RISKMAN®, Celebrating 20+ Years of Excellence!

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Abstract: RISKMAN® is a PC-based, general purpose, integrated tool for quantitative risk analysis. Initiated with software programs first developed for main frames, and with development supported by a user's group spanning three continents, the PC version of RISKMAN® now celebrates more than 20 years of risk-based applications. While mostly used in the nuclear power industry and related government organizations, RISKMAN® is also used in the offshore oil industry, marine industry, aerospace, and for specialty applications such as for assessing the risks associated with the excavation and destruction of abandoned chemical weapons.

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1. INTRODUCTION

The RISKMAN® PSA software package was developed after a long history of PRA methods development and practical implementation experience in nuclear power industry, starting in the mid-1970s and carrying right through to the first version of RISKMAN® in the late 1980s. See for example such methods development papers as References [1] through [7]. The first version of RISKMAN® for use on a PC was largely a porting and integration of existing programs developed over many years for use on mainframe computers. In addition to reduction of computing costs, a key driving force of this conversion was to take advantage of computer standardization; i.e., prior to widespread use of the PC, such mainframe programs had to be tailored to each utility's computing environment.

The methodology adopted for implementation in RISKMAN® is the large event tree approach to PSA sequence modeling, sometimes called the event tree with boundary conditions approach. This approach developed from the quantitative definition of risk as a set of triplets, and of a risk analysis being the answers to the following three questions [1]:

(i) What can go wrong?
(ii) How likely is it that it will happen?
(iii) If it does happen, what are the consequences?

As in the Reactor Safety Study (WASH-1400), event trees were found to best support the development and documentation of these sets of triplets. Event trees with top events ordered temporally, along with event sequence diagrams (ESDs), were found to be useful tools to collect plant response insights so necessary for accurate PSA modeling, from plant operational staff.

The initial event trees used were relatively small, not much larger than those constructed for the Reactor Safety Study. In the years after WASH-1400, however, it was recognized that consideration of dependencies between top events in event trees was essential for accurate sequence frequency calculation. The technique for considering such dependencies in use prior to the advent of the PC, was to quantify the relatively small event trees many times, conditional on the status of earlier plant states (e.g., on the status of power at key electrical buses) and then to collect the results from each event tree state quantification. This technique evolved to become the event tree with boundary conditions approach.

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By the time that RISKMAN® was developed for the PC (~1989), it was recognized that the earlier plant states could also be represented as an event tree (i.e., a support tree) and that by linking event trees together this avoided the need for collecting results from different trees, thereby simplifying the computational procedure for accident sequence frequency quantification. As the event tree sizes grew to consider more and more detailed dependencies, in part to include the status of support systems to permit comparisons with emergency operating procedures, this technique came to be known simply as "event tree linking."

Though the emphasis is on event trees, this approach to PSA modeling still makes extensive use of fault trees. Each event tree top event is modeled by its own fault tree. These fault trees are much smaller than those developed for the fault tree-linking approach to PSA modeling precisely because the dependencies on supporting systems are separately modeled. The event tree linking approach to PSA modeling as implemented in the RISKMAN® software therefore involves the separation of the plant response into many small fault trees and to use the logic of the large, linked event trees to assemble the fault tree results for quantification of the overall sequence frequencies. To achieve this assembly, the large event trees must be constructed in such a way that the fault tree results for a given event tree top event depend only on the initiating event and the status of earlier top events in the linked events tree for a given sequence path. With this property of the event tree construction satisfied, the sequence frequencies can then be readily computed by simply multiplying the results from the smaller fault trees for each top event as applicable along each sequence path.

By this approach, each path through the linked event trees is evaluated separately and can be stored to a database of sequences for later review and interpretation. The sequence frequencies so evaluated are exclusive of each other; i.e., there is no need to logically minimize the results across many sequences to avoid double counting. Since the accident sequence frequencies can be evaluated separately and simply added to determine end state frequencies the computer memory requirements are minimal. The size of the problem that can be evaluated is then only a function of the run time needed to walk the tree, quantifying each branch whose frequency is above a user specified cutoff.

2. STANDARD MODULES

There are four standard modules in the integrated RISKMAN® software package which have all been included in the integrated package for many years. The highlights for each are discussed below:

1. Data Analysis
2. Systems Analysis
3. Fragility Analysis
4. Event tree Analysis

2.1. Data Analysis Module

The Data Analysis module, as the name suggests, is where the analyst builds a library of parameter distributions for his model. These parameters are used in the quantification of the fault tree models constructed for each event tree top event, and for initiating event frequencies. The parameters typically developed include total component failure rates (e.g., for failure to start, failure to operate), maintenance frequencies and mean times to repair, test frequencies and durations, and parameters needed for specific common cause models. Each parameter is assigned a name which is then can be referenced throughout the other modules. While modeling parameters can be specified as simple numerical constants, developing an uncertainty distribution for each allows RISKMAN® to propagate these uncertainties through system and event tree models to obtain the uncertainties in core damage frequency or other end state frequencies. To develop the model specific list of parameter distributions, the analyst may choose from a library of analytical probability distributions, or by specifying in tabular form those distributions that do not conform, to the common analytical types. By using discrete probability distributions to represent each parameter, RISKMAN® need not assume

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the form of any resulting parameter combinations. Math operations are provided to combine probability distributions in the form of equations and there is a distribution merge feature.

The Data Analysis module includes features for combining generic prior parameter distributions with plant experience data. Both single stage and two-stage Bayesian updating features [2] are available. Further, the Bayesian updating tools included allow the incorporation of repair time data to update parameters representing the mean times to repair.

The Data Analysis module has been interfaced to allow exports of data parameter distributions to Microsoft's Excel™ and imports of data from Excel™.

2.2. Systems Analysis Module

The Systems Analysis module enables the analyst to construct fault tree models to represent the failure probabilities of individual plant systems or system trains. RISKMAN® has its own fault tree graphics program (i.e., PLGFT) but also has been structured to interface with other fault tree graphic tools; i.e., such as NEL, Inc.'s NELFT and EPRI's CAFTA. Basic event unavailability equations are developed using the parameter names from the Data Analysis module.

A feature within the System Analysis module allows user's to quickly add or modify common cause groups to the fault tree graphics. This feature also writes the common cause basic event unavailability equations automatically.

A unique feature of the Systems Analysis module is its ability to model alternate initial system alignments separately, weight each by the fraction of time the alignment will occur, and then combine this information to compute time-averaged system unavailability. This approach avoids the need to delete mutually exclusive maintenance events after the fact, since only those alignments specified are included. This approach also recognizes that alignment fractions are not true basic events since they also are subject to the constraint that the alignment fractions for a system top event must add to 1.0.

The different boundary conditions imposed on the smaller fault trees representing each event tree top event are quantified separately in the Systems Analysis module. The resulting failure probabilities are referred to as split fractions. It is the split fractions whose values are multiplied along a given event tree sequence path to obtain each accident sequence frequency.

Two general quantification methods are available in RISKMAN® for split fraction quantification. Each of the two methods can compute point estimates or propagate uncertainties using Monte Carlo techniques. One uses classical minimal cutset techniques in which the rare-event or min-cut upper bound approximations are utilized. RISKMAN® also provides its own minimal cutset routine and also has licensed the Aralia, BDD based tool, for minimal cutset determination.

The second method of split fraction quantification uses the BDD approach as implemented in Aralia. The BDD approach [8] is especially accurate because it uses no probability truncation and because it makes no approximations when totaling the contributors to the split fraction unavailability. It also treats NOT logic exactly. While application of BDDs methods to large fault tree-linking is not now feasible due to their great size, its application to the smaller RISKMAN® style fault trees is very effective.

Another unique feature available in the Systems Analysis module is the quantification of system fault trees for initiating event frequencies; i.e., frequencies per year rather than conditional probabilities of system failure in response to a plant trip. The method used is similar to that suggested in Reference [9]. It allows for consideration of recovery by approximating the repair times. See also Reference [10]. This method uses the system fault trees as normally constructed and simply requires some added input for the normally operating equipment specific for the system initiating event frequency calculation.

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The system initiating event frequencies and split fraction results are then used in the Event Tree Analysis module to quantify the accident sequence frequencies.

2.3. Fragility Analysis Module

The Fragility Analysis module is primarily used for earthquake risk calculations. The same approach can be used for other external hazards (e.g., such as for high winds). The module accepts as input the standard lognormal fragility parameters [4] and computes for each initiator range defined by the analyst the conditional component failure probabilities. The earthquake initiating event frequencies are also computed from tables of hazard exceedance curves. Both point estimate and uncertainty results are provided.

The Fragility Analysis module may be thought of as a supplement to the Systems Analysis module in that it too is producing initiating event frequencies and split fraction values for use in the Event Tree Analysis module. Seismic pre-trees are often used in order to incorporate earthquake related failure modes with other random, failure modes that are not influenced by the earthquake. The seismic pre-trees accounts for different combinations of seismic failure modes without double counting the contributions from such failures. This approach allows seismic failure probabilities to be readily integrated with random failure models for internal events without requiring modeling approximations to reduce the size of the models.

2.4. Event Tree Analysis Module

The Event Tree Analysis module enables the analysts to construct and link large event trees for each initiating event considered. The event tree structure is developed graphically. The event tree top events used are consistent with those defined in the System Analysis module. An event tree structure transfer feature combined with event tree linking enables the development of almost unlimited numbers of sequences for quantification. Logic rules are defined by the analyst to symbolically assign split fractions to the branching nodes of the tree structure and end states to each quantified sequence. This avoids the need to manually make these assignments, an approach which is not feasible for large models.

During individual sequence frequency quantification, the linked event trees are walked, multiplying the initiating event frequency and the success and failure branch split fractions to obtain the overall sequence frequency. A frequency cutoff is checked at each event tree branch to determine if further development of the current path is warranted. Only sequences walked from beginning to end are fully quantified and included in the end state totals.

Key features of the Event Tree Analysis module are:

- The number of sequences is limited only by the total run time.
- The number of top events in the linked event trees may be 500.
- Hundreds of end states may be computed in one quantification pass.
- The total frequency truncated is computed exactly so that convergence may be demonstrated mathematically.

The Event Tree Analysis module provides dozens of reports to help analysts interpret the results. The most basic of these reports is a listing of ranked sequences to a particular sequence group. The sequence groups can be defined in terms of initiating events, end states, and even logical combinations of top event states; e.g., a sequence group may be defined for all core damage sequences with failure of reactor trip. The model is not changed to define these groups, which makes it easy to add, delete, or modify the sequence groups as the need arises.

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The ranked sequences can be displayed in English using the user supplied descriptions for each top event, or the sequences can be displayed with the split fraction values for each path. For additional understanding, everything known about a single sequence path and its quantification can be displayed; i.e. the single sequence detailed report.

All commonly used importance measures (e.g., Fussel-Vesely, RAW, etc.) are presented and for different levels of the model; i.e., for basic events, components, fragility components, split fractions, top events, alignments, systems, and initiating events. Importance contributions from initiator fault trees are calculated directly as part of the basic event and component importance measures.

A particularly powerful feature of RISKMAN®'s importance calculations is that they are performed relative to a sequence group as opposed to a single end state like core damage. Recall that the sequences quantified by RISKMAN® are mutually exclusive and need not be minimized for a single end state. Many sequence groups may be defined for quantification of a batch of initiators and the importance measures are then computed for each of these sequence groups.

The sequence representations in RISKMAN® consider both failure and success states of all preceding events making them uniquely suitable for modeling dependencies between human error events. The ability to quantify hundreds of end states in one quantification pass also makes RISKMAN® well-suited for level 2 and Level 3 analyses.

2.5. Sequence Frequency Quantification

Figure 1 illustrates how the four standard modules are combined to develop and quantify an event tree style PSA model as implemented in RISKMAN®. The modeling parameters are developed in the Data Analysis module and made available to the Systems Analysis module. The Systems Analysis module uses these modeling parameters to quantify fault tree models for each event tree top event. System initiator frequencies are also developed in the Systems Analysis module. Human error rates are developed outside of RISKMAN® and then imported for use in the Data and Systems Analysis modules. Outputs from the Systems and Fragility Analysis modules are then input for use in the Event Tree Analysis module. Point estimate and uncertainties for each end state and sequence group are then quantified within the Event Tree Analysis module. Importance measures, including those from earthquake fragilities, are also developed in the Event Tree Analysis module.

The large event tree-linking approach to sequence modeling can be used to demonstrate the convergence as a function of truncation cutoffs on the computed sequence group frequencies. It is easily extended for earthquake and other external hazards. Such models can also be easily extended for Level 2 calculations (i.e., the determination of many release category frequencies) by linking the Level 1 models to an event tree representing the response of containment to severe accidents. Multiple state top events may also be modeled, not just binary states, making RISKMAN® especially well suited for modeling low power and shutdown events that involve many plant configurations and long periods of maintenance; i.e. regimes where the rare event approximation breaks down. RISKMAN® can be used to compute expected risk (i.e., consequence weighted end states) and importance measures with respect to expected risk; e.g., for plant unavailability and capacity factor analysis.

3. ADVANCED FEATURES

Section 2 describes the standard modules of RISKMAN® that were developed many years ago. This section summarizes features that have been added to RISKMAN® since the conversion to the Windows operating systems; i.e., since about 2000.

3.1. BDD Quantification

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The BDD approach [8] was touched on briefly in Section 2.2. The inclusion of a BDD approach to top event split fraction quantification greatly increased the speed and accuracy of the results generated by the Systems Analysis module. Rather than solving for the minimal cutsets of the top event fault tree once and apply the alignment and split fraction boundary conditions to just the truncated list of cutsets, the BDD approach enables RISKMAN® to completely resolve the fault tree for each alignment and split fraction combination. With the BDD approach, there is no need to apply probability cutoffs and the overlap between contributors is computed exactly.

A further advantage is the BDD approach's ability to accurately treat fault trees with NOT logic. NOT logic is needed for large event tree models for proper solution of split fractions for multi-state top events. The use of multi-state top events is required when the status of each train within a multi-train system is needed for evaluation of subsequent top events. For example, a four state, multi-state top event may represent the different possible states of electric power at two safety buses. By solving the multi-state split fractions directly from a single fault tree of both trains, the earlier need to evaluate split fractions as equations of other split fraction values can be avoided; e.g., where the state of the second train is dependent on the success or failure of the first train of a two train system.

The incorporation of the BDD approach as a quantification engine for system initiators also eliminates the unwarranted use of frequency truncation for computing such initiator frequencies.

3.2. Big Red Button

This Big Red Button feature refers to an option developed for sensitivity analysis. This tool is used in the Systems Analysis module to build a series of analysis steps, selected by the user, to modify a baseline model for repeated sensitivity calculations. When the batch of steps is exercised, a new set of split fraction results is saved for later quantification in the Event Tree Analysis module. The series of steps are documented in a report and a reset button then restores the baseline model to its original state.

3.3. Mini-Monitor

Using BDD quantification for split fractions and the standard event tree sequence quantification engine, a Mini-Risk monitor tool has been added to RISKMAN®. This tool enables users to specify an event tree engine case already developed in the Event Tree Analysis module consisting of a batch of initiating events and their associated set of linked event trees, to specify a list of split fractions needed for the batch quantification of initiators, and then to modify the basic event (or components) and initiator frequencies to define different plant configurations. The final outputs for each configuration evaluation are the sequence group frequencies; e.g., core damage frequency and large early release frequency are examples of two such groups. The mini-monitor enables the analyst to specify a set of plant configurations covering a week or longer and then to calculate the risk profile for the time period of interest. When specified as a batch of configuration cases, the cumulative impacts of each configuration are considered. The mini-monitor may be set up to run a "no maintenance" model, or to use the full time-averaged models from the Systems Analysis module; i.e., where all alignments are considered. The mini-monitor then selects the minimum number of split fractions which must be recalculated to incorporate the configuration definition and then call the event tree engine to evaluate the revised sequence group totals.

3.4. Fire Scenario Screening

A fire screening tool was also developed which works similar to the mini-monitor. One key difference is that the fire scenarios are evaluated separately; i.e., the impacts from different fires are not cumulated when run in a batch. The impacts on model basic events or plant components is developed for different fire scenarios offline, and then can be read directly from a Microsoft Excel™ file to define the fire scenario cases. In this way, a batch of fire scenario cases can be quickly defined and quantified within RISKMAN® without having to modify the baseline model. Once the risk

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significant fire scenarios have been identified this reduced set can then be incorporated into the baseline model.

3.5. Big Loop Monte Carlo

Even the earliest PC-based versions of RISKMAN® contained a feature for propagating uncertainties in the data parameters through to the core damage frequency. These early versions performed the propagation in two Monte Carlo uncertainty propagation steps: 1) first by computing the uncertainties in each split fraction and initiating event frequency; and then 2) using these uncertainty distributions along with the highest frequency core damage sequences to obtain the uncertainty of core damage frequency, or for any other sequence group.

Two limitations of this early approach are that the saved sequence list needed to be very large to be robust, and it did not fully correlate the data parameter distributions used in different top events.

To address these concerns, the Big Loop Monte Carlo feature was developed. This tool allows RISKMAN® to sample from the complete set of parameter distributions, evaluate all required split fractions, and then call the event tree engine many times in order to build up a set of sequence group (i.e., core damage frequency) sample values which can then be sorted to obtain the final uncertainty distributions.

Effectively this feature builds a Monte Carlo sample loop around the entire set of calculations needed to compute the core damage frequency. Since large models may take considerable time to complete many such sample, two features enable the user to streamline the Monte Carlo calculation. One, of course, is that the frequency cutoff specified for the event tree engine can be increased to limit the number of sequences quantified for each sample to only those which are important. The second feature is that the user may limit the split fractions to be recalculated each sample to only those deemed important. For example, importance measures using the point estimate calculations may be used to identify the subset of all split fractions that are deemed important.

3.6. Automated Split Fractions and Rules

The RISKMAN® event tree-linking approach requires that each event tree top event fault tree be evaluated many times, as dictated by its unique boundary conditions, and that the logic rules for assigning these split fractions to the event tree branching nodes be developed. These two steps have been the most manually intensive of the model development steps.

Beginning with Version 12.0 of RISKMAN® for Windows, features have been added to simplify both of these steps. In the Systems Analysis module users can now identify the house events which are to be varied to define the unique split fraction boundary conditions. The split fractions for a given fault tree top event are then automatically named, their boundary condition impacts defined, and the split fractions are inserted into the module. This feature works with both simple binary top events and for multi-state top events. At the same time, a mutually exclusive set of split fraction assignment rules are automatically generated. The Event Tree Analysis module then can be accessed to insert the split fraction assignment rules and associated top event macros into the desired event trees. This new feature automates the most tedious and error prone portion of RISKMAN® model development.

4. GENERAL MODEL FEATURES

The RISKMAN® tool is an integrated software package that addresses all of the main elements of PSA: data analysis, systems analysis, external event analysis, and event sequence analysis. It was designed to be used by multiple analysts working on the same model. Import and export routines for model parts and model backup and restore features allow users to transfer data from their models and machine to a model of record. Many models can be evaluated at once, and RISKMAN® does the

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housekeeping for the analyst. A model comparison feature allows the analyst to quickly compare the elements of different models.

RISKMAN® was developed in English but has now been translated to Japanese. Program screens are available in Japanese as are report titles. Kanji can now be used in all description and comment fields.

From the beginning, the developers of RISKMAN® adopted the tenet that a full treatment of uncertainties was necessary for quantitative risk management and therefore an essential part of risk assessment. The use of discrete probability distributions allows such distributions to be combined without having to make approximations assuming the specific analytical form of the resulting distribution.

Another key tenet of RISKMAN® development has always been to interface with other, existing quantitative risk tools offering users new features when deemed most efficient. ABS Consulting is instrumental in the Open PSA international initiative to facilitate such interfaces and development collaboration. This approach allowed RISKMAN® to become the first PSA tool to incorporate BDD technology (using Arboost Technology's Aralia). Today, RISKMAN® also interfaces with NRC's SAPHIRE program, and EPRI's CAFTA program. It allows the drop-in of fault tree solver routines such as KAERI's FTREX.

For risk monitoring applications, export features permit RISKMAN® models to be used directly in Scientech's Safety Monitor™ tool and in Nuclear Engineering Limited, Inc.'s, COSMOS program. Auxiliary programs (i.e., MSCAL – Maintenance State Calculator) have also been developed to allow RISKMAN® models to be used in STP's RASCAL program for on-line maintenance monitoring.

5. SITE UTILITIES

From time to time, RISKMAN® users request new features tailored for their own needs. Usually these features are modest in scope but occasionally can be extensive. A site utility feature allows these users to access their features.

One such extensive site utility example is that of South Texas Project's Balance of Plant Performance Predictor program (BOPPP). This tool makes use of RISKMAN®'s Data and Systems Analysis modules to construct fault tree models specifically for reactor trip frequencies. Far more than just a tool for computing initiating event frequencies, this tool is designed to provide input to decision making involving plant economic performance.

Four key features were added to support this application:

1. The Data Analysis module was augmented to import raw, equipment maintenance event summaries keyed to plant tag numbers and to assist the analyst in assigning each raw event to basic events in the BOPPP models. Data parameters were then added to representing the failure modes and repair times for each basic event. BOPPP provides a batch program to perform Bayesian updates for all data according to the time interval specified by the user.

2. The basic event database was augmented to add attributes for repair times and type code events for power reduction flags, alignments, and failure modes. The raw event data is also cross-referenced to the model basic events and their associated data parameters.

3. Special fault tree quantification routines were written to evaluate the frequencies of system cutsets and to assign plant down times for each.

4. Finally, routines for computing key plant economic indicators in terms of the cutset contributions were developed. Outputs of BOPPP include: plant trip frequencies, plant

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capacity factor, expected megawatt hours lost, forced outage rate, and unplanned production loss.

6. CONCLUSION

The RISKMAN® tool addresses all of the main elements of PSA: data analysis, systems analysis, and event sequence analysis. Its large event tree linking approach to sequence modeling has permitted it to be used to tackle the most complex, highly redundant plants and those sharing cross-ties between units. It has been applied for both internal and external events, at-power and shutdown conditions, and with extensions to Level 2 and Level 3 consequence modeling. The authors contend that the approach to PSA model development, as implemented in RISKMAN® has already solved many of the issues now plaguing PSA analysts. This includes demonstrating the convergence of results despite frequency truncation and robust importance calculations including the contributions of basic events from initiating events modeled using fault trees.

The RISKMAN® Technology Group (RTG), a users' group now in its 21st year of existence continues to guide and fund the maintenance, support, and development of RISKMAN®.

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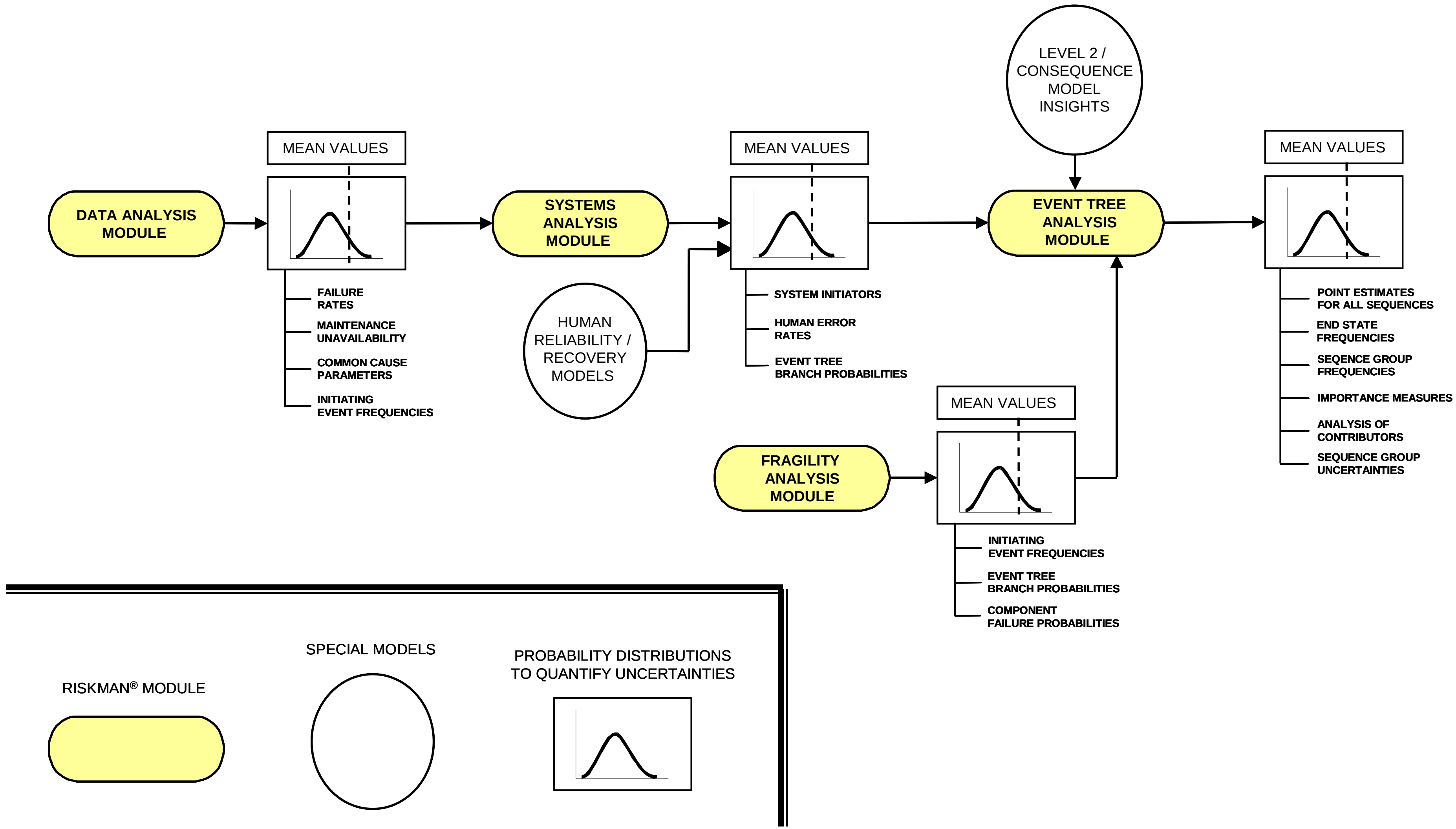
Figure 1: RISKMAN® Quantification Flow Chart



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