SYSTEMS ENGINEERING APPROACH TO DYNAMIC PROBABILISTIC SAFETY ANALYSIS USING GPGPU PARALLEL COMPUTING

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Dynamic probabilistic safety analysis (DPSA) complements and improves the deterministic safety analysis and probabilistic safety analysis (PSA) of complex systems. However, its application to critical infrastructures is a new field of research that presents different and complex challenges. This study leverages the efficiency of systems engineering to decide the best approaches and the best models to perform DPSA on critical infrastructure systems based on the latest state of the art progress in different fields. The study draws from seismic probabilistic safety analysis focusing on nuclear power plants but the method can be applied to other systems. Once the problem and the solution domains have been established, given a clearer systematic application to the ecosystem of the dynamic PSA the requirements can be reviewed from a different stakeholders' stand point to fulfill the verified and intended functions and objectives. Dynamic event tree analysis (DETA) is the model used for DPSA. The data required by such analysis is: hard to retrieve, complex to analyze, and lead to a larger number of outcomes than a traditional PSA. While the number of branches in a classic event tree analysis is set by the analyst, in a dynamic event tree analysis it is driven by the state variables of the system. This creates a large number of outcomes that must be handled by a supercomputer equipped with thousands of CPU and GPU. Nowadays, general purpose graphic processing unit (GPGPU) allows large scale computing to be carried out by a workstation. However, all the algorithms and models developed for DETA must be rewritten and reshaped to the new architecture. This is a challenge on its own explained in this study.

I. INTRODUCTION

Dynamic Probabilistic Safety Analysis (DPSA) is an improvement over the traditional PSA of complex system. The theory is not new but its application proved to be unfeasible due to computational power limitation to handle the state space explosion [1]. Furthermore, its application to PSA of critical infrastructure systems is a new field of research that presents new different and complex challenges. This study will consider probabilistic seismic safety analysis of nuclear power plants which can be extended to conventional power plants and other complex systems. Systems engineering will guide the DPSA of complex systems because it give the engineer or analyst vital overview of the critical impact on the cost, reliability and feasibility of the design in consideration [2]. One of the three categories of DPSA propounded by [3] which is the continuous-time methods adopts the continuous even tree (CET) approach.

The steps to DPSA using system engineering approach which will for the section of this work can be considered in two broad domains, the problem and solution domains

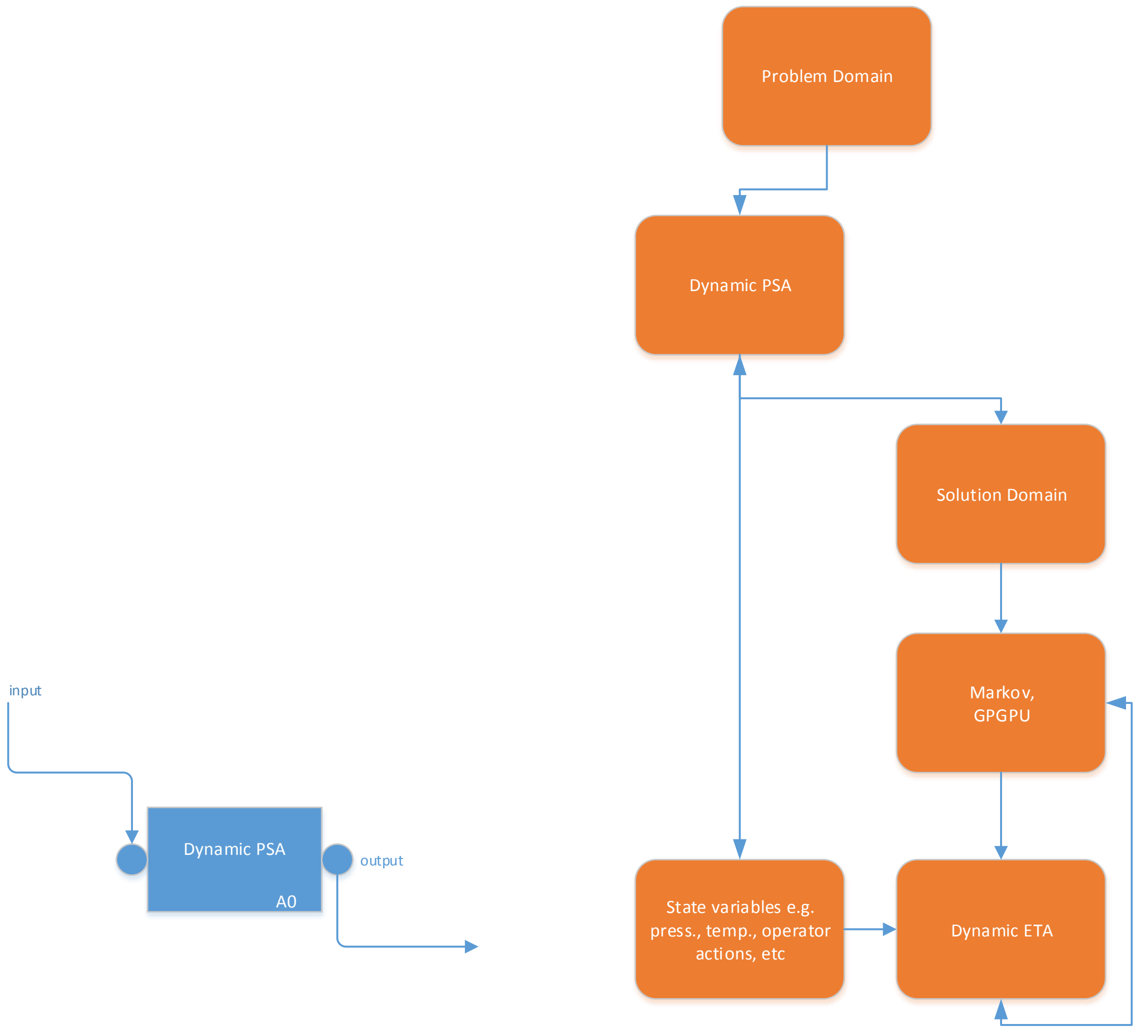


Fig. 1: IDEF0 and flowchart of systems engineering approach to DPSA

II. PROBLEM DOMAIN

Traditional PSA have been not been able to account for uncertainties like human behavior and state vectors in event trees [4]. This presents a major challenge, however, DPSA using DET will be able to provide a deeper understanding of the state of the system outside the dual state given in traditional PSA. Figure 2 provides an explanation to how the time component is accounted for in the dynamic PSA while the traditional PSA only accounts for the dual (yes or no) component.

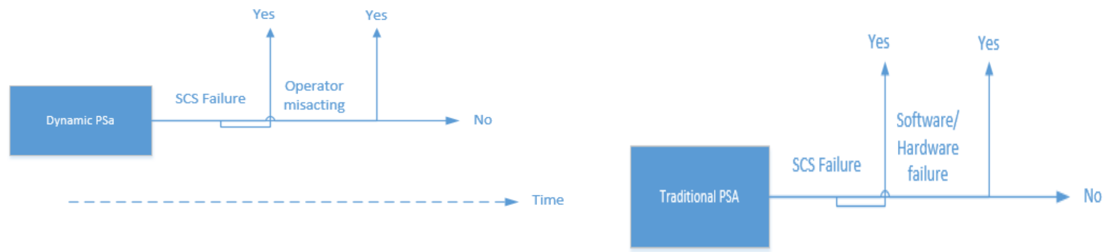


Fig 2. Schematic Dynamic Event Tree Shutdown Cooling System (SCS)

The integro-differential balance equation which accounts for the dynamic system transitions is derived from the Chapman-Kolmogorov equation to give eqn. 1

$$\frac{\partial}{\partial t} p(x,c,t) = \sum_j \frac{\partial}{dx_j}\left[xp(x,c,t)\right] + \int_{c'} W(c|c',x)\, p(x,c',t)\,dc' - \Gamma(c,x)\, p(x,c,t) \quad ..1$$

The formulation of equation 1 represents a physical system with a state vector *x(t)* at time *t*. the solution to this equation can be cumbersome but some algebraic manipulations can be done to reduce it to codable format.

III. SOLUTION DOMAIN

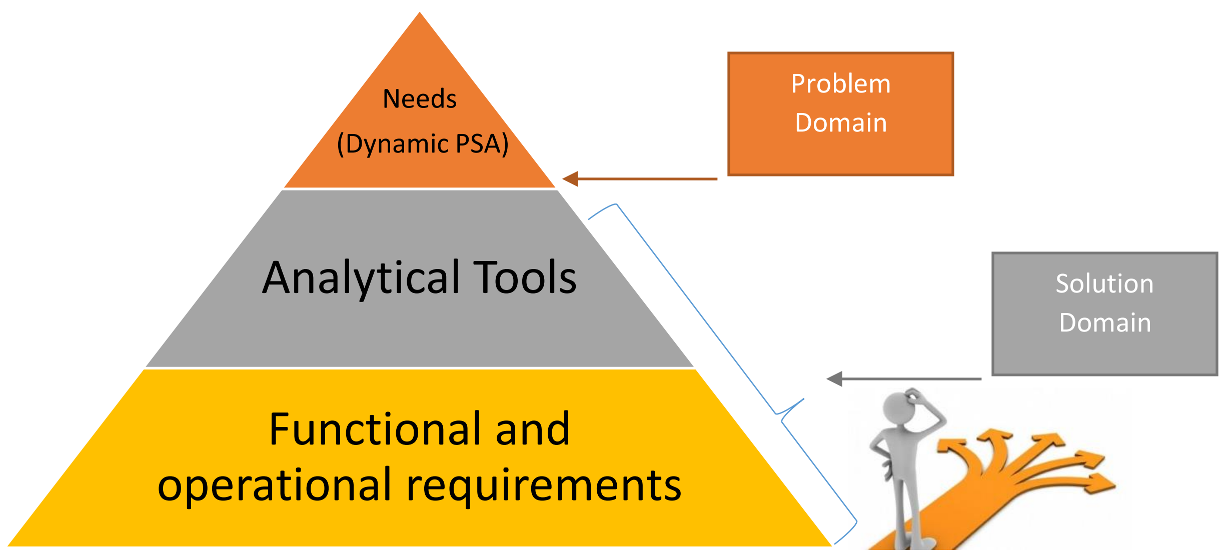


Fig. 3: systems engineering domains for DPSA

Several methods have been proposed and applied to solving the dynamic PSA problem but no standard have been set yet. However, the framework proposed in this study is that the need for dynamic PSA drives the requirement which leads to developing designs and analytical tools to meeting those needs.

a. Stakeholders needs

This varies from the viewpoint of the developers to the users. Dynamic PSA aims to study and reduce risk while providing the reliable way of operating the system. The shutdown cooling system for example must be able to provide for decay heat removal after the power plant is shutdown. The stake holders involved may include the earthquake engineer who estimates the SSE under which the plant remains operational or not, the operators, the utility company, the government and so on. This work will not elaborate on the different stakeholders. Rather the analyst who applies the tools to making the DPSA is the main technical leader of the solution domain under consideration. Thus, the state space explosion is the main need we want to meet in the DPSA hence the GPGPU computing platform is suggested and applied.

b. Analytical tools

The tools used to do DPSA includes analytical, numerical, graphical and simulation methods however, the systems to be considered must be defined and then decomposed with measureable amount of data to satisfy the failure data requirement.

i. System Identification

This work considers the shutdown cooling system as a candidate system for DPSA. Hence the initiating event which is an earthquake of certain magnitude will trigger the failure event (top event).

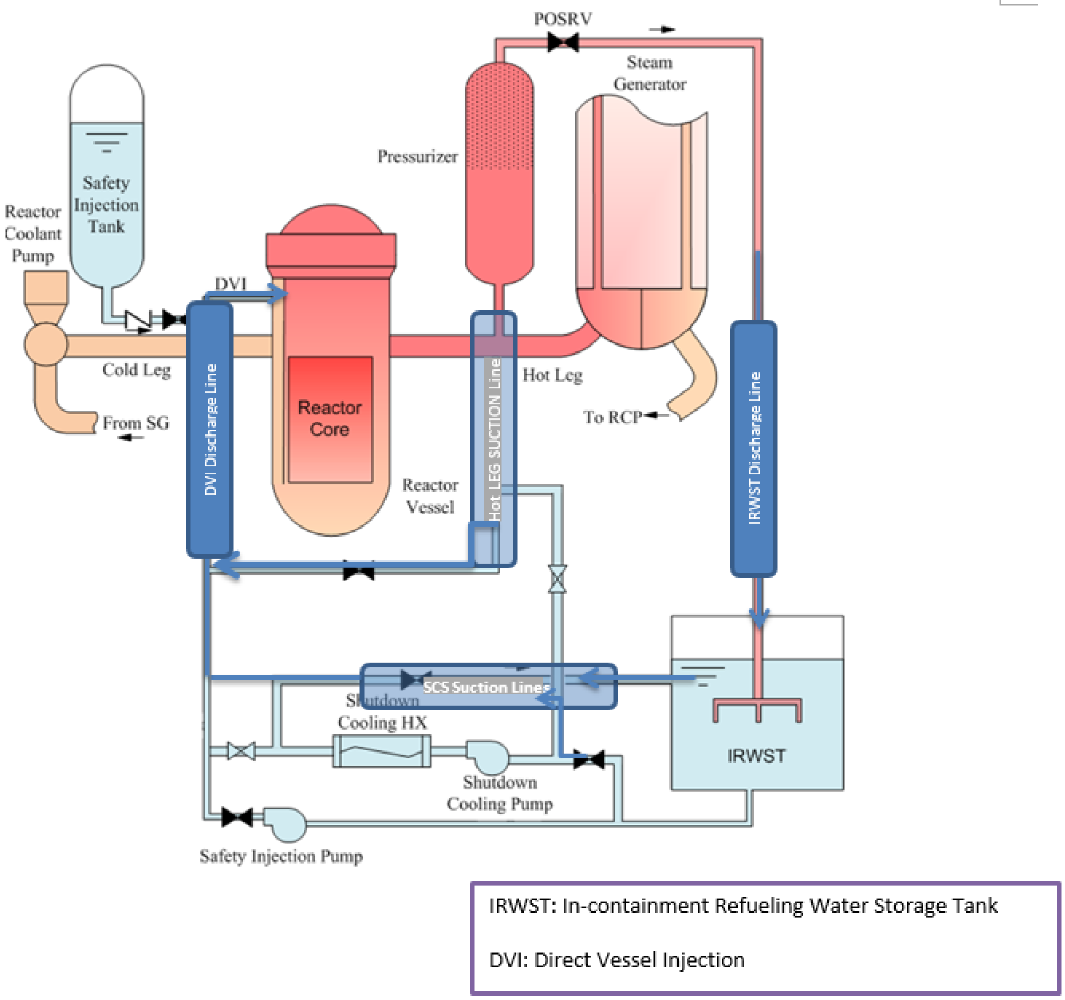


Fig. 4: Schematic SCS for APR140

In figure 3 above, during initial shutdown cooling, a portion of the reactor coolant flows out the SCS nozzles located on the reactor vessel outlet (hot leg) pipes and is circulated through the SCS heat exchangers by the SCS pumps.

The return to the Reactor Coolant System (RCS) is through SIS direct vessel injection (DVI) nozzles. For APR1400, the pressure and temperature of the RCS system varies from 450 psia (31.6 kg/cm^2 A) and 350^{0}F (176.7^{0}C) at the initiation of shutdown cooling to atmospheric pressure and 120^{0}F (48.9^{0}C) at refueling conditions [5]. The SCS suction side pressure and temperature follow RCS conditions. The discharge side pressure is higher by an amount equal to the pump head. The temperature is lower at the shutdown cooling heat exchanger outlet.

Shutdown cooling flow is measured by flow orifices installed in each train of the SCS discharge piping. The information provided is used by the operator for flow control during SCS operation. The cool down rate is controlled by adjusting flow through the heat exchangers with throttle valves on the discharge of each heat exchanger. The operator maintains a constant total SCS flow to the core by adjusting the heat exchanger bypass flow to compensate for changes in flow.

ii. Accident Initiating Event

An earthquake of the 2011 Tohoku magnitude (9.0) is considered to be the imitating event that triggers component failures in the system. For a system under earthquake, the equation 2 below give how to analyze the system reliability.

$$f = \phi(\ln(a / A_m) / B_R) \quad \ldots 2$$

Where,

f - Component failure probability under earthquake

a - peak ground acceleration level

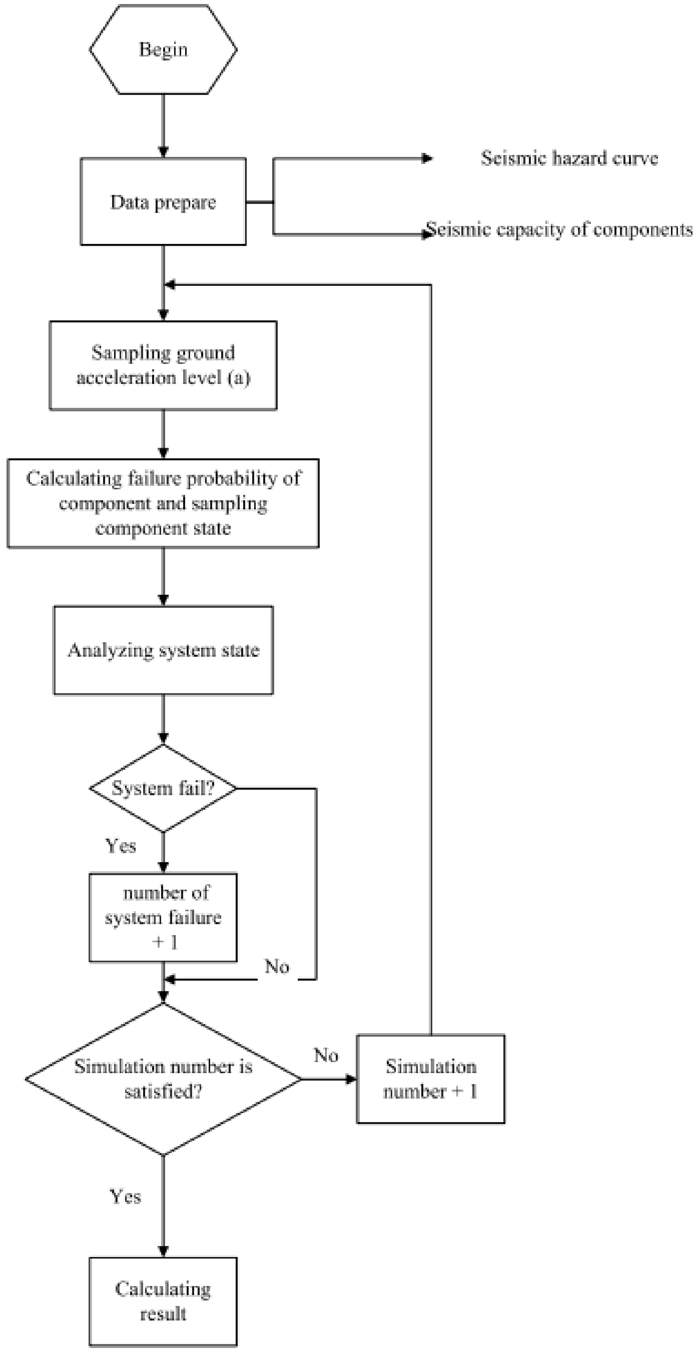
A_m - median ground acceleration capacity

B_R - randomness between earthquake and effects and

ϕ - Standard cumulative Gaussian function

c. Requirement Analysis

The multiple explosion of state variables from the decomposition of the fault tree gives much computational load but Monte Carlo method has been adopted to solve this problem in part using the flow chart adopted from [6].



IV. RESULT

…to be updated

V. CONCLUSION

… to be updated

VI. **ACKKNOWLEDGEMENT**

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VII. **REFERENCES**

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