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Conditional Tree Reduction in the ADAPT Framework

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INTRODUCTION

Probabilistic Risk Assessment (PRA) uses fault tree/event tree analysis to evaluate the environmental impacts of nuclear power plants due to internal or external initiating events. In a fault tree, basic failure events are assembled using primarily AND/OR logic to determine the combinations of failures that lead to failure of the system as a whole. An event tree is forward-facing, and begins with a single initiating event. From there the analysis considers what event may occur next, and branches out among the possible configurations of occurrence and non-occurrence of that event. This branching continues until end states are reached. End states may include a safe and stable configuration of the plant, or any number of differing failure states. Both fault and event trees require basic event probabilities as inputs to provide insight on the likelihood of different outcomes.

PRA has been applied to nuclear power plants as an analysis tool since the 1975 Reactor Safety Study [1]. In a traditional PRA, the order of events is prescribed by the analyst and each event is typically a binary aleatory uncertainty: occurrence or non-occurrence. Discrete dynamic event tree (DDET) analysis [2] eliminates this subjectivity in ordering of events by using the output of a dynamic system model (simulator) to inform the branching. Branching conditions are triggered by the existence of a relevant plant state in the code, and therefore only occur as physically appropriate. The DDET approach also allows consideration of both epistemic and aleatory uncertainties on a phenomenologically and stochastically consistent platform.

A DDET may be orders of magnitude larger than a traditional event tree for the same initiating event, as more of the uncertainty space is likely to be explored and the tree does not require manual assembly. Because of the size, manual inspection of the entire DDET is often infeasible. This problem may be approached from the front by reducing the number of sampled branching values or by online pruning of the tree, thus reducing the total number of branches. Two such approaches are discussed in References [3] and [4, 5]. Utilizing post-processing techniques to draw actionable insights via clustering has also been proposed [6, 7].

One post-processing tool to reduce the DDET according to user-defined rules has been recently implemented in the Analysis of Dynamic Accident Progression Trees (ADAPT) DDET driver code [8, 9]. The tool creates a "slice" of the DDET comprised of the set of branches that meet a set of user-input rules, for immediate visualization or for further calculations conditional on the rules being met. This extension is expected to ease analysis of the results of large and complex DDETs, leading to greater applicability of DDETs in PRA.

BACKGROUND

ADAPT was developed jointly by Sandia National Laboratories and The Ohio State University and has been used with nuclear power plant safety codes such as MELCOR [10], RELAP-5 [11], MAAP4 [12], and SAS4A [13]. It is designed with maximum flexibility in mind, and may be linked with any code that meets a simple set of requirements. These requirements are common among DDET driver codes, namely: to stop when a branching condition is reached, to indicate the branching condition that caused the stoppage, and to restart from that point with changed parameters. ADAPT comprises two long-running processes: *adapt-server*, which waits for and run branches, and *adapt-webmin*, which is a web interface from which the user may create or interrogate a DDET. Both processes connect to a central database, which stores information about branches and the overall DDET.

Depending on the number of branching conditions and values, the number of branches may grow very large. Each binary branching decision, if it occurs once and only once in every branch, doubles the number of end states. It is not uncommon to finish a tree with tens of thousands of end states, and hundreds of thousands of intermediate branches. This leads to difficulties for the analyst in visually inspecting the tree, as it is far too large to view in its entirety.

A sample DDET involving an interfacing system loss of coolant accident (ISLOCA) modeled in MELCOR and controlled with ADAPT is used to demonstrate the newly-developed tree reduction feature [14]. An ISLOCA is a possible incident in a nuclear power plant where a relatively low-pressure system is exposed to high pressures by errant or malicious opening of valves. It may result in immediate leaking of radioactive primary system water past the walls meant to contain it. If the condition persists, it may lead to failure of the low-pressure system as well as significant loss of primary cooling water and overheating of the nuclear fuel.

The demonstration case features a small number of branching conditions which represent uncertainty in how the incident will progress. Two distinct ISLOCA conditions may occur independently of each other, either failure in the low-pressure safety injection (LPSI) and/or residual heat removal (RHR) system. Each of these events, if it does occur, faces further uncertainty in the timing of its inception. Additionally, the high-pressure safety injection (HPSI) and LPSI system may or may not function due to internal failures or human actions. This DDET results in 120 end states, which is small enough to evaluate visually. Its reduction will serve as an example of the methodology.

DESCRIPTION OF WORK

The slicing tool was built into the ADAPT web interface and depends on simulator outputs and heritage information being available for each branch. Three tasks were required to implement the tool: output data processing, database manipulation, and finally rule-checking logic.

Output Data Processing

Each branch in ADAPT is controlled by a script known as a "wrapper" (see Figure 1), which runs the simulator and records the result to the database. The final required action in the wrapper is to determine any new branches that may be required and add them to the queue. Commands may be added at arbitrary points in the wrapper to accomplish post-processing or storage reduction tasks. A snippet of code is run to retrieve simulator outputs in the proper format for the slicing tool. The code required will differ depending on the simulator being used.

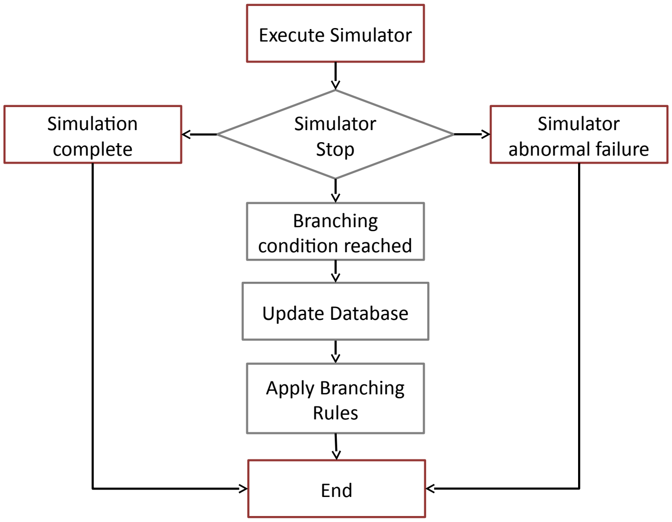


Fig. 1: Simplified ADAPT Wrapper Structure

Database Manipulation

When taking a slice of a DDET, a copy of the DDET is created. This is done within the ADAPT database, and proceeds from the initial branch to end states, preserving heritage and probabilities. Copying the target DDET allows greater manipulation of the sliced tree and recalculation of probabilities conditional on the slicing rules if desired. Three tables are updated. First, a new experiment is added to the "experiments" table with a description indicating it is a copy. The branches are copied next, and proceed iteratively by generation. This is to preserve the heritage of branches and thus the shape of the DDET. Finally, each job is copied in order to locate output data files associated with each branch. The files from the original DDET are referenced rather than copied to minimize the impact on storage space required, as a large DDET may require terabytes of storage.

A slice of a DDET may be manipulated in the database and viewed in the web interface in the same way as its parent. This includes updating the probability of the root branch as well as conditional probabilities of branching conditions. These probabilities may have changed given that the conditions in the slicing tool are met. ADAPT includes a tool named *adapt-fixprob*, which propagates new overall probabilities through the DDET entries in the database based on updated branching probabilities.

Rule-Checking Logic

When building a sliced DDET the user first chooses a DDET to examine from among those that have finished running. A complete copy is created, to be trimmed later in the process. Next, "rules" are created, which are comprised of the 6 Fields shown in Table I. A set of sample input is also shown in Table I.

TABLE I: Required Input & Sample Input for Rules

Input Field	Sample Input
Name	*Low primary pressure early*
File	*plot_CVH-P_520*
Parameter Value	*8 MPa*
Parameter Operator	*2*
Time Value	*3600 s*
Time Operator	*2*

Using the sample rule in Table I, ADAPT will expect the file "plot_CVH-P_520" to exist in each branch directory and to have two columns which give simulation time and value. Parameter Operator and Time Operator types, given in Table II, define whether the plotted simulator data must be greater than, less than, or equal to the rule value in order to pass. The sample rule is satisfied if at any time less than 3,600s there is a pressure value less than 8MPa. It is anticipated that Parameter Operator 3 and Time Operator 3 in Table II will be used only where a parameter has discrete values or when the data plotting time interval is prescribed, respectively.

TABLE II: Parameter and Time Operator Values for Rules

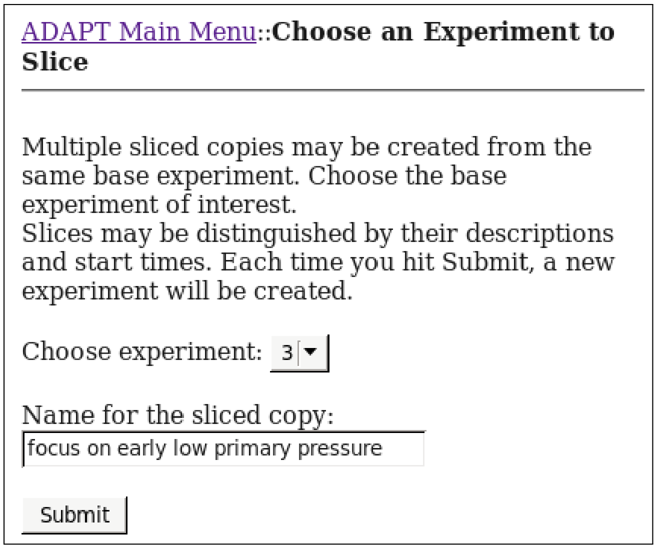
Operator	Intent
1	Plot value greater than rule value
2	Plot value less than rule value
3	Plot value equal to rule value

Once all rules are entered, the DDET is searched for end states. These are identified by finding branches that are finished and are not listed as parent branches. The heritage of each end state is identified by following parentage until the root branch is reached. An outer loop is performed over all end states, and an inner loop is performed over all rules. For each end state and rule, data is assembled by reading the file specified by the rule for all branches from the root to the end state and combining the values in order. Next, the data is searched for entries within the relevant time period that meet the rule. If any entries are found, the end state passes the rule.

All branches are initially marked to delete, and a branch that does not include a time step relevant to a rule is considered to have failed that rule. This is important to note in cases where the simulation may end early due to certain conditions being met. After every rule has been evaluated, the end state and all intermediate branches are marked to keep if all rules were passed. Once all end states have been evaluated, branches that are still marked for deletion are removed, creating the sliced DDET.

RESULTS

Two slices are taken of the sample DDET to demonstrate the new feature in ADAPT. The first uses the sample rule described in Table I. At the first step in the process, shown in Figure 2, a base experiment is chosen and a copy is created. The next step is purely informative, telling the user the experiment number and description of the copy. The third step in the user interface is shown in Figure 3, and allows the user to enter all parameters associated with a rule. This rule results in only those scenarios with an early ISLOCA and disabled HPSI being retained. The final step in the user interface, whose results are partially shown in Figure 4, describes the effects of the rules, including a list of branches that were removed. Figure 4 does not show the state of all branches, for purposes of space. At this point the copied experiment exists in a queryable form in the ADAPT database. In this case, the DDET was reduced from 151 branches to 36, and from 120 end states to 24 end states. The resulting branches represented $1.6 * 10^{-11}$ of all problem likelihood, normalized to the initiating event probabbility.

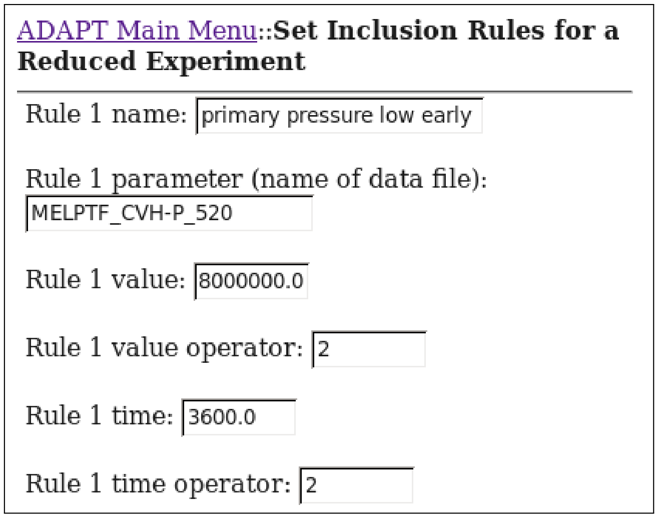

ADAPT Main Menu::**Choose an Experiment to Slice**

Multiple sliced copies may be created from the same base experiment. Choose the base experiment of interest.
Slices may be distinguished by their descriptions and start times. Each time you hit Submit, a new experiment will be created.

Choose experiment: 3

Name for the sliced copy:
focus on early low primary pressure

Fig. 2: Experiment Copy Interface


ADAPT Main Menu::**Set Inclusion Rules for a Reduced Experiment**

Rule 1 name: primary pressure low early

Rule 1 parameter (name of data file):
MELPTF_CVH-P_520

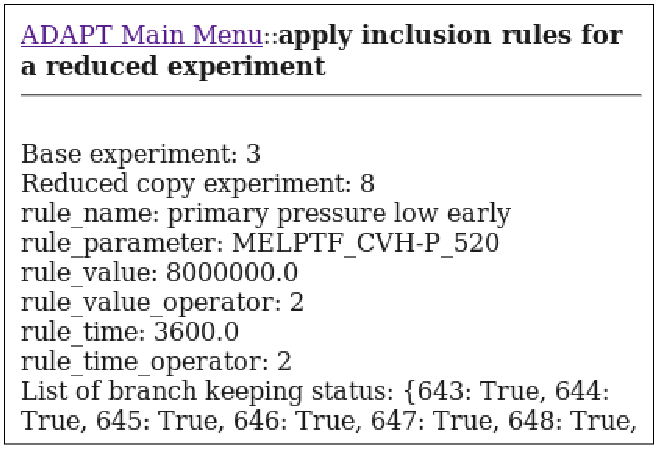
Rule 1 value: 8000000.0

Rule 1 value operator: 2

Rule 1 time: 3600.0

Rule 1 time operator: 2

Fig. 3: Rule Entry Interface


ADAPT Main Menu::**apply inclusion rules for a reduced experiment**

Base experiment: 3
Reduced copy experiment: 8
rule_name: primary pressure low early
rule_parameter: MELPTF_CVH-P_520
rule_value: 8000000.0
rule_value_operator: 2
rule_time: 3600.0
rule_time_operator: 2
List of branch keeping status: {643: True, 644: True, 645: True, 646: True, 647: True, 648: True,

Fig. 4: Slicing Results

The next set of rules was based on the plant state near the end of the scenario, and is described in Table III. Rule 1 focuses on hydrogen generation, which is an indication that the core has become uncovered and fuel has been damaged. This rule is satisfied if hydrogen production occurs before 3 hours after the start of the scenario. The second rule is based on the amount of radioactive cesium that has escaped to the environment. This rule is satisfied if a release has occurred 7 hours into the scenario. Because releases do not have a path back into the plant from the environment, this rule will be satisfied even if the release occurred early in the scenario. The release of radioactive cesium may be used as a rough indication of the offsite consequences of the scenario, and does not necessarily correlate to the amount of core damage. Only 47 branches passed both of these rules, corresponding to 29 end states. These were generally end states where the HPSI system failed, LPSI ISLOCA occurred early, and RHR ISLOCA occurred late or did not occur at all. The resulting branches represented 10^{-7} of all problem likelihood, again normalized to the initiating event probability.

CONCLUSION

A new feature of the ADAPT DDET driver code was described, which takes slices of a DDET based on user-input rules. The tool returns a tree conditional on all rules, which may be viewed and numerically interrogated in the same way as the original tree. An example case was given in which a DDET of an ISLOCA scenario induced by a cyber failure comprised 120 end states and 151 total branches. This was reduced in two separate slices to 24 and 29 end states, respectively. Calculations related to results and probabilities

TABLE III: Two Additional Slicing Rules

Input Field	Rule	Value
Name	1	*Early hydrogen production*
File	1	*MELPTF_COR-DMH2-TOT*
Parameter Value	1	*10.0 kg*
Parameter Operator	1	*1*
Time Value	1	*10800 s*
Time Operator	1	*2*
Name	2	*Late cesium release*
File	2	*MELPTF_CFVALU_9032*
Parameter Value	2	*0.01 kg*
Parameter Operator	2	*1*
Time Value	2	*25200 s*
Time Operator	2	*1*

may be performed on these slices in an identical manner to the overall DDET. This technique will simplify the analysis of complex DDETs by empowering the analyst to interrogate a narrow section of the DDET.

NOMENCLATURE

ADAPT	Analysis of Dynamic Accident Progression Trees
DDET	Discrete Dynamic Event Tree
HPSI	High Pressure Safety Injection System
ISLOCA	Interfacing System Loss of Coolant Accident
LPSI	Low Pressure Safety Injection System
PRA	Probabilistic Risk Assessment
RHR	Residual Heat Removal System

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