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Survey of Dynamic PSA Methodologies

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1. Introduction

Event Tree(ET)/Fault Tree(FT) are significant methodology in Probabilistic Safety Assessment(PSA) for Nuclear Power Plants(NPPs). ET/FT methodology has the advantage for users to be able to easily learn and model. It enables better communication between engineers engaged in the same field. However, conventional methodologies are difficult to cope with the dynamic behavior (e.g. operation mode changes or sequence-dependent failure) and integrated situation of mechanical failure and human errors.

Meanwhile, new possibilities are coming for the improved PSA by virtue of the dramatic development on digital hardware, software, information technology, and data analysis. More specifically, the computing environment has been greatly improved with being compared to the past, so we are able to conduct risk analysis with the large amount of data actually available. One method which can take the technological advantages aforementioned should be the dynamic PSA such that conventional ET/FT can have time- and condition-dependent behaviors in accident scenarios.

In this paper, we investigated the various enabling techniques for the dynamic PSA. Even though its history and academic achievement was great, it seems less interesting from industrial and regulatory viewpoint. Authors expect this can contribute to better understanding of dynamic PSA in terms of algorithm, practice, and applicability.

2. Review of Dynamic PSA Methodologies

Figure 1 shows the over-arching classifications which are applicable for the dynamic PSA [1].

In Figure 1, the methodologies to support the dynamic PSA are mainly into two categories: continuous and discrete time approaches. These approaches can be represented by various visualization techniques. Methods for software were separately classified because they are required to make a model for software reliability[1].

2.1 Continuous time method

Continuous Event Tree(CET) has been introduced to solve the reactor dynamics problems. CET is derived from stochastic balance equation was obtained through the Chapman-Kolmogorov equation. CET is difficult to be applied to a full-scale nuclear system because of extensive calculation requirements of continuous time method [2].

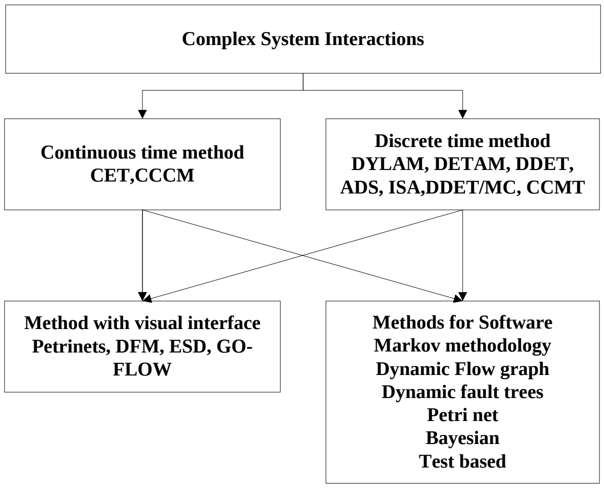

Figure 1. Classification of Dynamic PSA Methodologies

2.2 Discrete time method

2.2.1. Discrete dynamic event trees

Discrete Dynamic Event Tree(DDET) is simulation-based framework that integrates models to generate ET dynamically and automatically. DDET has been used a lot for complex systems and the effectiveness of DDET was demonstrated by a number of case studies. Table 1 shows the examples of DDET[3-4].

The advantages of DDET are as follows:

- Flexibility to model the integrated response due to better communication,
- Operator action models to simulate their behavior in plant,
- Modeling safety systems(e.g. recovery, variability),
- Fewer assumptions and boundary conditions,
- Quantitative frequencies for all sequences,
- Termination of unnecessary sequences.

Table 1. DDET Examples

Tools	Group	Application	Remarks
DYLAM **(DYnamic Logical Analytical Methodology)**	JRC, Italy	Dynamic reliability	1986
DETAM **(Dynamic Event Tree Analysis Method)**	MIT, US	Level 1 PSA	1992
ADS **(Accident Dynamics Simulator)**	UMD, PSI	Dynamic PSA/HRA	1996, 2007
DENDROS **(Dynamic Event Network Distributed Risk Oriented)**	Munoz, Spain	Level 1 PSA	1996, 2007
MCDET **(Monte Carlo Dynamic Event Tree)**	GRS, Germany	Uncertainty	2006
SCAIS **(Simulation Code System for Integrated Safety Assessment)**	CSN, Spain	Safety Margin	2008
ADAPT **(Analysis of Dynamic Accident Progression Trees)**	OSU & SNL	Level 2 PSA	2009
Simulink SAPHIRE **(Systems Analysis Programs for Hands-on Integrated Reliability Evaluations)**	OSU & INL	Digital System PSA	Using CCMT

The Steam Generator Tube Rupture(SGTR) accident in Pressurized Water Reactor(PWR) was analyzed by using Dynamic Event Tree Analysis Method(DETAM) approach and some important details be described when DDET developed for accident sequence analysis should be solved problems[3]. In references 5, DDET was applied to Medium-break LOCAs (MLOCAs). Simulation was conducted by using ADS-TRACE tool[5]. The uncertainty of physical model of DDET and analysis methods were describe and the case of the depleting tank problem was discussed[6].

2.2.2. Cell-to-cell mapping technique

Cell-to-Cell Mapping Technique (CCMT) is the systematic procedure to describe the dynamic behaviors for linear and non-linear system (in discrete time and discretized system state space).

CCMT requires top events. State represents the combination of the system configuration for a given period of time and includes information about the operational status of each component. Dynamic behaviors are usually described by a set of differential or algebraic equations, and control laws, and operating and failure states of each component is specified by the user.

CCMT has the following assumptions [1]:

- Component of system is not change state during time interval
- For a given component state combination n and cell is uniformly distributed over
- If the modeling is conducted in the CVSS, no two controlled variable trajectories arrive at the same point in state space at the same time and move in different directions for the same component state combinations.

The study conducting inherently safe dynamic reliability analysis of Boiling Water Reactor(BWR) by CCMT and providing the overview for the method was published[7].

2.3. Methods with visual interface

2.3.1. Petri-nets

A Petri-net model graphically illustrates a bipartite graph with two nodes (places, transitions) in a circle shape. Petri-nets provide state space diagrams and analytical solution. Petri-net is a more focused way for intuitive depiction than quantitative analysis using Monte-Carlo Simulation(MCS) provides a quantitative analysis [8].

Petri-nets are usually difficult to avoid the problem that the states of size increase because of the use of a Markov chain. So it is difficult to solve large scale problems. The previous study provided simple case studies, modeling method and results of Petri-nets for the dynamic PSA[9].

2.3.2. Dynamic reliability block diagrams

Dynamic Reliability Block Diagrams(DRBD) can represent the subsystem connection with the features and reliability relationship of the system diagram graphically. DRBD is an easy-to-use model can be easily obtained from the specifications. DRBD has been developed based on the format of the existing RBD. Each component is divided into state, active, failed, and standby.

The biggest advantage is the ability to model the dependencies between their reliability interactions of the subsystems or components. Quantitative analysis is possible with conventional Markov chain or MCS [8].

2.3.3. Reliability graph with general gates

The conventional reliability graph is an intuitive method that is able to model a system by using a one-to-one match graph. However, the reliability graph is not widely used because it is less capable of expression; it can only express the characteristics of an OR gate.

On the other hand, Reliability Graph with General Gates(RGGG) minimizes the loss of the existing RG intuitive and has the advantage of an existing RG. In order to calculate reliability, we need to convert RG to Bayesian network with probability tables for all nodes. User can directly establish an RGGG from intuitive signal flow.

RGGG is good for the reliability analysis of complex systems due to the excellent intuitive and helps in quick judgment and action of the operator. Results of RGGG do not have truncation errors[8].

2.3.4. Dynamic flow graph method

Dynamic Flow graph Method(DFM) is an analytical toolset developed to support PSA. DFM is the combination of multi-valued logic modeling and analysis capabilities and suitable for configured system that has degraded state and represented dynamic behavior. It is especially preferable for non-coherent logic structures analysis

DFM clearly indicates the cause-and-effect and timing correspondences between the parameters of the significant states. DFM provides FT and Failure Mode and Effect Analysis (FMEA)[1].

2.4. Methods for Software

2.4.1. Dynamic fault tree

Dynamic Fault Tree(DFT) can take the role for the actual time dependent profile of the risk assessment of the NPP. DFT includes the control logics and operation modes of the equipment and contributes to the improvement of the maintenance activity and test of safety equipment in NPPs. Conventional FT cannot make time requirements model in the safety system and cannot monitor top event probability on configuration of the system that change with time.

The most important requirement to use the DFT is to select appropriate probabilistic models for basic events. DFT can optimize the parameters of probabilistic models to assess the time dependent risk profile and to minimize the overall risk[9].

A reference[9] described the application of DFT for integration of structural equipment and the improvement of maintenance activities and test of safety equipment in NPPs.

2.4.2. Dynamic Bayesian networks

It has been proposed to convert the solution method into Bayesian networks to overcome the limitations of the solution obtained using the Markov model.

As the converted Bayesian Networks(BNs), there are discrete-time and continuous-time based methods.

If a discrete-time based method is used, a standard BN inference algorithm can be used. However, discrete-time based method is less accurate because of lack of assumption for the discrete-time based method.

The Continuous-time based method provides a closed-form solution for system reliability. However, continuous-time based method should be given all marginal probability distributions for the exact expression[8].

There was a study to introduce an application the methodology to DBN heated tank system[10]. In this study, a heated tank system is modeled by DBN to describe the dependencies between variables and the quantification method is also briefly introduced. A reference[11] described various formulas and basic concepts of DBN, modeling methods and application of DBN

2.4.3. Monte Carlo simulation

Monte Carlo Simulation(MCS) can lead to the occurrence of events any time and can make model of random events. MCS is not affected by the complexity and size of the system. MCS can be included in the assumption of the model (e.g. non-fixed failure rate assumption, random delays, components, process dynamic interaction).

In general, MCS is used to directly evaluate the system safety of reliability[12]. Advantages and disadvantages of the MCS are as follows:

Advantages of MCS

- All the traditional tools of statistics analysis are used.
- The probability of an event related to an output parameter is obtained.
- The error estimate converges towards zero when the number of tests is increased.
- Test can put forward various correlation (or non-correlation) between the parameters that could have escaped a preliminary analysis

Disadvantages of MCS

- A great number of simulations are required.
- If any simulation is expensive in time, this default quickly becomes crippling
- It is impossible to have complete security on the results from a qualitative point of view, the uncertainty of the parameter is determined by judgments the output parameter is biased by this preliminary judgments.
- The probabilistic results can be sometimes difficult to interpret, and they are certain not easy to present to a non-expert audiences.
- The method requires the establishment of functions of distribution for various dubious parameters. It can sometimes be very difficult and vague [13].

2.4.4. Markov modeling

Markov modeling is a classical modeling technique used for assessing the time-dependent behavior of many dynamic systems.

In a Markov chain, transitions between states are assumed to occur only at discrete points in time. On the other hand, in a discrete Markov processes, transitions between states are allowed to occur at any point in time. Markov modeling also provides analytical solutions and the state space diagrams. However, Markov modeling is not easy to solve large scale problems [12].

3. Summary and Discussion

A variety of enabling techniques for the dynamic PSA introduced in Chapter 2 are summarized in Table 2. Short reviews and the characteristics of each methodology are described in Table 2.

Table 2. Summary of Dynamic Methods in PSA

Type	Method	Key features	Remarks
Continuous	CET (Continuous Event trees)	Complexity and extensive computation	Difficult to apply to realistic scale
Discrete	DDET (Discrete dynamic event tree)	Simulates in the time discretization space	The most widely used
	CCMT (Cell to cell Mapping Technique)	Required Top Events of knowledge	Linear and non-linear system
Visual interface	Petri-nets	State space diagrams and analytical solution	Difficult to solve large scale problems
	DRBD (Dynamic reliability block diagrams)	Easy to use	Graphical representation
	RGGG (Reliability Graph with General Gates)	Excellent intuitive	Good for complex system analysis
	DFM (Dynamic Flow graph Method)	software analytical toolset	Good for non-coherent logic structures analysis
Methods for Software	DFT (Dynamic fault tree)	Dynamic Gates (PAND, SEQ, etc.)	Pre-requirement of physical process response
	DBN (Dynamic Bayesian networks)	Improvement of Markov model problem	Closed form solution
	MCS (Monte Carlo Simulation)	Required many of simulation	Good for represent the correlation or non-correlation among parameters
	Markov Modeling	State space diagrams and analytical solution	Difficult to solve large scale problems

4. Conclusions

In paper, the overview for the dynamic PSA was conducted. Most of methodologies share similar concepts. Among them, DDET seems a backbone for most of methodologies since it can be applied to large problems.

The common characteristics sharing the concept of DDET are as follows:

- Both deterministic and stochastic approaches
- Improves the identification of PSA success criteria
- Helps to limit detrimental effects of sequence binning (normally adopted in PSA)
- Helps to avoid defining non-optimal success criteria that may distort the risk
- Framework for comprehensively considering uncertainties and variability
- Benefits for risk informed decision-making
- As it demands robust PSA results
- In addition to risk measures, decision makers want information on uncertainties

Nevertheless, each of the methods has advantages and disadvantages, so we, first, need to find the nature of the problems that we are interested in. As a next step of this study, authors are going to investigate the specific problems or issues that require the support of the dynamic PSA, and develop the detailed algorithms.

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