

A Visualization Technique for Dynamic Probabilistic Risk Assessment

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Abstract: Dynamic Probabilistic Risk Assessment (PRA) is an advanced methodology for risk assessment that uses a computational process to generate a large number of possible scenarios corresponding to the evolution of a system’s state in response to an initiating event. Each scenario consists of a series of possible branches that span the time between the initiating event and either a set ending time or the occurrence of system consequences, such as core damage in a nuclear power plant. Each branch corresponds to the occurrence of a particular stochastic event, and may be a part of multiple different scenarios. The scenarios (consisting of a series of branches) can all be connected in the form of a tree, which functions similarly to a conventional event tree in conventional PRA event tree analysis. However, the event tree constructed from scenarios generated in dynamic PRA, is typically much larger, including scenarios that are difficult to model using conventional PRA methods. These scenarios include physics dependent events, complex dependencies, or variable event times or orders. Part of the value of a conventional event tree is the structure of the tree itself, but since event trees constructed with dynamic PRA methods are significantly larger and more complex, it is challenging to visualize the event tree. This work develops a method to automatically generate graphical event trees from dynamic PRA simulation data. The trees include relevant system dynamics information, as well as depict the scenarios that have been visited and possible branches that were not visited due to the high computational cost of generating scenarios. Visualization of these trees allows for a qualitative analysis of the dynamic PRA analysis that generated the scenarios, and improves the usefulness of dynamic PRA results.

1. INTRODUCTION

Dynamic Probabilistic Risk Assessment (PRA) is an approach to estimate the risk associated with the operation of a variety of engineering systems including nuclear power plants, maritime ships, and space systems [3–5]. Dynamic PRA methods differ from more conventional PRA methods in that they utilize a computational process to generate a substantial number of scenarios, rather than a manual, peer-reviewed process that generates scenarios. Each scenario corresponds to a postulated series of stochastic events and corresponding system dynamics that have the potential to lead to system failure and the occurrence of some negative consequences. In conventional PRA, it is reasonable to create visual depictions of the generated scenarios and their relationships, often using event trees. In dynamic PRA, however, the number of generated scenarios is greatly increased due to the use of a computational method for scenario generation. This makes it incredibly challenging to manually depict all the possible scenarios using an event tree. An example view of part of an event tree is shown in Figure 1. Figure 1 only depicts a small portion of the generated scenarios and is

already nearly unusable due to the amount of information presented. To address this limitation, this paper describes an automated event tree visualization technique designed for dynamic PRA data. The visualization technique is demonstrated using a simple tank system from the dynamic PRA literature [2, 6, 8]. The tank system is analyzed using a sampling based method for dynamic PRA called the Exploratory Nuclear Tree Sampler (ENTS) [7].

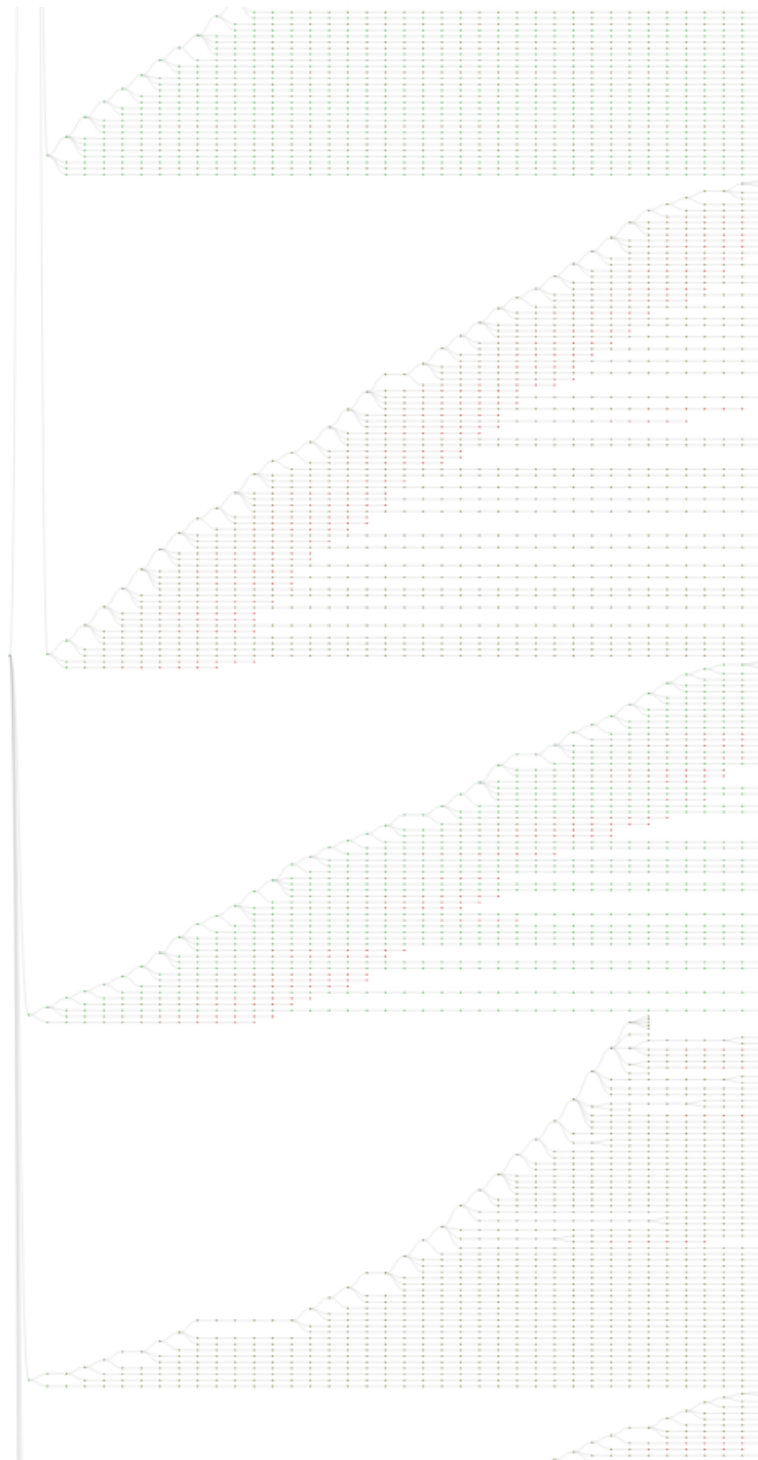


Figure 1: Example Segment of Automatically Generated Event Tree

ENTS uses constant length discrete time steps to evaluate the system dynamics. Stochastic events, such as component failures, are allowed to occur at the beginning of each time step. At each time step, a possible stochastic event is sampled. ENTS is distinct from other sampling-based methods in how this sampling is achieved, using a proposal probability distribution calculated using information from prior generated scenarios (more details can be found in [7]). This corresponds to the occurrence of a possible branch of a given node. Branches are depicted as arrows in Figure 2, and each node occurs at a decision point (e.g. Decision Point A in Figure 2), depicted as dots. Branches describe the physical evolution of the system state over each time step, and nodes describe the system state including stochastic events at the bounds of each time step. For a sufficiently small time step, this process directly emulates the complete evolution of the system dynamics over time. The node stores the system state information at a particular place in time conditioned on any parent branches and nodes. When the process of sampling and simulating new branches reaches either a condition corresponding to system failure (e.g. core damage in a nuclear power plant) or a maximum scenario time (corresponding to a scenario with no system failure), a complete scenario has been sampled. The process of generating scenarios is repeated until an acceptable level of uncertainty in the overall risk estimate is obtained (i.e. the risk estimate is converged).

A representative, manually generated event tree as would be generated by ENTS is shown in Figure 2. This depiction does not show any of the nodes (i.e. decision points) that are included in the corresponding dynamic PRA analysis, nor any of the branches. Instead, this tree is easier to understand because of its smaller size and representative nature when compared to the actual tree shown in Figure 1.

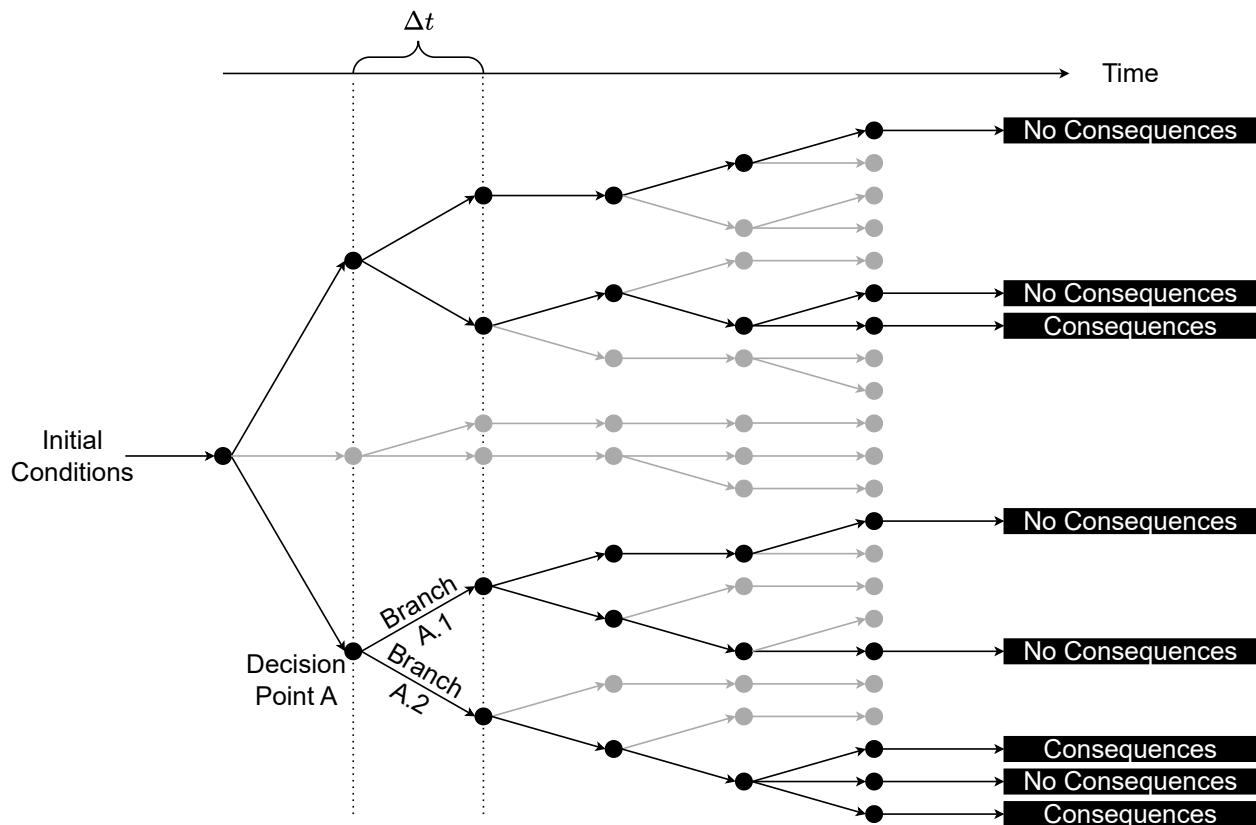


Figure 2: Manually Created Event Tree [7]

2. VISUALIZATION TOOL DESIGN

Dynamic PRA data includes system dynamics information, such as physical variables describing the physical conditions inside the system, as well as information about the stochastic component of the system state. Both categories of information are of interest in a risk analysis, but most important is the stochastic state information. This information should therefore be presented as directly as possible, to ensure its usability. Because a dynamic PRA analysis typically generates such a large number of possible scenarios, the amount of information to be presented is significant. System dynamics information is of interest in a dynamic PRA analysis, so its display is also required. This information is potentially high-dimensional and complex, so its display is more challenging.

The visualization technique developed in this paper establishes a data pipeline that transforms dynamic PRA data into an interactive visualization in the form of the underlying generated event tree. When dynamic PRA is conducted using the ENTS approach, the scenario space of interest is explored following an implicitly defined event tree [7]. This pipeline preserves everything about the original event tree, including the data in all the nodes, the relationships between all the nodes and the physical information at each node, enabling visualization of the complex tree structure. In order to present the information about the stochastic part of the system state, as noted previously, the technique generates a large event tree depiction of the scenarios explored during a given dynamic PRA analysis. This depiction works in the same way as a conventional event tree, but is significantly larger (see Figure 1 for example). To ensure the entire event tree can be viewed, zoom and pan features are developed so analysts can inspect the entire tree at once or focus on particular areas of interest. In addition to the zoom and pan features, the event tree can be optionally only drawn to an analyst-specified depth, and then later selectively expanded. This allows the created view to be specifically focused on only those areas of interest to the analyst. Information about the system's physical state is retained and presented in pop-ups and using color grading. When general trends about physical state information are of interest, such as which scenarios tend to lead to large changes in physical variables, the color of the nodes in the event tree figure is altered to highlight the physical variable of interest. Specific values of physical variables are accessible on hover over the node(s) of interest, shown in a pop-up with all the numerical information used to depict each node.

The input data for the event tree figure is generated by the ENTS dynamic PRA approach and is stored in nested Python objects. These objects are stored in the form of pickled files for asynchronous access later, so it is not necessary to run an entire dynamic PRA to generate figures. The pickled files are unpickled using the built-in Python utility, and then converted into JSON objects. Each event tree view presented in this paper corresponds to a single JSON object generated by recursively iterating through the original pickled Python objects and creating a single unified figure. The JSON objects are converted into the figure using a Javascript utility called d3.js or simply d3 [1]. D3 produces the final interactive figure as an HTML web page that can be accessed locally through a web browser.

3. CASE STUDY

To demonstrate the visualization technique developed in this paper, a case study system from the dynamic PRA literature [2, 6, 8] is analyzed using a sampling-based dynamic PRA methodology. The case study system consists of a tank with three valves, a level controller, and a heater. The system is depicted in Figure 3. The objective of the system is to maintain a level of water within the tank between 4m and 10m above the bottom while also ensuring that the temperature of the water remains below 100°C. The valves are subject to random failures with temperature-dependent failure rates, possibly becoming stuck open or stuck closed. When a valve fails, it is unable to be repaired, and remains stuck until the end of the scenario. It is assumed that only one valve failure can occur at each time step, reducing the number of branches that

must be considered at each node. This assumption is reasonable if the time step is small enough, because the probability of any single failure is small, so the joint probability of multiple simultaneous failures becomes negligible. The level controller is assumed to be perfectly reliable, although it does not have access to information about the possible failures of the valves, only the level of the water. The heater provides energy at a constant rate to the water within the tank. Additional details about the system and its dynamics are given in refs. [6] and [7].

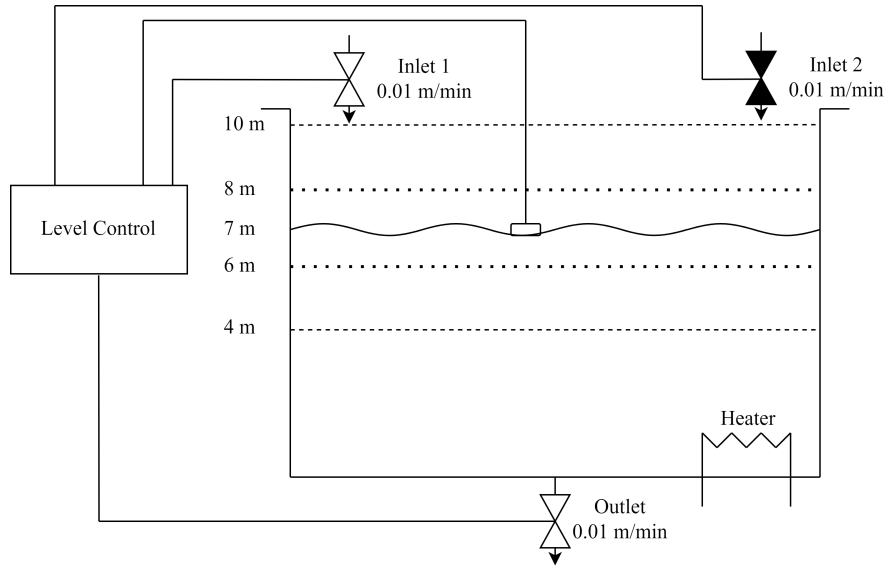


Figure 3: Heated Tank System

The dynamic PRA methodology used to analyze the tank system is the Exploratory Nuclear Tree Sampler (ENTS) approach [7]. This method is based on sampling, and utilizes importance sampling to reduce the computational cost of the analysis. A detailed presentation of such analysis and the corresponding results is given in ref. [7], and is summarized below. The probability of the fluid level in the tank falling below 4m or exceeding 10m or the bulk temperature of the water exceeding 100°C is approximately 5.4×10^{-3} . Assuming the consequences have a value of 1 if any failure condition occurs, the risk is equal to 5.4×10^{-3} system failures per initiating event. The ENTS method (with nominal hyperparameters) generates approximately 5500 unique scenarios that should be included in an event tree depiction of the analysis. Each of these scenarios was generated with a time step of 30 minutes and a maximum time of 1200 minutes, corresponding to a maximum depth of the tree of 40 nodes. A total of approximately 82 thousand nodes are generated as a part of this relatively small scale dynamic PRA analysis.

4. RESULTS AND DISCUSSION

Because it is assumed that there are no simultaneous failure events, the root node of the tree has precisely seven branches and corresponding child nodes. Six of these branches correspond to the occurrence of one of the possible valve failure modes (e.g. Inlet 1 stuck open, Inlet 1 stuck closed, Inlet 2 stuck open, etc.), and one branch corresponds to no failure occurring at that time. This means that if the dynamic PRA analysis included only one time step, there would be a maximum of seven scenarios that would be included in the event tree. Since the analysis conducted includes 40 time steps, and if a valve fails it cannot be repaired, there are significantly more possible scenarios that might be included in the event tree. A segment of the event tree generated in the analysis of the tank system is shown in Figure 4. The main focus of this view is

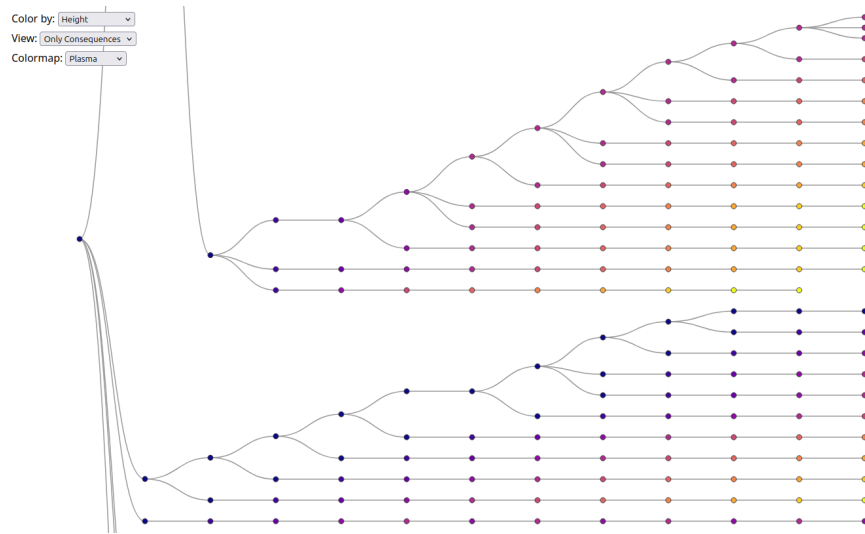


Figure 4: Visualized Event Tree

on the root node and the first 12 time steps.

Figure 4 also shows a set of drop down menus that allow the user to select three possible options for the visualization. The first (“Color by”) selects what variable is used to determine the color of the nodes in the depicted event tree. In Figure 4, the selected option “Height” corresponds to the height of the fluid in the tank. As the height deviates from its nominal value of 7m, the color becomes increasingly different. The specific colors used are determined by the final drop down menu, “Color map”. The second (“View”) allows the user to see either nodes corresponding to scenarios that lead to consequences only or to see all nodes included in the event tree. This filtering option makes navigating the space of risk-important scenarios easier, since filtering out the majority of scenarios (which do not lead to consequences) allows the analysis to focus on those scenarios which may be important for risk management or other risk-informed activities. The third and final drop down, as mentioned previously, is “Colormap”. This option allows the user to select from a set of different coloring schemes to make the event tree easier to see and use. For example, a color scale from green to red representing heights close to 7m and heights close to 4m or 10m may be more challenging to use in certain applications, so other options are given. In this work, all the views use the Plasma color scale which uses dark purple to represent nominal values and moves through red to orange to yellow as values move further from nominal. Other options include red-green, Viridis (purple through green to yellow), and Inferno (black through red, orange, and yellow). There is no functional difference between the color scales, but they improve usability and accessibility of the generated views.

4.1. Feature: Navigation

As discussed in Section 1 and as can be seen in Figure 1, the whole generated event tree is extremely large. In order to improve usability and make the individual nodes more visible, a zoom and pan feature is developed. This allows the user to focus on particular sections of the generated event tree and look at nearby portions easily. In the context of the case study presented in Section 3, this is critical because of the geometry of the generated event tree. The number of time steps included in each scenario (40) and the number of generated scenarios (5500), relating to the branching behavior of the system’s stochastic state evolution discussed previously, result in a generated event tree that is very tall (dimension corresponding to scenarios) relative to its length (dimension corresponding to time steps). Navigating this event tree is challenging without the ability to zoom and pan.

A section of the generated event tree is shown in Figure 4. This section is truncated in both the dimension corresponding to scenarios as well as the time dimension. The truncation in the time dimension is done to allow the analysis to focus on the first few time steps, and the truncation in the dimension corresponding to scenarios is necessary to see the actual nodes. In contrast to the section shown in Figure 1, this section is much easier to see due to the increased zoom. The ability to zoom and pan would allow for an analyst to consider both the section shown as well as some alternate pathways not seen in Figure 4. For example, starting from the leftmost node, there are a number of possible branches, and Figure 4 focuses primarily on one of these branches. It may be of interest to inspect the other possibilities in detail, and it is easy to pan over to the relevant portion of the event tree.

4.2. Feature: Expansion

In addition to the navigational features described in Section 4.1, the event tree visualization tool developed in this work includes an expand/collapse feature that allows for a targeted exploration of possible scenarios forward in time. Since the event tree view is truncated in the time dimension to focus on the first few time steps, there may be relevant information about the system performance that is not immediately visible. For the tank case study, it is possible that some of the scenarios correspond to the occurrence of consequences due to system dynamics and/or stochastic events that occur late in time. These events and dynamics are not displayed in the initial, truncated view.

To see branches and nodes that follow any node displayed in the event tree, the analyst can click on the relevant node (generally one of the nodes at the extreme right of the diagram) and all branches conditioned on the selected node's occurrence are displayed. These branches along with the relevant nodes are now included in the diagram. This expansion behavior can be seen in Figure 5. Figure 4 shows the first few time steps of scenarios, colored by height, and filtered to show only scenarios with consequences. It can be seen that several of the scenarios shown do not lead to consequences within the first time steps, based on the color map. Selecting one of these nodes reveals that there are many scenarios that do lead to consequences, but that the system dynamics do not approach the failure condition until the later time steps.

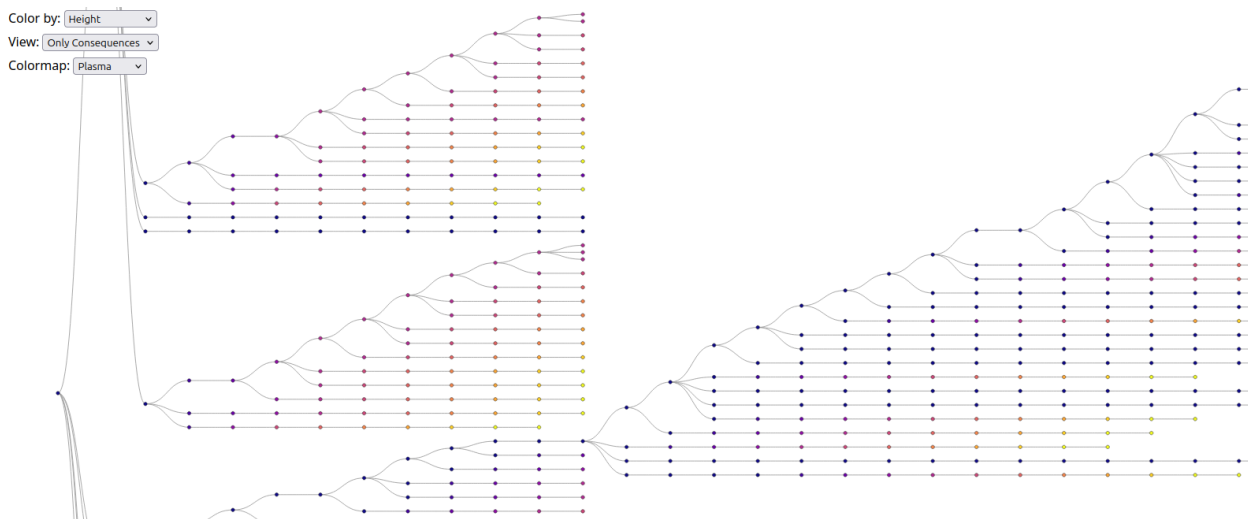


Figure 5: Expansion of Scenario(s) of Interest

4.3. Feature: Color Gradient

A critical part of dynamic PRA analysis is the simulation of system dynamics. The information generated in this portion of the analysis can be of great value to the overall risk assessment, and is preserved in the pickled Python objects used as inputs to the visualization tool developed in this work. System dynamics information is also preserved in the transformation of the pickled Python objects into the JSON object used to draw the event tree. The system dynamics information is included in two ways, this section will discuss the first and Section 4.4 will discuss the second. The first way system dynamics information is included and presented in the generated event tree views is with color grading on the drawn nodes. In the context of the tank case study, for example, nodes whose height is approaching the safety bounds (i.e. 4m or 10m) should have a color that is substantially different from the nodes where the height is close to nominal (7m). This allows an analyst to quickly see which nodes are near to failure, and to use that information for other purposes. In the tank case study there are only two physical variables, namely height and temperature, and color grading can be used to visualize either. Color grading can also be used to visualize the other variables stored in each node. For example, the number of visits to a node gives an indication as to how important that node was determined to be by the ENTS approach to dynamic PRA. Nodes with more visits are potentially more important because they are more often sampled. The color gradient function in the tool developed in this work can also be used to visualize this information across the whole tree.

An example of the color gradient can be seen in Figure 4, although it is included in all the figures in this paper. In Figure 4, the scenarios which end with yellow nodes are scenarios that quickly result in consequences. This assessment is based on the fact that those scenarios include nodes which are colored yellow close to the initial node, since their height is depicted as quickly deviating from 7m. It should be noted that all the scenarios shown in Figure 4 eventually lead to consequences, but the scenarios described above have system dynamics leading to failure very quickly, so they are colored yellow while other scenarios leading to failure are not. These other scenarios will have nodes colored yellow later in their progression (see the discussion in Section 4.2 for more information).

4.4. Feature: Node Hover

The color gradient described previously is useful for qualitatively understanding the trajectories of physical variables over time during the scenarios shown in the event tree, but more specific information may be of interest for analysis. For example, near-miss scenarios, or scenarios where consequences almost occur but do not may be of interest from a risk-informed design perspective, since they can inform design improvements in future iterations. Such scenarios may be easily avoided by small design changes. Near-misses may also be of interest from a regulatory perspective, since the simulation of system dynamics is imperfect, and the initial conditions of the reactor are uncertain, near-miss scenarios in a dynamic PRA analysis may correspond to scenarios that lead to consequences in an actual accident situation. In the context of this case study, it is possible that the height of the fluid reaches close to 10m, but remains below 10m. The color gradient would indicate that the height is very far from the nominal value, but it may be challenging to determine if it leads to consequences using the color only.

To allow a more quantitative and in-depth analysis of the specific system state at each node, all the simulated information generated during the initial dynamic PRA analysis is preserved and saved as a part of the visualization. Hovering over a node reveals additional information about the node (see Figure 6), including the actual values of the physical variables (in this case height and temperature), and other information, specifically the internal name of the node, total accumulated reward, total accumulated visits, and the number of unexplored child nodes (ghost children). The internal name of the node is arbitrary, but can be used to locate specific scenarios within the overall event tree figure. The total accumulated rewards and visits are used in

the calculation of proposal probabilities used by the ENTS approach [7] to sample branches and generate scenarios. Unexplored child nodes correspond to a “blind spot” in the exploration of the scenario space, possibly indicating that there are important scenarios not included in the risk assessment. It should be noted, however, that some ghost nodes are expected even in an analysis that is not missing any important scenarios because the ENTS approach is based on sampling, and only a finite number of scenarios are sampled, so it is likely some scenarios are missed. Based on the properties of the ENTS approach, namely its biased sampling of scenarios with high likelihood and high consequences, it is expected that these missed scenarios are not high-risk [7].

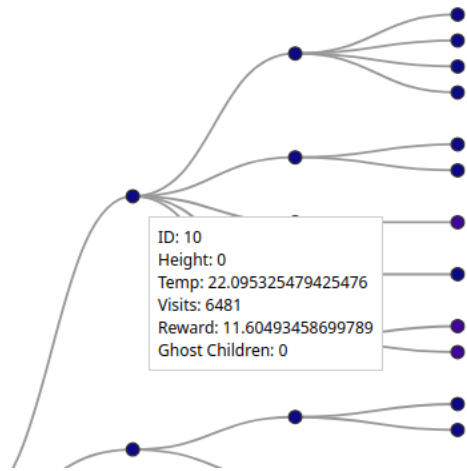


Figure 6: Information Displayed on Hover

5. CONCLUSIONS AND FUTURE WORK

This paper develops a new visualization tool for dynamic PRA data that generates interactive and dynamic figures that depict the event tree generated by a dynamic PRA analysis. In this work, the dynamic PRA analysis is conducted using the ENTS approach to dynamic PRA [7]. The visualization tool incorporates zoom and pan navigation, selective expansion of nodes and scenarios of interest, color grading by system dynamics variables or dynamic PRA analysis variables, and pop ups that show detailed information about each node. This allows an analyst to directly inspect the outputs from a dynamic PRA analysis and make informed decisions.

Because the tool developed in this work utilizes a data pipeline that converts pickled Python objects into JSON format and then uses d3.js [1] to create the visualizations, the tool is currently limited to accepting inputs from ENTS only. Future work can include the adaptation of the acceptable input formats to allow other dynamic PRA tools to be used. The tool is demonstrated in this paper using only a simple tank case study system from the dynamic PRA literature, resulting in a particular geometry of the generated event tree. In their more general application, dynamic PRA methods can generate event trees with less restricted geometries. Therefore, the visualization tool in this work should be applied to analysis of other case study systems to verify its utility across other event tree geometries.

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