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Risk Informed Validation Framework for External Flooding Scenario

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ABSTRACT

Safety of nuclear plants against external flooding has gained significant attention following the accident at Fukushima Daiichi nuclear power station. In United States, Oyster Creek nuclear plant was safely shutdown when high storm surge during hurricane Sandy caused a potential flooding threat. Subsequently, the nuclear energy industry experienced a significant activity in Probabilistic Risk Assessment (PRA) for external flooding. Increasingly, methods of computational fluid dynamics including advanced simulation codes are being considered to evaluate the sequence of events during different scenarios of flooding at a plant. One of the key limitations in the use of advanced codes for external flooding is related to a lack of credibility of such simulations. The motivation of this study is to develop a formal validation approach that provides a basis to quantify credibility of risk assessments that are based on advanced simulation codes. In this paper, we take a simple synthetic example to evaluate the applicability of the proposed framework to validation of flooding PRA scenario.

INTRODUCTION

In recent years, flooding at nuclear power plants (NPP) has increased emphasis on considering advanced simulation codes to evaluate the vulnerability of nuclear plants. Absence of a complete and sufficient verification and validation (V&V) of advanced simulation codes results in adoption of greater uncertainty by experts in risk informed evaluations which in turn leads to conservative assumptions. Past experience has shown that such conservative assumptions in the context of safety assessment for other external hazards such as seismic have resulted in highly over-designed nuclear power plant systems and excessively high costs. Therefore, it is quite important that various uncertainties in this process are appropriately identified and included through formal uncertainty quantification (UQ). A robust framework for verification and validation is needed to not only include uncertainties but also to formalize the confidence in predictions of PRA studies that are based on advanced simulations.

The concept of developing formal strategies for verification, validation, and uncertainty quantification (VVUQ) is not new in nuclear power plant safety applications and a few different frameworks already exist. The widely used frameworks are (i) Code Scaling, Applicability, and Uncertainty methodology (Boyack et al., 1990), (ii) Evaluation Model Development and Assessment Process (U.S. Nuclear Regulatory Commission and Regulatory Guide 1.203, 2005), (iii) Predictive Capability Maturity Model (Louis Oberkampf et al., 2007), and (iv) Predictive Capability Maturity Quantification (Athe, 2018). Each of these methodologies have certain specific aspects that are quite powerful and yet none of them can be directly extended to a risk consistent approach for validation particularly in the context of flooding PRA.

In this study, we propose a new approach to VVUQ engrained in performance-based probabilistic risk assessment. This methodology employs a probabilistic index to quantify the degree of validation within the context of uncertainty (Kwag et al., 2018). In this framework, Fault trees and Event tree for system level performance are mapped into a Bayesian Network (BN) that allows formal propagation of uncertainty at component-level validation to assess the degree of validation at system-level. The framework uses Bayesian inference for identifying the risk-consistent events along a critical path and evaluates the need for additional validation that may be required. Identification of critical path from a validation standpoint within a risk-informed framework in this approach provides a basis for improving the overall validation through identification of specific events along the critical path. The overall validation can be improved either by enhancing the simulation models of components along the critical path or by collecting additional validation data until the adequacy of the system level validation is satisfied. The proposed methodology serves as a vehicle to enable clarity, consistency, and completeness of the risk informed validation framework for external flooding. In this study, a synthetic flooding scenario is used as case study to allow a preliminary interrogation of the proposed framework.

VALIDATION METRIC – OVERLAPPING COEFFICIENT

The entire framework is based on the definition of an overlapping coefficient that is used as the validation index to quantify the degree of validation within the context of uncertainty. Overlapping coefficient (OC) is simply defined as the percentage of overlapping area between two probability density curves (Figure 1) and is given by Eq. (1). OC ranges from 0 to 1. A value of equal to zero represents complete disagreement between the probabilistic distributions of any quantity as calculated from the simulation and the experiments. On the contrary, a value of 1 represents a perfect agreement within the context of uncertainty.

$$OC = \int_{R_n} \min(f_1(x), f_2(x))dx \tag{1}$$

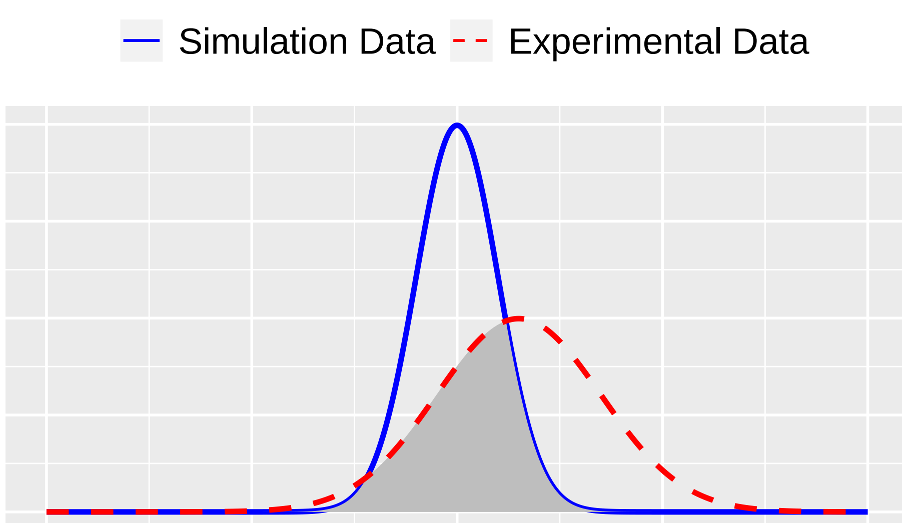

Figure 1. Overlapping Coefficient

RISK INFORMED VALIDATION FRAMEWORK

The framework employs two key stages that are described below. The complete framework is illustrated through the flowchart in Figure 2.

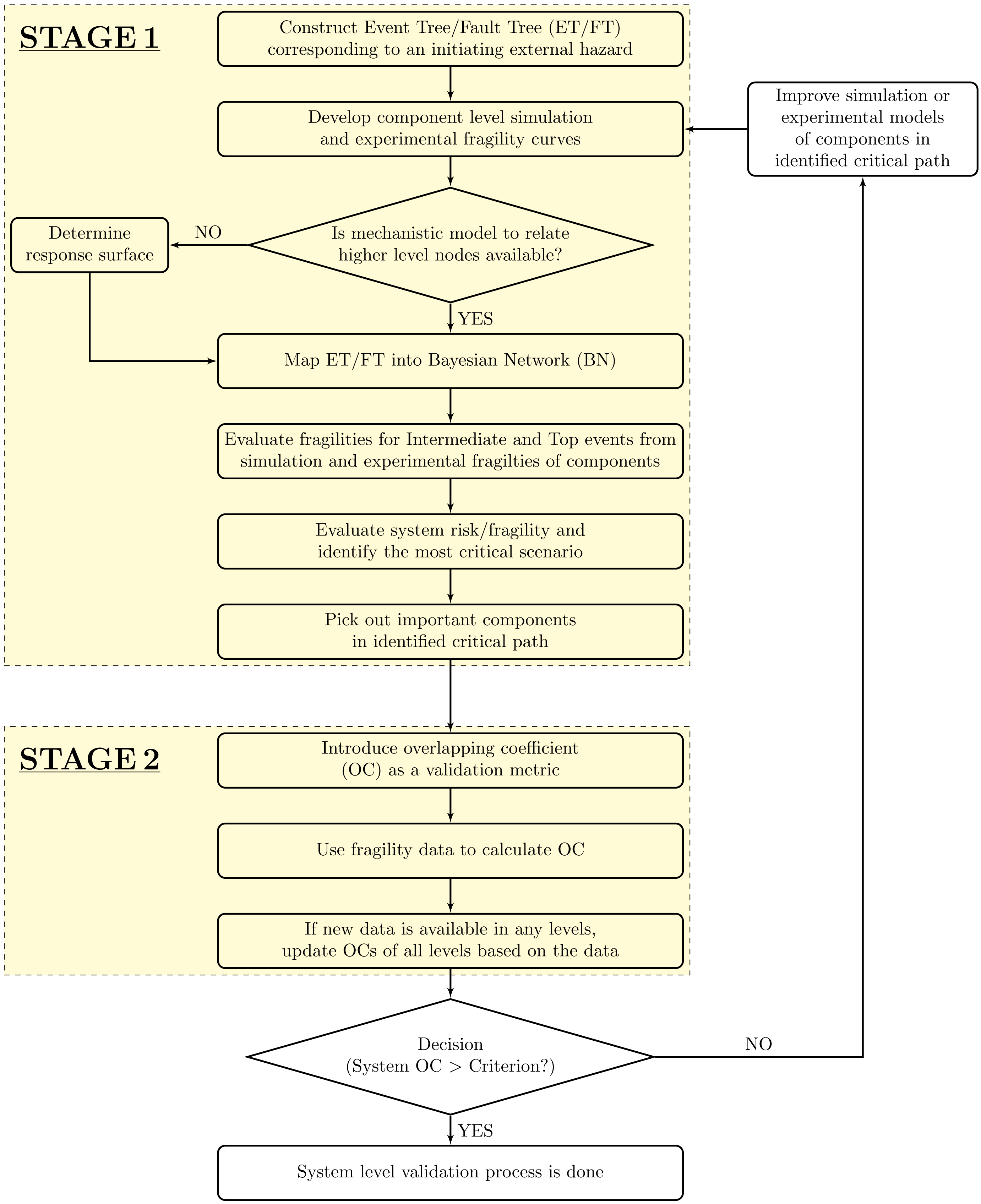

Figure 2. Flowchart of Proposed Validation Framework

STAGE 1

- Develop an event tree to represent all possible accident scenarios resulting from an initiating external flood hazard.
- Construct required fault trees to obtain the failure probability of top events in the event tree.
- Develop simulation and experimental fragility curves for all the basic events. In general, fragility assessment requires use of a Monte Carlo approach to include uncertainties from various sources. However, if sufficient knowledge base has been developed then one can make use of the standard lognormal fragility parameters.
- Develop response surfaces between the basic events and intermediate events especially if a mechanistic relationship is not directly known.
- Map the event tree and fault trees into a Bayesian network.
- Evaluate system fragility by propagating the simulation fragility information from basic events through the Bayesian network.
- Identify critical events with respect to system vulnerability.

STAGE 2

- Calculate overlapping coefficient based on simulation and experimental fragility curves.
- At this stage if new data becomes available, update overlapping coefficients.

DECISION

- Compare system level overlapping coefficient with a predefined acceptance criterion.
- If the adequacy of system level validation is not satisfied collect more experimental data or improve simulation models of the identified critical events.

ILLUSTRATION OF FLOODING CASE STUDY

In this section, we illustrate the application of the proposed framework to a synthetic example of a simplistic flooding scenario. The synthetic example is shown in Figure 3 and the scenario begins with an external flooding event caused by a storm surge. The floodwall protecting the plant can either fail or be overtopped due to the storm surge. In either case, it leads to flooding at the plant. This is known as Landscape flooding. When the landscape starts overflowing, the vent at the diesel generator (DG) room can break and be overtopped. Failure of vent will eventually lead to flooding of the DG room and failure of the DG. For simplicity, we consider the accident sequence up to the DG failure. Next, we connect the individually validated events through the PRA informed validation framework proposed in this study.

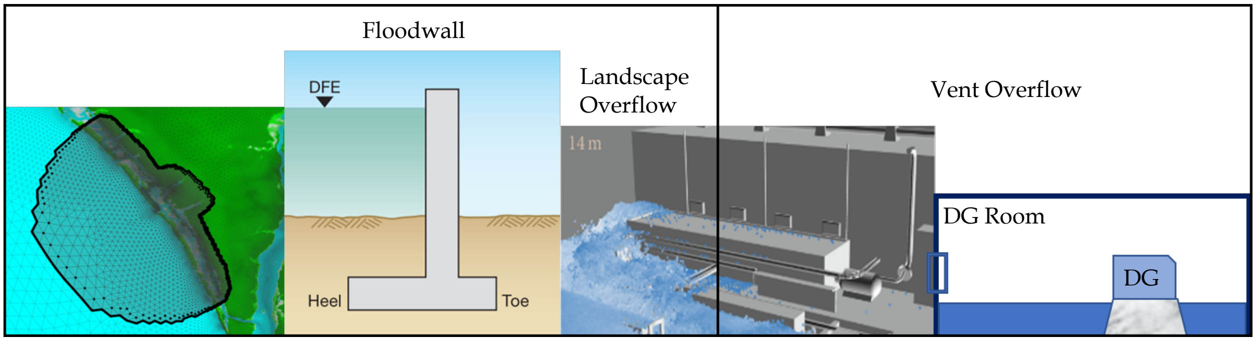

Figure 3. Accident sequence layout of Synthetic Example

Event Tree / Fault Tree Logic

The event tree resulting from this synthetic example is shown in Figure 4, and includes the following top events: Initiating Event, Protective Floodwall, Protective Vent, and Onsite AC Power.

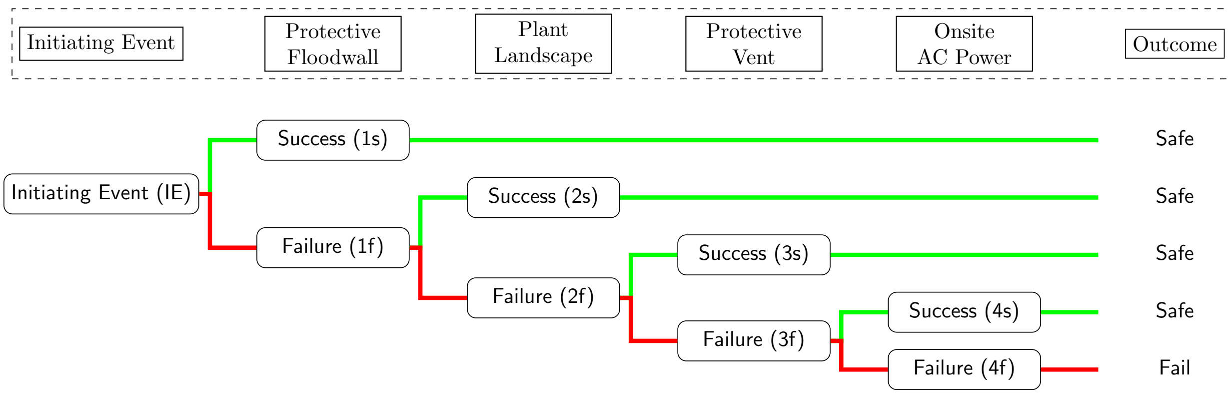

Figure 4. Event Tree logic for the synthetic example

Fragility Estimates

Development of simulation-based fragility models for the top events mentioned in section Event Tree / Fault Tree Logic can be either a finite element (FE) or a smoothed-particle hydrodynamic (SPH) analysis (Bodda, 2018; Dinh et al., 2015; Lin, 2019; Prescott et al., 2015; Smith et al., 2014). In this study, the intensity measure for the initiating event is storm surge height. Therefore, all the fragility models need to be developed based on the surge height for risk calculation. Moreover, in a PRA informed validation framework as we propagate fragilities from basic events to intermediate-level events, the intensity measure must be same for all the events. However, the intensity measure for the flooding fragility analysis of individual events can be different. For example, the water level in the DG room depends on the flood elevation over the vent. Similarly, the landscape flooding inundation depends on the height of the water over the floodwall which in turn depends on the surge height. In order to have same intensity measure for all the events, it requires interaction between different models, software, and domains.

Table 1: Simulation and Data-driven fragility parameters

TOP EVENT	*Simulation Fragility*		*Data-driven Fragility*	
	Median, $\hat{\lambda}$ (ft.)	**SD**, β_{AU}	**Median**, $\hat{\lambda}$ (ft.)	**SD**, β_{AU}
1. Floodwall Failure	1.9	0.20	1.7	0.30
2. Landscape Flooding	2.0	0.20	1.6	0.35
3. Vent Overflow	2.2	0.15	2.3	0.25
4. DG Failure	3.9	0.20	3.1	0.35

Critical Events

In this study, the critical events are obtained based on simulation models. When we propagate fragilities through the Bayesian network, the end state fragilities are governed by the DG Failure event as shown in Figure 5 and the reason is explained as follows. The end state fragility is simply obtained by multiplying all the top event fragilities. As seen in Figure 5, the simulation fragility of DG Failure event starts around a storm surge height of 2.5 ft and the rest all events reach a failure probability of 1 around this surge height. Therefore, when the end state simulation fragility is computed, the DG Failure event nullifies the effect of all other events.

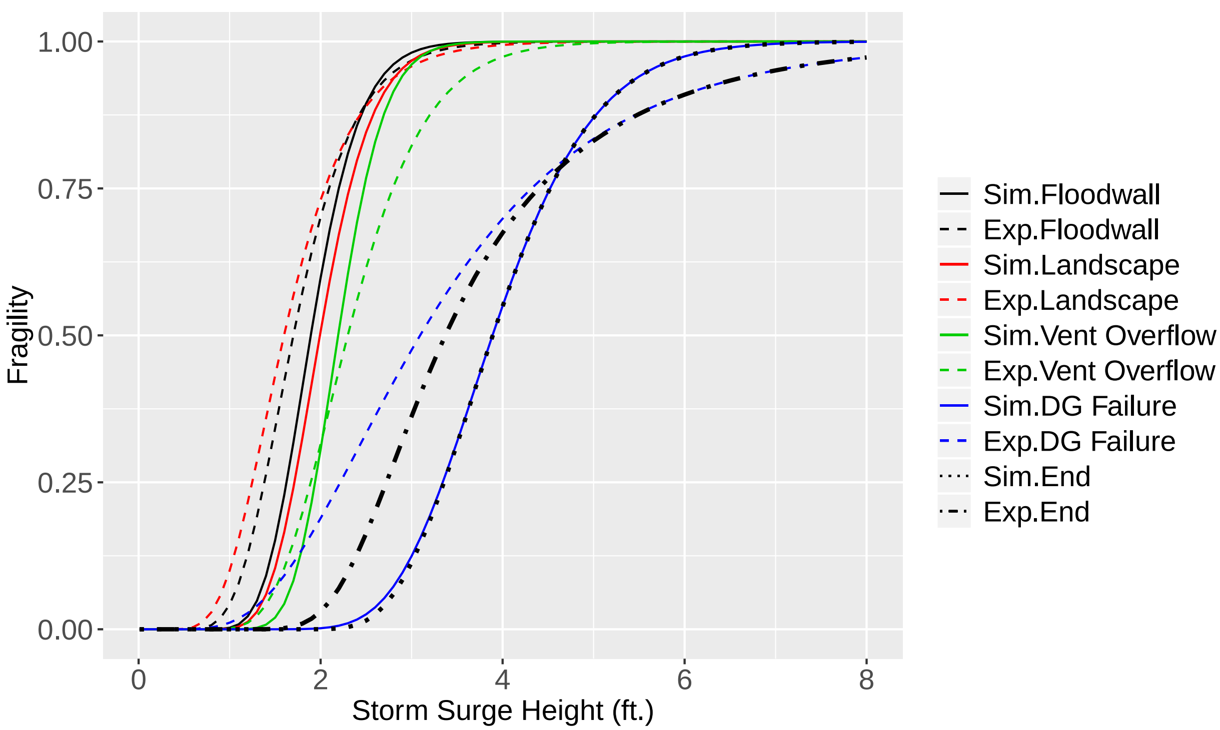

Figure 5. Simulation and Experimental (median) fragility curves

Validation Metric

In the next step, overlapping coefficient is calculated for all the top events as shown in Table 2. The OC for the system level has a mean of 59% which would be unacceptable if an acceptance criterion of 75% is adopted. Therefore, the overall validation has to be improved either by enhancing the simulation model or collecting additional experimental/field data for the DG Failure event until the adequacy of the system level validation is satisfied.

Table 2: Validation Metric of all Top Events and System level

TOP EVENT	**Overlapping Coefficient**
1. Floodwall Failure	71.86 %
2. Landscape Flooding	60.06 %
3. Vent Overflow	63.67 %
4. DG Failure	50.04 %
System Level (End State)	58.55 %

Additional Data – Updating

In this study, we assume additional field data is collected for the DG Failure event. The additional data is given in terms of failure rate as shown in Table 3. Based on this new information, the experimental fragility curves and the subsequent OCs are updated using Bayesian inference (NIMBLE Development Team, 2019). The updated value of OC for the DG Failure event is 71.40% and the OC for the system level is 75.1%. Therefore, the validation of DG Failure event has improved due to the additional data and thereby improving the overall system level validation.

Table 3: Additional Failure data for DG Failure event

Surge Height (ft.)	**No. of Failures**	**Total Test Cases**
3	5	50
4	28	50
5	45	50
6	49	50

SUMMARY AND CONCLUSIONS

This paper presents a novel approach to quantitatively assess the system level validation by connecting individual validation events through a PRA informed validation framework. Event tree and fault trees are constructed for the system level performance, and they are mapped into a Bayesian network that allows propagation of fragility information from component level to system level. In this study, the system level validation and the identification of critical events are evaluated based on fragility estimates. To improve the overall validation, we either enhance the simulation models of events along the critical path or collect additional field data until the adequacy of the system level validation is satisfied. This process helps in allocating the resources efficiently thereby reducing the effort to conduct high fidelity simulations and large-scale experiments. The robustness of the proposed framework is illustrated by enabling clarity, consistency, and completeness for a synthetic example of a simplistic flooding scenario.

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