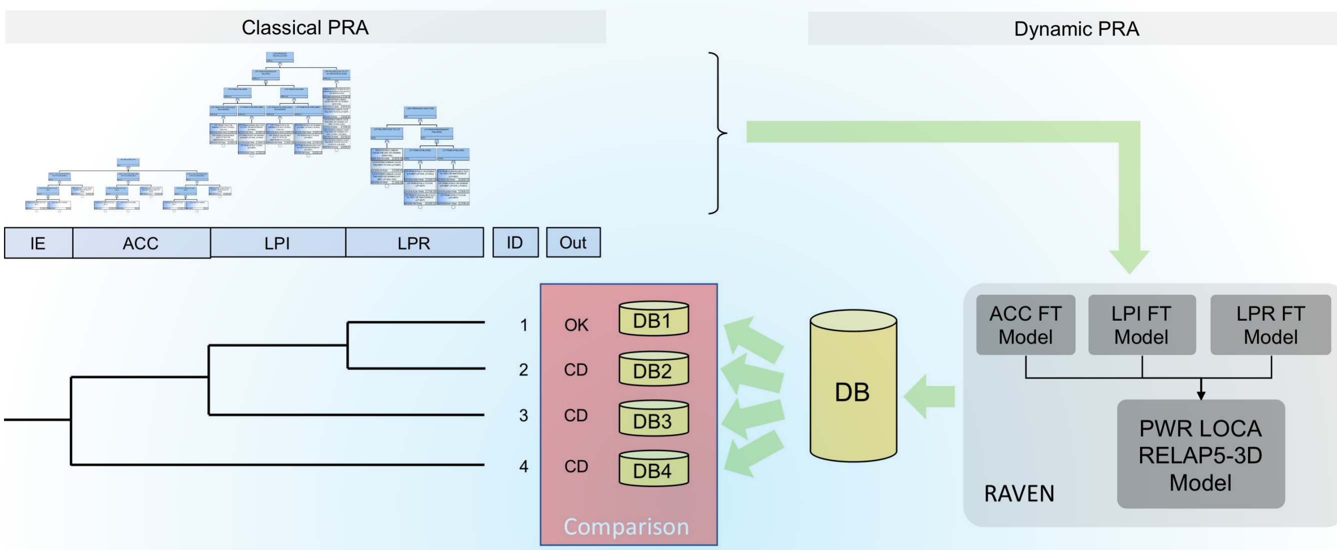

Figure 3. Scheme of the Classical and Dynamic PRA integration for the LB-LOCA test case.

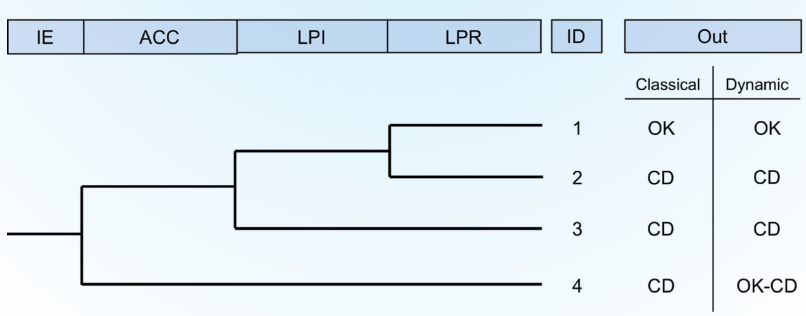

Figure 4. Comparison of Classical and Dynamic PRA results.