Chapter 7

Risk Estimation And Comparison

Chapter Contents

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RISK ESTIMATION AND COMPARISON

7

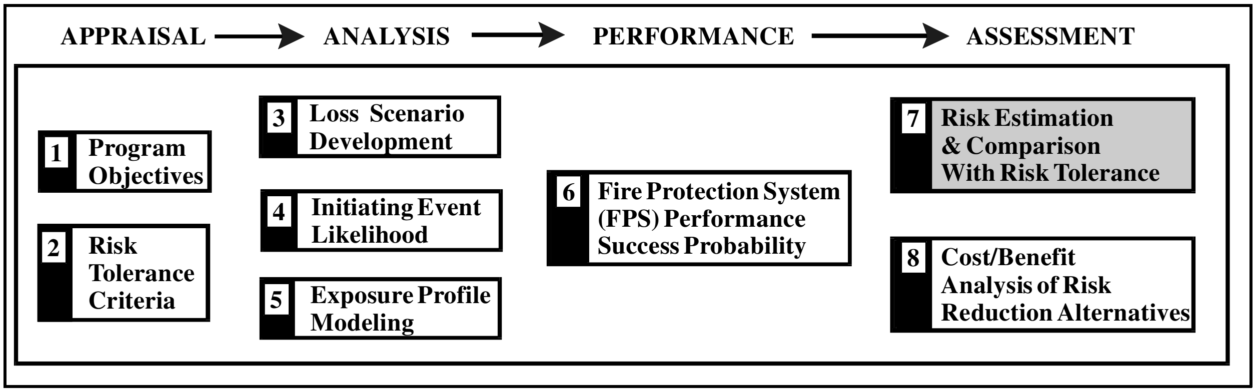
7.1 INTRODUCTION

Risk Estimation and Comparison, which is Step 7 in the Risk-Informed, Performance-Based decision making process, provides the methodology for:

- Estimating consequence levels associated with defined event tree loss scenarios in terms of an equivalent monetary value and annualized risk basis
- Comparing the estimated risk to established risk tolerance criteria to determine if risk reduction analysis (Step 8) is needed

As presented in Fig.7.1, previous Steps 4, 5, and 6 provide quantification of the initiating event likelihoods, exposure profiles, and performance success probability for fire protection systems. In Step 7, the results from these previous steps are combined to estimate potential risk levels and to provide a comparison with the risk tolerance criteria established in Step 2.

Fig. 7.1: Risk-Informed, Performance-Based Fire Protection Steps



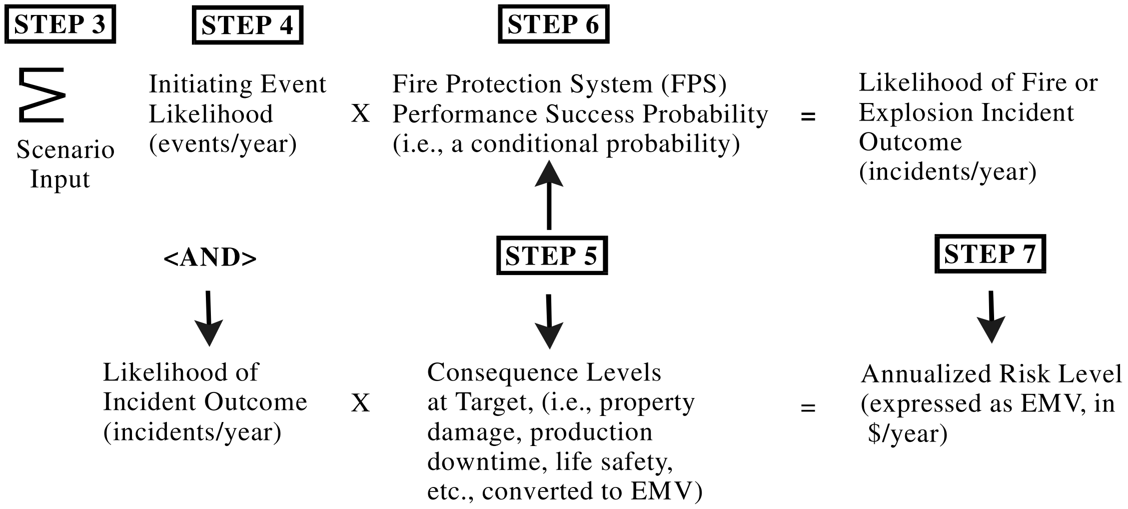
The Risk Estimation and Comparison process involves:

1. Quantifying the risk for defined event tree loss scenarios in terms of an "annualized equivalent monetary risk" (risk calculation)
2. Comparing the risk levels ($ per year) to "annualized risk tolerance limits" to determine if risk reduction is needed (risk comparison)
3. Addressing risk uncertainty issues

Section 7.2 of this chapter describes the risk estimation calculation steps using the event tree modeling framework. As part of the estimation process, the exposure levels that were developed in Step 5, Exposure Profile Modeling, are converted to equivalent monetary values. This provides a single measure of consequences that allows risk to be calculated in terms of dollars at risk per year from fire or explosion potentials. Using an equivalent monetary measure of risk also allows cost/benefit analysis to be performed on risk reduction alternatives when the decision makers risk tolerance criteria is exceeded. Section 7.3 provides examples of graphical profiles of risk comparison. Section 7.4 provides an overview of computer-assisted simulation to quantify risk uncertainty.

Risk Estimation Refresher

Risk Estimation, Step 7, provides quantification of the annualized risk levels in terms of an equivalent monetary value (EMV):



Step 4:	**Initiating Event Likelihood:**	Provides the scenario-specific initiating event, which is the initial input into the FPS performance evaluation.
Step 5:	**Exposure Profile Modeling:**	Provides a graphical profile of the fire or explosion source intensity versus distance (i.e., at the target) and time, which is a primary factor in evaluating FPS performance and estimating consequence levels.
Step 6:	**FPS Performance Success Probability:**	Based on the input from Steps 4 and 5, the conditional probability (a number between 0 and 1) of the FPS is estimated based on performance measures that include the response effectiveness, availability, and operational reliability.
Step 7:	**Risk Estimation and Comparison:**	The annualized risk level is the product of Steps 4, 5, and 6. The annualized risk is usually expressed as an EMV to allow cost/benefit analysis of risk reduction alternatives (Step 8) if the risk tolerance criteria is exceeded.

7.2 RISK CALCULATION

This section describes the risk calculation process. Figure 7.2 presents the general fire risk event tree framework with identification of the risk calculation steps. Table 7.1 summarizes the event tree information developed in previous steps.

Table 7.1: Previously Developed Event Tree Information

EVENT TREE SEGMENT	EVENT* TREE I.D.	STEP	INFORMATION
Initiating event likelihood	[A]	Developed in Step 4	Likelihood: events/year
Fire protection system (FPS) performance success probability	[B]→[E]	Developed in Step 6	Condition probability: A number between 0 and 1.0. The probability of success plus the probability of failure must equal 1.0
Exposure profile/consequence levels	[G]→[J]	Developed in Step 5	These numbers are associated with damage categories, ranges, or consequence levels
* Refer to Fig. 7.2			

The risk calculation process (identified in Fig. 7.2) includes the following steps:

① Calculation of the branch line probabilities [F]
② Estimation of the aggregate equivalent monetary values [K]
③ Calculation of the annualized risk levels [L]
④ Calculation of the total annualized risk, $/year [Total of L]

7.2.1 Branch Line Probabilities

The branch line probabilities illustrated in Fig.7.3 are the product of the initiating event likelihood [A] and the conditional probabilities of FPS performance [B] → [E]. For example, for branch line 1 in Fig. 7.3,

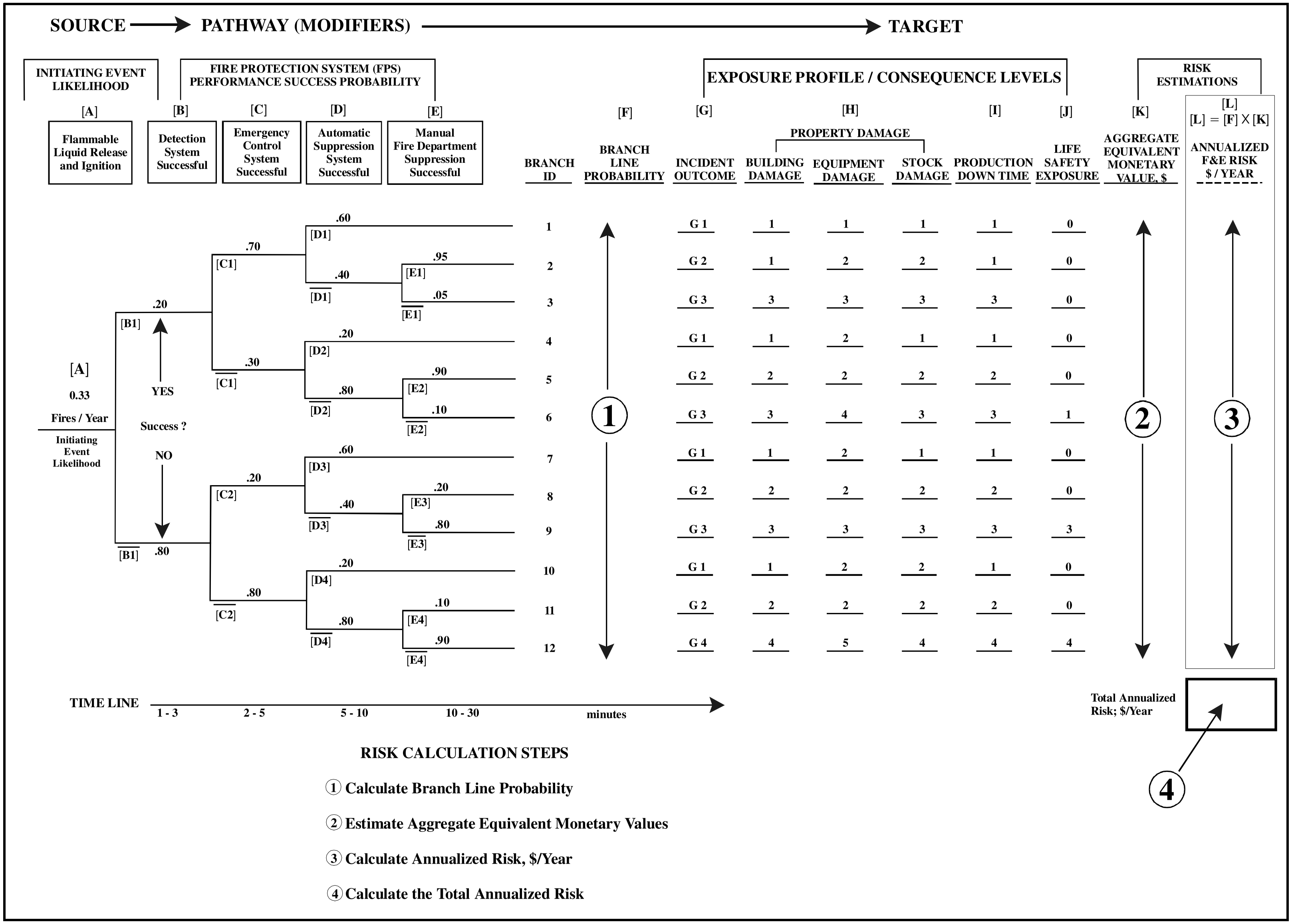
Branch ID - 1 = [A] x [B1] x [C1] x [D1]

Branch ID - 1 = 0.33 x 0.20 x 0.70 x 0.60 = 0.028

The 0.028 is the likelihood (0.028 events/year or 1 event/35 years) of the specific branch line scenario, which for branch line 1 is the occurrence of a fire that is detected, controlled, and successfully suppressed within 10 min following ignition.

Each branch line in the event tree, Fig. 7.3, is calculated in a similar manner. As a check, the branch line probabilities (branch lines 1 →12) should add up to equal the initiating event likelihood of 0.33 (see “check” in Fig.7.3).

Fig. 7.2: Example Event Tree Framework Identifying Risk Calculation Steps



BRANCH ID	INCIDENT OUTCOME	BUILDING DAMAGE	EQUIPMENT DAMAGE	STOCK DAMAGE	PRODUCTION DOWN TIME	LIFE SAFETY EXPOSURE
1	G 1	1	1	1	1	0
2	G 2	1	2	2	1	0
3	G 3	3	3	3	3	0
4	G 1	1	2	1	1	0
5	G 2	2	2	2	2	0
6	G 3	3	4	3	3	1
7	G 1	1	2	1	1	0
8	G 2	2	2	2	2	0
9	G 3	3	3	3	3	3
10	G 1	1	2	2	1	0
11	G 2	2	2	2	2	0
12	G 4	4	5	4	4	4

RISK CALCULATION STEPS

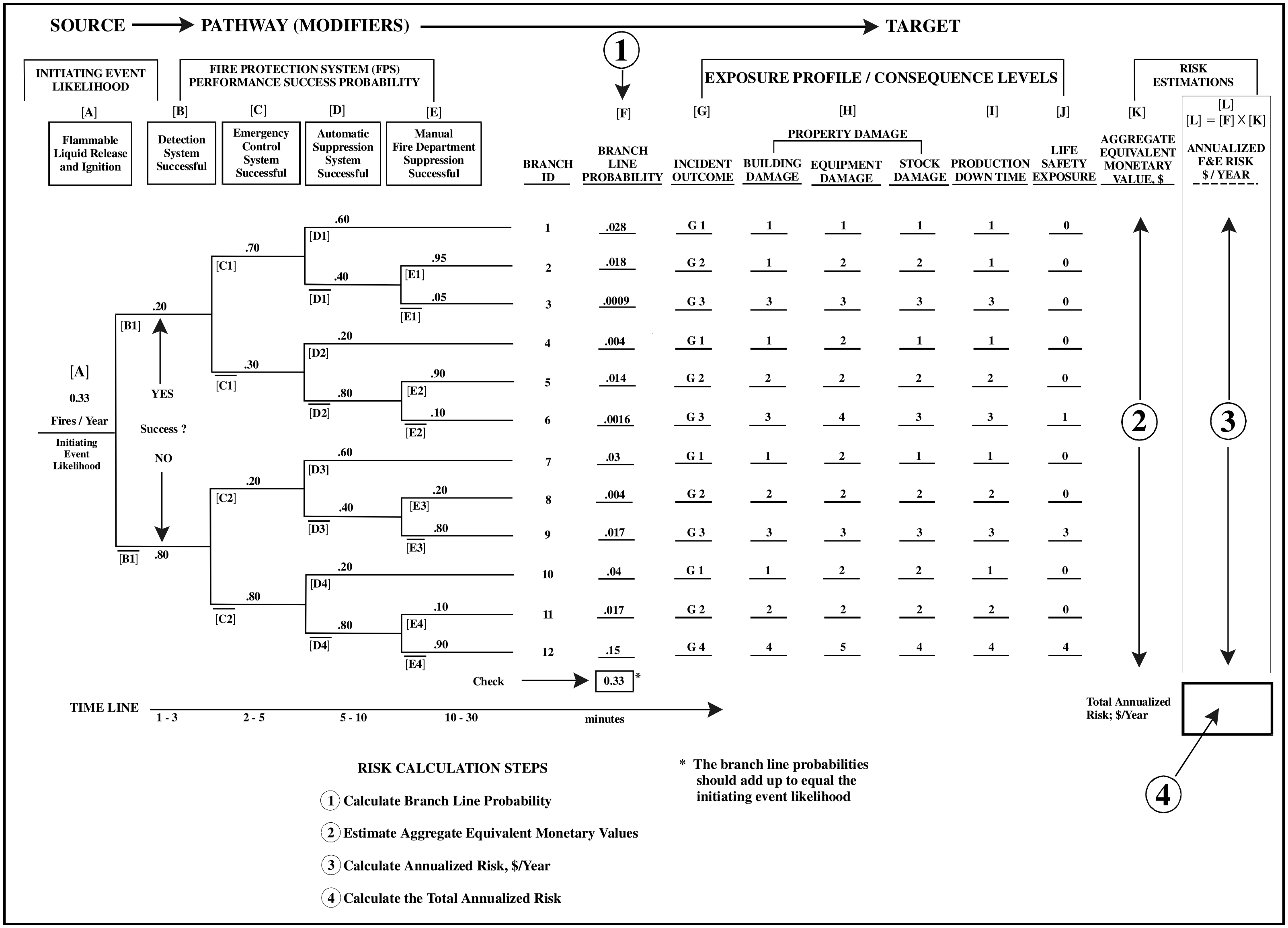
① Calculate Branch Line Probability

② Estimate Aggregate Equivalent Monetary Values

③ Calculate Annualized Risk, $/Year

④ Calculate the Total Annualized Risk

Fig. 7.3: Example Event Tree Framework Estimating Branch Line Probabilities



BRANCH ID	[F] BRANCH LINE PROBABILITY	[G] INCIDENT OUTCOME	[H] PROPERTY DAMAGE: BUILDING DAMAGE	[H] PROPERTY DAMAGE: EQUIPMENT DAMAGE	[H] PROPERTY DAMAGE: STOCK DAMAGE	[I] PRODUCTION DOWN TIME	[J] LIFE SAFETY EXPOSURE
1	.028	G 1	1	1	1	1	0
2	.018	G 2	1	2	2	1	0
3	.0009	G 3	3	3	3	3	0
4	.004	G 1	1	2	1	1	0
5	.014	G 2	2	2	2	2	0
6	.0016	G 3	3	4	3	3	1
7	.03	G 1	1	2	1	1	0
8	.004	G 2	2	2	2	2	0
9	.017	G 3	3	3	3	3	3
10	.04	G 1	1	2	2	1	0
11	.017	G 2	2	2	2	2	0
12	.15	G 4	4	5	4	4	4
Check	0.33*						

RISK CALCULATION STEPS

① Calculate Branch Line Probability

② Estimate Aggregate Equivalent Monetary Values

③ Calculate Annualized Risk, $/Year

④ Calculate the Total Annualized Risk

* The branch line probabilities should add up to equal the initiating event likelihood

7.2.2 Aggregate Equivalent Monetary Values

Column [K] in Fig. 7.4 is for estimating the aggregate EMV. To do this, all the consequence levels must be related to an equivalent monetary value:

- Building Damage
- Equipment Damage
- Stock Damage
- Production Downtime
- Life Safety Exposure
- “Other” Exposures

Equivalent Monetary ($) Values at Risk

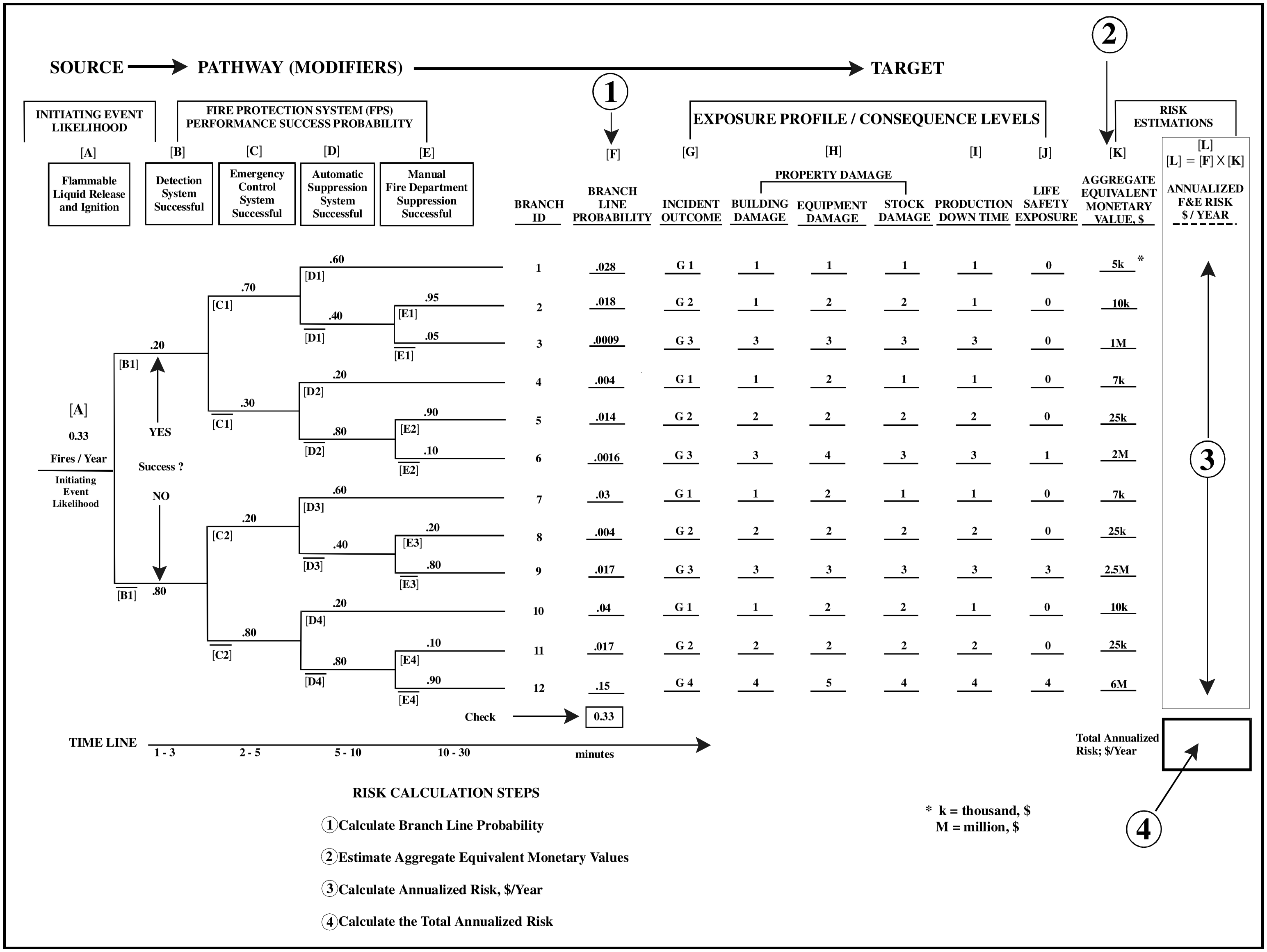
To evaluate the target’s aggregate value, which may be exposed to fire or explosion loss, the contribution of all the consequences must be recognized and estimated in terms of EMVs. This provides a framework that allows cost/benefit analysis of risk reduction opportunities based on total risk exposure.

Although there will be some level of uncertainty in estimating an overall risk potential at the target, it is very important to identify consequence contribution and provide an equivalent monetary measurement of the aggregate risk. Table 7.2 provides a general breakdown of relative confidence in assigning an EMV to consequences.

Table 7.2: Relative Confidence In Assigning Equivalent Monetary Values

POTENTIAL VALUES AT RISK FROM FIRE & EXPLOSION INCIDENTS		RELATIVE CONFIDENCE IN ASSIGNING EQUIVALENT MONETARY VALUES	REMARKS
Property damage	PD	High	Building, equipment, and stock replacement costs usually available
Business interruption (i.e., Production down time costs)	BI	Moderate – High	Production down time costs/estimates usually available
Life safety exposure (i.e., employees/public)	LS	Low – Moderate	May be difficult to relate to equivalent monetary terms
Environmental impact (clean-up, decontamination)	EV	Low – Moderate	In many cases, may be difficult to estimate
Other risks: • Regulatory fines • Lawsuits • Bad publicity (i.e., company image)	OT	Low – Moderate	In many cases, may be difficult to estimate

Fig. 7.4: Example Event Tree Framework Estimating Aggregate Equivalent Monetary Value



BRANCH ID	[F] BRANCH LINE PROBABILITY	[G] INCIDENT OUTCOME	[H] PROPERTY DAMAGE: BUILDING DAMAGE	[H] PROPERTY DAMAGE: EQUIPMENT DAMAGE	[H] PROPERTY DAMAGE: STOCK DAMAGE	[I] PRODUCTION DOWN TIME	[J] LIFE SAFETY EXPOSURE	[K] AGGREGATE EQUIVALENT MONETARY VALUE, $
1	.028	G 1	1	1	1	1	0	5k *
2	.018	G 2	1	2	2	1	0	10k
3	.0009	G 3	3	3	3	3	0	1M
4	.004	G 1	1	2	1	1	0	7k
5	.014	G 2	2	2	2	2	0	25k
6	.0016	G 3	3	4	3	3	1	2M
7	.03	G 1	1	2	1	1	0	7k
8	.004	G 2	2	2	2	2	0	25k
9	.017	G 3	3	3	3	3	3	2.5M
10	.04	G 1	1	2	2	1	0	10k
11	.017	G 2	2	2	2	2	0	25k
12	.15	G 4	4	5	4	4	4	6M
Check	0.33							

RISK CALCULATION STEPS

① Calculate Branch Line Probability

② Estimate Aggregate Equivalent Monetary Values

③ Calculate Annualized Risk, $/Year

④ Calculate the Total Annualized Risk

* k = thousand, $
M = million, $

Each one of the following exposures will be overviewed in this section with the focus on developing damage or vulnerability categories that can be related to monetary values:

- Property Damage (damage categories can be associated to % equipment and/or building damage and directly related to monetary values)
- Loss of Production/Business Interruption (BI) (categories can be associated with days downtime, % production loss, and directly related to monetary values)
- Life Safety Exposure (categories can be associated with potential human vulnerability levels and can also be related to potential monetary ranges)
- Environmental Damage (categories can be associated with toxic air emissions, soil, water contamination levels from fire combustion products, and suppression agents and can be related to monetary ranges)
- Other (legal liabilities, regulatory/fines, company image, loss of customers) can be defined in some cases and related to monetary ranges using relative scales

Property Damage

Property damage (PD) values are usually broken down into building, equipment, and stock replacement costs. PD estimates are highly plant-, facility-, and operation-specific.

The starting point is to estimate the replacement value of buildings and equipment based on current replacement value (present value) and an estimated replacement value at the end of the useful life (future value), so that average replacement values can be estimated.

Table 7.3 provides a simplistic example of this. In this example, the future replacement value is only adjusted upward for an assumed constant inflation rate. Other factors that could contribute to an increase in future replacement values should be considered where applicable.

Table 7.3: Example of Property Replacement Value Estimation

REPLACEMENT VALUE ESTIMATES FOR BUILDING AND EQUIPMENT			
Building Value	Building replacement: EMV =	$25,000,000	Present value
	Building useful life:	30	Years
	Building replacement: EMV =	$52,440,000	Future value (Assumes 2.5% annual inflation rate)
	Building replacement: EMV =	$38,720,000	Average replacement value
Equipment Value	Production equipment replacement: EMV =	$14,000,000	Present value
	Production equipment useful life:	15	Years
	Production equipment replacement: EMV =	$23,454,200	Future value
	Production equipment replacement: EMV =	$18,727,100	Average replacement value
NOTE: The $ values inserted in this table are for example purposes only.			

Other items of property replacement value that may need to be considered include building utilities and support equipment such as ventilation and heating equipment, electrical equipment, etc., which may or may not be included with the building structure replacement cost estimate. Also stock (raw materials, intermediate products, finished products) replacement values may be a consideration when evaluating total facility replacement costs.

The PD levels are selected based on the Exposure Profile modeling conducted in Step 5. The total replacement value for each PD item (building, equipment, stock) would be placed in damage level 6 (100% damage) as shown in Table 7.4. As a first-order estimate, the dollar replacement value (RV) can be multiplied by the percent central damage factor. A second-order estimate would include additional detail and analysis and may be warranted depending on the scope of the project.

Table 7.4: Example of Property Damage (PD) Levels and EMV

PD LEVELS	DAMAGE FACTOR RANGE (%)	CENTRAL DAMAGE FACTOR (%)	GENERAL DEFINITION	PD EQUIVALENT MONETARY VALUE EMV
1 – Slight	0 – 1	0.5	Limited localized minor damage not requiring repair	0.5% × RV
2 – Light	1 – 10	5	Significant localized damage of some components generally not requiring major repair	5% × RV
3 – Moderate	1 – 30	20	Significant localized damage of many components warranting repair	20% × RV
4 – Heavy	30 – 60	45	Extensive damage requiring major repairs	45% × RV
5 – Major	60 – 100	80	Major widespread damage that may result in the facility being razed, demolished, or repaired	80% × RV
6 – Destroyed	100	100	Total destruction of the majority of the facility	100% Replacement Value (RV)
NOTE: EMV estimates are facility- and operation-specific. RV = Replacement Value. Separate tables can be developed for building, equipment and stock.				

In the preceding discussion and in Table 7.4 we focused on RV. In many cases building structures and equipment can be repaired; therefore repair costs should be considered.

When estimating property repair and replacement costs:

- Solicit the experience of your engineering, accounting, procurement, and insurance departments. Contact manufactures. Use cost estimating references.
- Get the people (internal and external) who know the buildings and equipment best together as part of the repair and replacement estimating team. When needed apply consensus-based expert opinion to form an estimate.

Business Interruption

BI estimates are usually broken down into days downtime, percent production loss, and dollars per day production loss. Estimating BI is very facility- and operation- specific.

Variables in the BI evaluation include the value of the product being produced, the market cycle of the product, the product profit margins, and BI interdependency if the product is used in other parts of the overall production process or at another plant. The Operations Department should be able to provide good data support in these areas.

Table 7.5 provides a simplified example for estimating BI potential. As discussed in the section on property damage, the present and future dollars per day downtime should be evaluated so that some average value ranges can be interpreted. For future value, usually some type of product or market index is used. Also both direct BI and interdependent BI (effects of loss of production on other operations or at other plants) should be evaluated.

Table 7.5 Example of Business Interruption (BI) Value Estimation

BI VALUATION			
Direct BI Value	Business Interruption: EMV =	$15,000	Present value – per day
	Production Equipment: Operational Life Cycle:	15	Years
	Business Interruption: EMV =	$29,030	Future value – per day (assumes 4.5% annual inflation rate)
	Business Interruption: EMV =	$22,015	Average value – per day
Interdependent BI / Extra Expense Value	Interdependent BI / Extra Expense: EMV =	$10,000	Present value – per day
	Production: Operational Life Cycle:	15	Years
	Business Interruption: EMV =	$19,353	Future value – per day (assumes 4.5% annual inflation rate)
	Business Interruption: EMV =	$14,677	Average value – per day
NOTE: The $ values in this table are for example purposes only.			

The 100% BI value would be placed in BI Level 6 as shown in Table 7.6 As a first-order estimate, the BI value (dollars per day lost from production downtime) can be multiplied by the average production downtime. A second-order estimate would include additional detail and analysis which may be warranted depending on the scope of the project.

Table 7.6: Example of Business Interruption (BI) Levels and EMV

BI LEVELS	PRODUCTION DOWNTIME RANGE, DAYS	AVERAGE PRODUCTION DOWNTIME, DAYS	GENERAL DEFINITION	BI EQUIVALENT MONETARY VALUE (EMV)
1 – Slight	0 – 1	0.5	Limited localized minor equipment damage not requiring repair, but clean up and minimal downtime	0.5 x BIV
2 – Light	1 – 10	5	Significant localized damage of some equipment components with minor production downtime	5.0 x BIV
3 – Moderate	10 - 30	20	Significant localized damage of many equipment components with moderate production downtime	20.0 x BIV
4 – Heavy	30 - 90	60	Heavy damage requiring major equipment repair & replacement and downtime	60.0 x BIV
5 – Major	90 – 270	180	Major widespread damage that may result in extensive repairs and equipment replacement with major downtime	180.0 x BIV
6 – Maximum	270 - 365	318	Extensive downtime of the majority of the facility	100% $ Value (BIV)
NOTE: EMV estimates are facility- and operation-specific. BIV = business interruption value, represented as dollars per day lost from production downtime.				

Life Safety Exposure

Life safety exposure can be broken down into vulnerability levels that associate fire or explosion related injury to operators, employees, or contractors on site; potential serious injuries or fatalities on-site; and in some cases, life safety exposure off-site to the public.

Applying an equivalent monetary value to these categories is more focused on relative estimation consistency then trying to achieve any absolute level of monetary value.

Table 7.7 provides a general example of establishing some life safety (LS) exposure levels and associated average EMVs.

Table 7.1.7: Example – Life Safety (LS) Exposure Levels and EMV

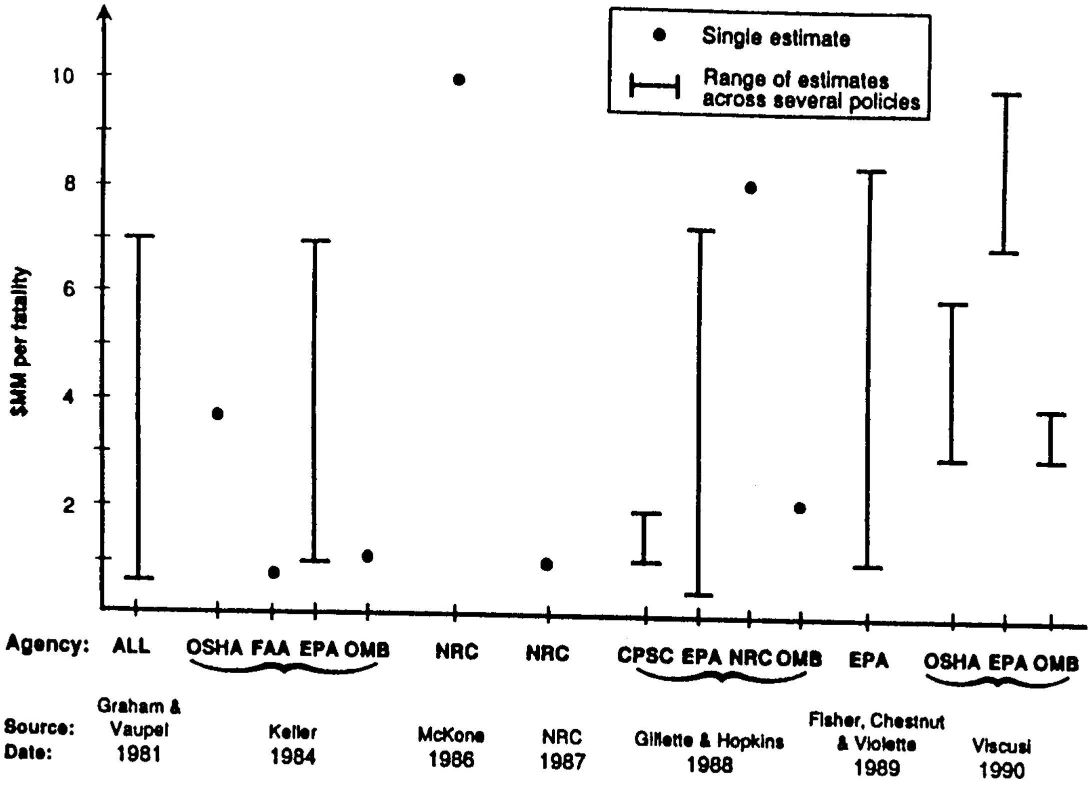
LIFE SAFETY EXPOSURE LEVELS			LS EMV ($)
Injuries	1	First aid – one person (primarily smoke-related)	1,000
	2	Moderate burn injury – one person (may require hospital treatment)	10,000
	3	Severe burn injuries – hospital treatment 1-3 people	100,000
Fatalities	4	Employee/on-site contractor – single fatality	1,000,000
	5	On-site – 1 – 3 fatalities	5,000,000
	6	Off-site fatality	20,000,000

EMV = Equivalent Monetary Value
LS = Life Safety
NOTE: The $ values in this table are for example purposes only.

Putting a value on human life is a difficult and controversial task. In some cases, there is reluctance to assign dollar values to human life, and there is no general consensus in the United States on what the EMVs should be. However, risk-based decisions for situations where life safety exposures are of concern either implicitly or explicitly include such valuations. Also, this valuation is needed to conduct cost/benefit analysis of risk reduction measures.

Figure 7.5, from reference [1], provides a summary of life value estimates used in some U.S. risk assessment projects. As presented, values range from $300,000 to $10,000,000.

Fig. 7.5: Value-Of-Life Estimates Used in Government Cost/Benefit Analysis



Although there may be resistance to assigning an EMV to life safety, it is necessary to support credible and consistent decisions regarding risk tolerance levels and for targeting risk reduction opportunities. By using consistent singular values related to life safety exposure categories, a relative ranking of life safety risk from fire and explosion (F&E) exposures and a prioritization of FPS performance improvements can be obtained.

Environmental Damage

Potential environmental impacts related to F&E incidents are difficult consequences to estimate in terms of an EMV as environmental impacts following a fire can take several forms. There may be clean-up costs associated with toxic material spills or contamination, and there may be costs associated with treatment and disposal of waste streams. Though this is a real potential cost, it is often not considered in fire risk assessments, and it should be.

The costs for cleanup of environmental spills can be estimated along with potential regulatory fines that the company may incur. Other consequences, such as the effects of negative publicity surrounding F&E related environmental accidents, are more difficult to estimate.

Table 7.8 provides a general example of establishing some environmental exposure categories and associated average equivalent monetary values.

Table 7.8: Example – Environmental Damage and Equivalent Monetary Value (EMV)

CONTAMINATION TYPE	ENVIRONMENTAL DAMAGE LEVEL EFFECTS	EMV ($)
Soil	**SC1** / Negligible	1,000
	SC2 / Local-Extensive	20,000
	SC3 / Major	250,000
Water	**WC1** / Negligible	1,000
	WC2 / Local – Extensive	250,000
	WC3 /Major	2,000,000
Air	**AC1** / Negligible	1,000
	AC2 / Local – Extensive	500,000
	AC3 / Major – Extends Offsite	5,000,000

EMV = Equivalent Monetary Value

EMV estimates are facility-, operation-, and location-specific.
The $ values in this table are for example purposes only.

Other Consequence Considerations

Other consequence considerations can include regulatory fines, media reaction, public perception and company image. Noncompliance costs result directly from fines and penalties that may be imposed should a regulatory agency find violations. In addition to the more common fire consequences, an often overlooked but critical risk faced by companies are those driven by public perception, community and customer goodwill. Perception and company image can have significant impacts on shareholder equity and, in the case of consumer product companies, loss of customers and direct impact on sales.

The relative importance of these types of risks varies depend on the true nature of operations at a plant site and the types of business. The challenge is to estimate potential unplanned costs associated with these risks.

Table 7.9 provides a general example of establishing some levels for regulatory and media reaction consequences and providing an average associated monetary value.

Table 7.9: Example Regulatory and Media Reaction Equivalent Monetary Value (EMV)

OTHER POTENTIAL CONSEQUENCES		EMV ($)
Regulatory Fines	**RF1** Minor Fines	1,000
	RF2 Moderate Fines	20,000
	RF3 Major Fines	250,000
Media Reaction	**MR1** Local News – Brief	1,000
	MR2 State News – Moderate	200,000
	MR3 National News – Strong	1,000,000
EMV = Equivalent Monetary Value The $ values in this table are for example purposes only.		

Table 7.10 provides an example of grouping scenarios based on loss expectancy definition. The example data entered into the table is from Fig. 7.8

Table 7.10: Loss Expectancy Grouping

GROUPED SCENARIOS	LOSS EXPECTANCY DEFINITION	LIKELIHOOD EVENTS/YEAR	CONSEQUENCE $, EMV	RELATIVE % OF TOTAL ANNUALIZED RISK
G1 – Automatic sprinklers successful	Best-case situation generally related to an NLE – normal loss expectancy analysis	0.102	29,000	.20%
G2 – Sprinkler system not successful/fire department successful	Selected probable case generally related to a PML – probable maximum loss analysis	0.053	850,000	.25%
G3 – Sprinklers/fire dept. not successful – assumes delayed fire department suppression at 60 min.	Selected probable case generally related to a PML – probable maximum Loss analysis	0.0195	5,500,000	6%
G4 – Uncontrolled fire – assumes a 2-hr fire duration	Worst-case situation generally related to an MFL – maximum foreseeable loss analysis	0.15	6,000,000	93.55%

In Table 7.10, the likelihood and consequences (in terms of equivalent monetary value) are added up from the data in Columns [F] and [K] in Fig. 7.8, for each group, G1→G4. The last column in Table 7.10 is the relative percentage of the total annualized risk contributed by each group. As illustrated in Table 7.10, G4 (uncontrolled fire situation) contributes 93.55% of the total annualized risk, which is a very undesirable situation, usually necessitating immediate risk reduction analysis. This high relative percentage related to reaching a worst-case situation is due to the high initiating event likelihood (0.33 fires/year or 1 fire every 3 years) coupled with the high FPS failure probabilities.

Likelihood of Exceeding a Defined Consequence Level

In some cases the risk evaluation team may want to examine the likelihoods related to specific consequences and defined consequence levels. For example, the risk evaluation team may want to break down the life safety exposure in more detail, evaluating those scenarios and likelihoods associated with high exposure levels, denoted in Table 7.11 as a level 3 or above.

Table 7.11 : Example of Life Safety Exposure Levels

HUMAN VULNERABILITY EXPOSURE LEVELS	GENERAL DEFINITION
1 – Low	First aid – (one person) Primarily smoke-related exposure
2 – Moderate	Moderate burn injury potential; may require hospital treatment – (1 person)
3 – High	Severe burn potential requiring hospital treatment – (1 – 2 people)
4 – Very High	Potential for multiple injuries, single person death
5 – Extremely High	Potential for 2 – 10 fatalities
6 – Catastrophic	Potential for greater than 10 fatalities

From the event tree example, Fig. 7.8, there are two scenarios where the life safety exposure is at level 3 or above:

BRANCH LINE 9

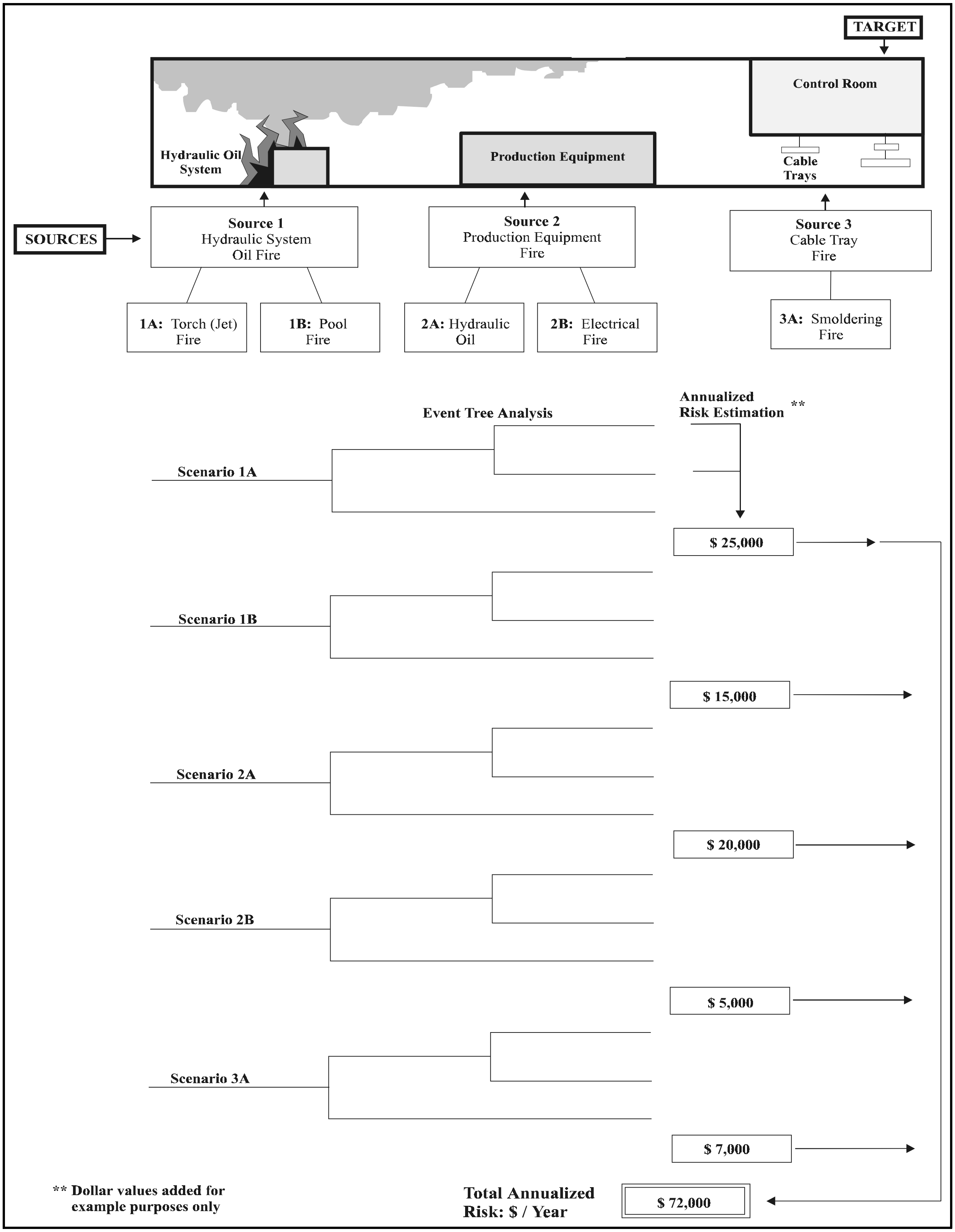
- Likelihood – 0.017 events/year
- G3 Group – Sprinklers not successful/ delayed Fire Department fire suppression
- Life Safety (LS) – LS 3 Consequence Level

BRANCH LINE 12

- Likelihood – 0.15 events/year
- G4 Group – Uncontrolled Fire
- Life Safety (LS) – LS 4 Consequence Level

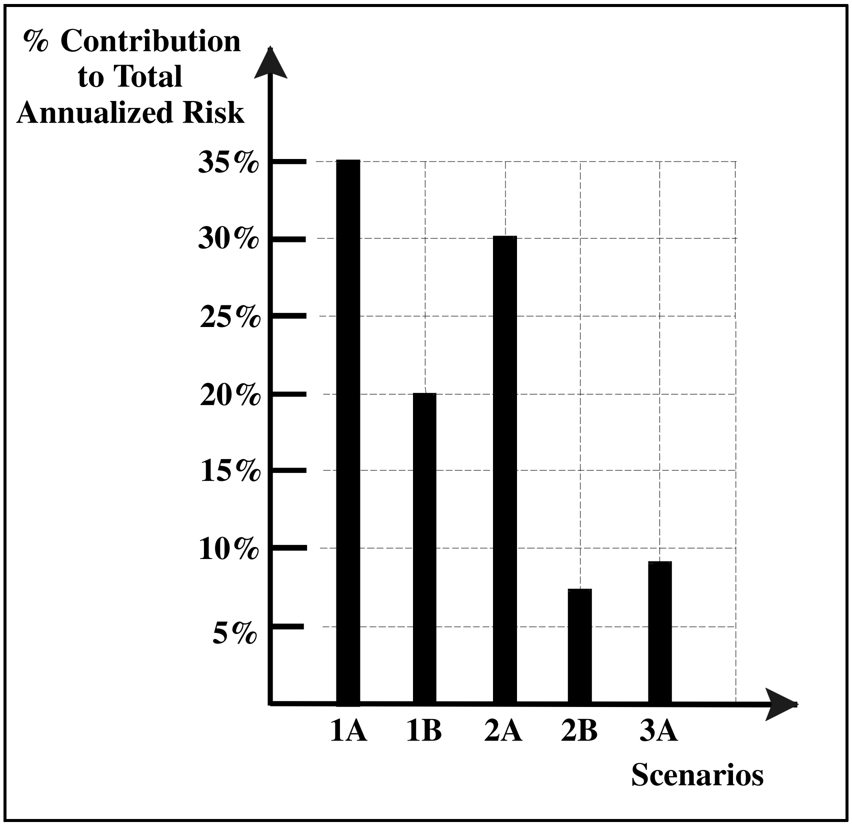
Figure 7.9 provides a simple graphical presentation of the likelihood of specific life safety levels 3 and 4. Another common graphical depiction would be an accumulative profile indicating for example the accumulation likelihood of exceeding a life safety level of 2 (which in this example would be 0.167 events/year). Similar break downs of consequence levels versus likelihood could also be performed for PD or BI exposures. Comparative risk profiles are discussed in Sect. 7.3.

Fig. 7.10: Summation of Scenario-Based Annualized Risk Estimates



It is important to recognize how much each scenario contributes to the Total Annualized Risk estimate in order to focus on and prioritize risk reduction opportunities. Figure 7.11 presents an example graph of scenario contribution as related to Fig. 7.10. As presented in this graph, scenarios 1A, 1B, and 2A contribute to more than 80% of the total annualized risk.

Fig. 7.11: Scenario Contribution to Total Annualized Risk



7.3 RISK COMPARISON

The estimated annualized fire or explosion risk discussed in Sect.7.2 must be compared to the decision maker(s) risk tolerance criteria to determine the need for risk reduction analysis (Step 8). The risk tolerance criteria was established in Step 2.

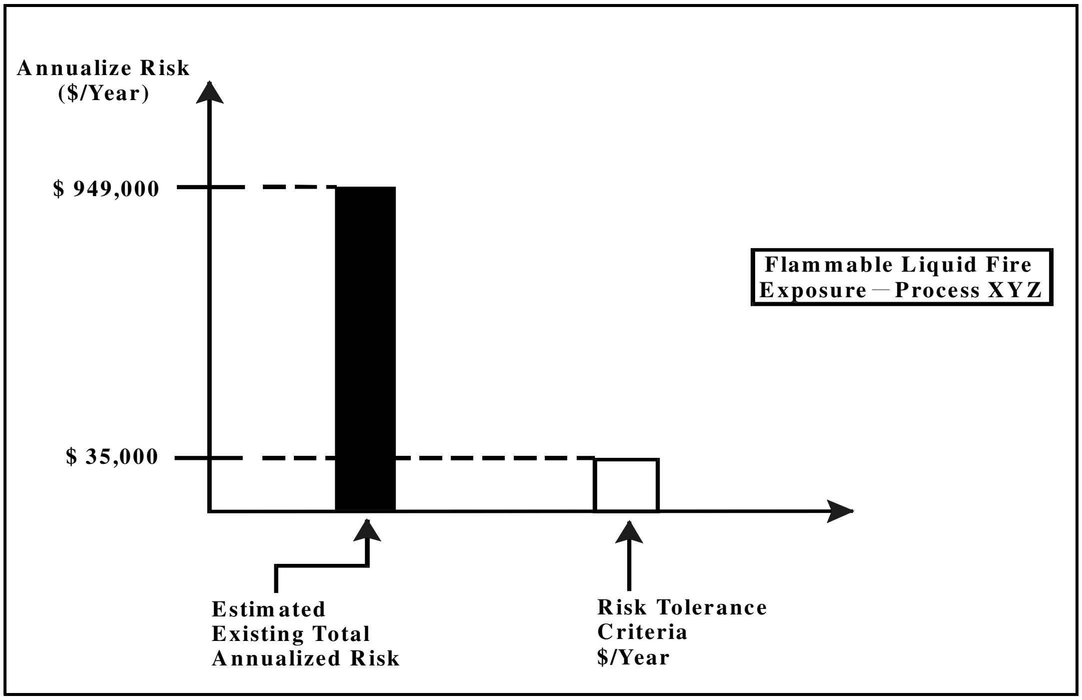
In this section we will address risk comparison expressed in terms of:

- Annualized Economic Risk
  - Total annualized risk
  - Loss expectancy grouping
  - Likelihood of exceeding a defined consequence level
- Annualized Life Safety Risk
  - Likelihood of exceeding a defined life safety exposure level

Comparison with the Total Annualized Risk Estimate

The total annualized risk is the summation of the calculated risk levels for all the event tree branch line scenarios evaluated in the risk-based study. Figure 7.12 presents an example of a bar graph depicting an estimated total annualized risk versus the risk tolerance criteria. As depicted in this example graph, the existing total annualized risk greatly exceeds the risk tolerance criteria, thus warranting risk reduction evaluation.

Fig. 7.12: Example Depiction of Total Annualized Risk



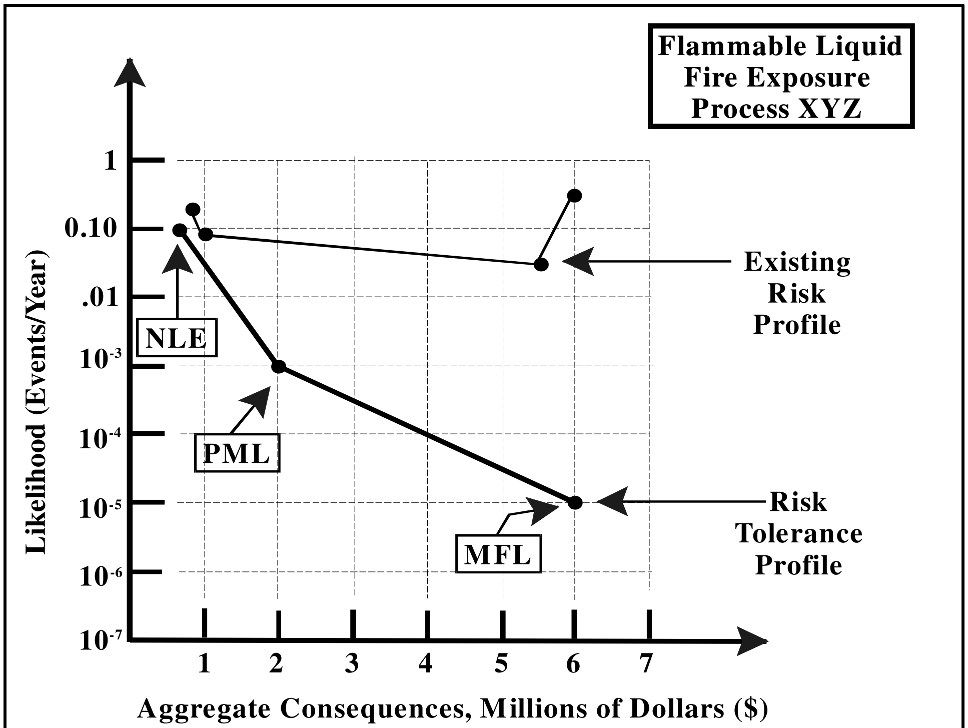
Comparison with Loss Expectancy Risk Tolerance Profile

Figure 7.13 presents a graphical depiction of an existing loss expectancy risk profile versus a loss-expectancy-based risk tolerance profile which focuses on property damage (PD) and business interruption (BI) consequences. This graph presents a risk tolerance profile using the following example data:

EVENT	LIKELIHOOD	PD AND BI CONSEQUENCES
NLE	0.10	$ 50,000.00
PML	0.001	$ 2,000,000.00
MFL	0.00001	$ 6,000,000.00

As depicted in this example graph, the existing risk profile greatly exceeds the risk tolerance, especially for the MFL, thus warranting risk reduction evaluation. The concept of NLE, PML, and MFL is discussed in Chap. 3.

Fig. 7.13: Example Loss Expectancy Risk Comparison



NOTE: NLE - Normal Loss Expectancy; Best-Case Situation
PML - Probable Maximum Loss; Selected Probable Case(s)
MFL - Maximum Foreseeable Loss; Worst-Case Situation

Likelihood of Exceeding a Defined Consequence Level

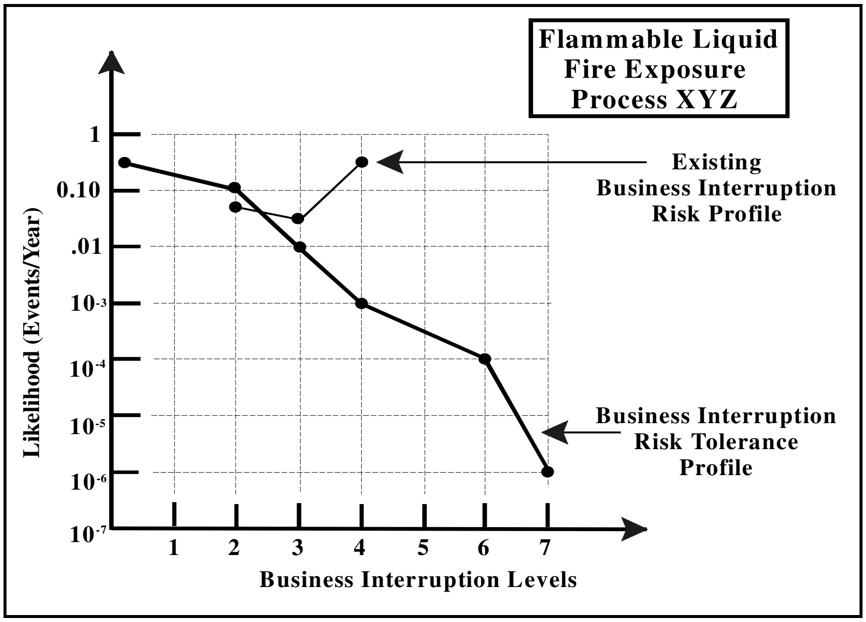
We can graphically display and perform risk comparison on any of the type of consequences evaluated in the event tree analysis. For example, decision makers may want to evaluate the likelihood of production downtime exceeding a level 2 as defined in Table 7.12.

Table 7.12: Example of Business Interruption (BI) Categories

BI LEVELS	PRODUCTION DOWNTIME RANGE, DAYS	AVERAGE PRODUCTION DOWNTIME, DAYS
1 – Slight	0 – 1	0.5
2 – Light	1 – 10	5
3 – Moderate	10 - 30	20
4 – Heavy	30 - 90	60
5 – Major	90 – 270	180
6 – Critical	270 – 360	315
7 – Total	1 – 2 Years	Use maximum expected

Figure 7.14 presents a graphical depiction of an existing BI risk profile (see production downtime in Fig. 7.8) versus an example BI risk tolerance profile. As depicted in this example graph, the existing BI risk exceeds the BI risk tolerance profile; therefore, risk reduction measures should be evaluated.

Fig. 7.14: Example BI Risk Comparison



Life Safety Risk Comparison

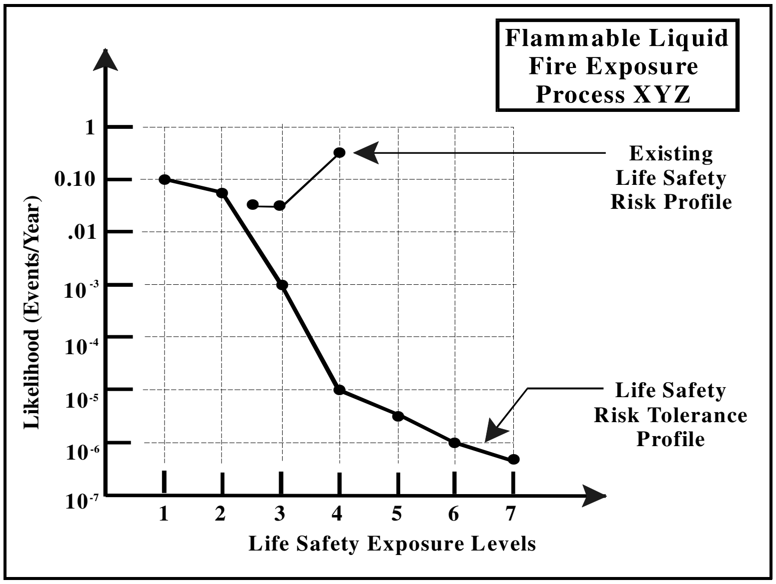
Decision makers may want to isolate life safety consequence levels and likelihood in order to perform risk comparison and to focus risk reduction efforts. For example, decision makers may want to evaluate the likelihood of life safety exposure levels exceeding a level 2 as defined in Table 7.13.

Table: 7.13: General Example of Life Safety Exposure Categories

LIFE SAFETY EXPOSURE	GENERAL DEFINITION
1 – Low	First aid – (one person) (Primarily smoke-related exposure)
2 – Moderate	Moderate burn injury potential may require hospital treatment – (one person)
3 – Heavy	Severe burn potential requiring hospital treatment – (1-2 people)
4 – High	Potential for multiple injuries, single person death on site
5 – Very High	Potential for 2-10 fatalities on site
6 – Extremely	Potential for multiple injuries or single person death – OFF-SITE
7 – Catastrophic	Potential for multiple fatalities – OFF-SITE

Figure 7.15 presents a graphical depiction of an existing life safety risk profile (see life safety exposure in Fig. 7.8) versus an example life safety risk tolerance profile. As depicted in this example graph, the existing life safety risk exceeds the life safety risk tolerance profile; therefore, life safety risk reduction action should receive immediate consideration.

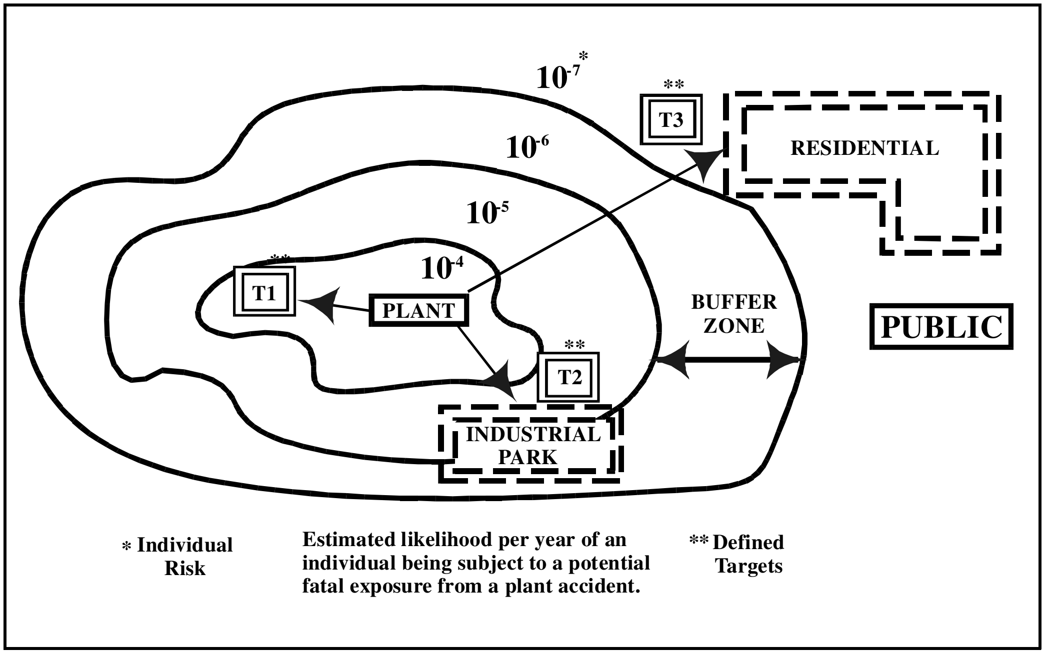
Fig. 7.15: Example Life Safety Risk Comparison



Individual Risk Contours

In some cases, the risk evaluation team may want to plot a risk contour depicting individual risk levels at various target distance from the fire or explosion source. Figure 7.16 provides an example of this. In this figure, target [TI] is a selected target within the plant site boundaries. Target [T2] is a selected target at an adjacent industrial park. Target [T3] represents off-site risk to the public.

Fig. 7.16: An Example Individual Risk Contour Plot



* Individual Risk

Estimated likelihood per year of an individual being subject to a potential fatal exposure from a plant accident.

** Defined Targets

7.4 RISK UNCERTAINTY

This section provides an overview of:

- Areas of uncertainty versus project quality control measures
- Computer assisted simulation to quantify uncertainty

Uncertainty must be accounted for in the communication of risk estimation to the decision makers. Uncertainty assessment is a measure, qualitative or quantitative, of the degree of doubt or lack of certainty associated with risk estimating inputs, variables, probability values, deterministic models, and EMVs. Figure 7.17 highlights some of the primary areas of uncertainty in the event tree risk analysis model:

- Scenario categorization
- Branch line probability estimations
- Modeling exposure and consequence levels
- Determining EMVs

Project quality controls are intended to reduce uncertainty and increase the overall confidence in the risk estimation results. Table 7.14 provides an example of some of the primary project quality controls associated with the areas of uncertainty.

Two key quality controls listed in Table 7.14 are:

- Interactive Team Reviews
- Documentation

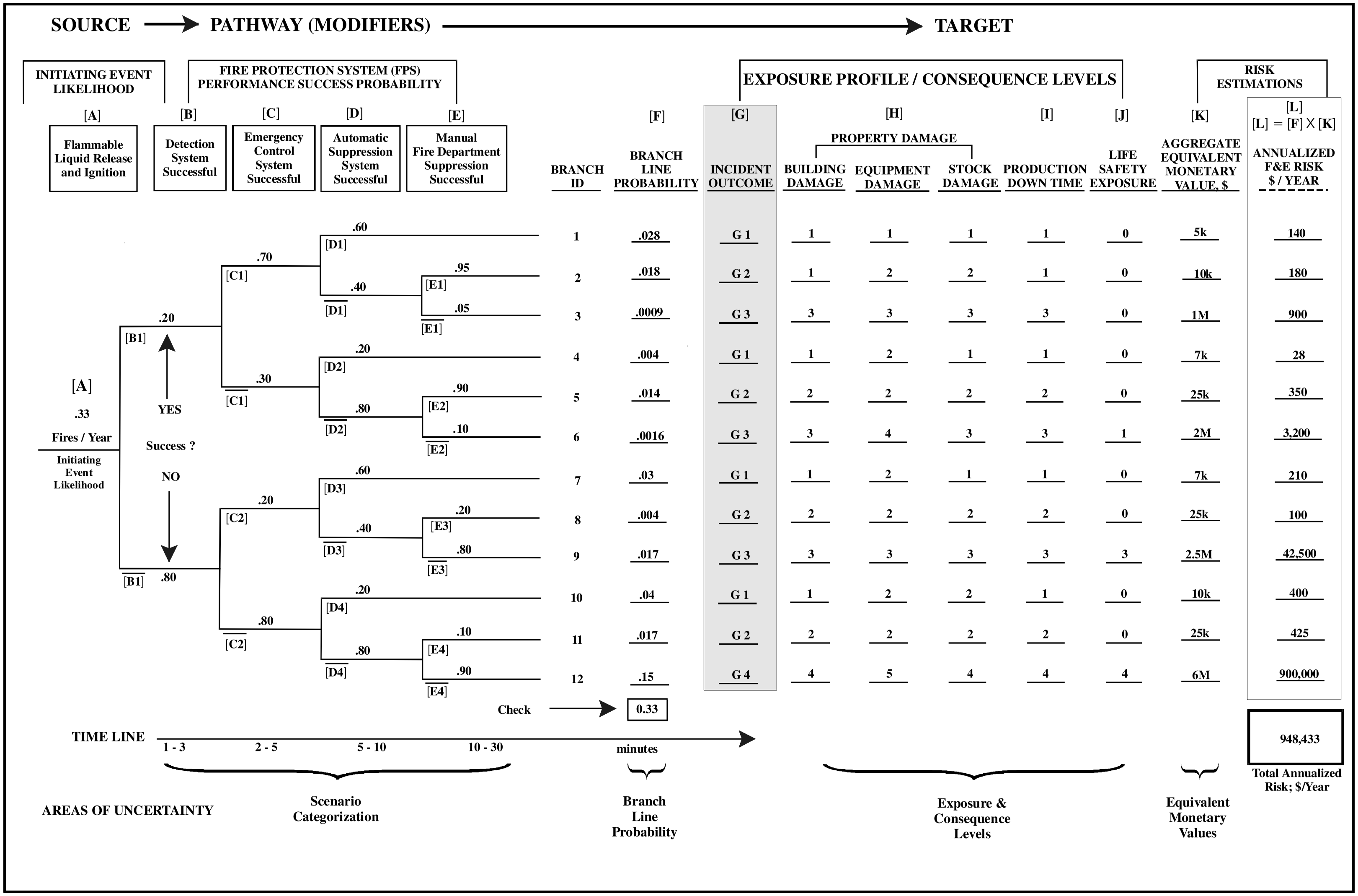
Interactive Team Reviews

As stated in previous chapters, the risk estimation process must include a team consensus approach. Team members should include representatives from the plant knowledgeable in the specific facility hazards, operations, and maintenance practices; representatives from environmental, safety, fire protection; and risk management and financial personnel.

Capabilities of the plant consensus team should include:

- Knowledge of the facility, operations, equipment, and safety features under:
  - Normal operations
  - Abnormal emergency conditions
- Experience with:
  - Plant loss incident history
  - Contributing factors to loss incidents
  - Modifications and changes made following losses
- Understanding of fault tree analysis (FTA) and event tree analysis (ETA) models
  - A team leader knowledgeable in FTA and ETA
  - Team members should have a rudimentary understanding of FTA and ETA tree logic and methodology
- Knowledge of financial loss potentials
  - Values at risk
  - Contingency plans
  - Risk management strategies

Fig. 7.17: Example Event Tree Framework Areas of Uncertainty



	[F]	[G]	[H]			[I]	[J]	[K]	[L]
			PROPERTY DAMAGE						[L] = [F] X [K]
BRANCH ID	BRANCH LINE PROBABILITY	INCIDENT OUTCOME	BUILDING DAMAGE	EQUIPMENT DAMAGE	STOCK DAMAGE	PRODUCTION DOWN TIME	LIFE SAFETY EXPOSURE	AGGREGATE EQUIVALENT MONETARY VALUE, $	ANNUALIZED F&E RISK $ / YEAR
1	.028	G 1	1	1	1	1	0	5k	140
2	.018	G 2	1	2	2	1	0	10k	180
3	.0009	G 3	3	3	3	3	0	1M	900
4	.004	G 1	1	2	1	1	0	7k	28
5	.014	G 2	2	2	2	2	0	25k	350
6	.0016	G 3	3	4	3	3	1	2M	3,200
7	.03	G 1	1	2	1	1	0	7k	210
8	.004	G 2	2	2	2	2	0	25k	100
9	.017	G 3	3	3	3	3	3	2.5M	42,500
10	.04	G 1	1	2	2	1	0	10k	400
11	.017	G 2	2	2	2	2	0	25k	425
12	.15	G 4	4	5	4	4	4	6M	900,000

Table 7.14: An Example of Some Risk Estimation Quality Controls

AREAS OF UNCERTAINTY	CREDIBILITY IMPLICATIONS	QUALITY CONTROLS
Scenario Categorization: • Incomplete identification of failures and/or improper categorization of representative fire or explosion scenarios • Event tree is not properly structured to present fire protection system (FPS) performance stages or sequences	• Underestimation of the risk	• Require proper documentation of data sources and methods • Involve experienced people and provide technical peer reviews • Establish interactive team reviews by facility design and operations personnel
Branch Line Probability Uncertainty: Unavailability or incompleteness of initiating event frequencies or FPS performance probability data	• Uncertainty in selected initiating fire event frequencies and conditional probabilities of FPS performance success	• Document available and relevant generic failure data and historical incidents • Document factors that influence failure frequencies and probability ranges • Apply structured and consistent expert review/judgement in the probability selection process • Compare probability estimates against similar historical incident data, fault trees, and previous risk assessment studies, if available
Exposure & Consequence Uncertainties: Invalid fire and explosion consequence modeling assumptions, uncertainties in damage thresholds and associated exposure levels	• Underestimation or overestimation of damage and exposure levels depending on modeling inputs and assumptions	• Document that models are applied within a valid range intended by model developers • Ensure that numerical approximations and assumptions do not compromise credible results and are clearly documented • Check results against similar models or historical incidents • Provide interactive team technical quality reviews
Equivalent monetary value (EMV) Uncertainty: Uncertainty associated with relating all consequence levels to monetary values	• Underestimation or overestimation of aggregate consequences in terms of EMV and total annualized risk estimate	• Provide documentation of the data source(s) and methods to establish EMV • Establish interactive team reviews with designated personnel

Documentation

Figure 7.18 provides an abbreviated example event tree that highlights some of the primary documentation requirements at the bottom of the figure.

Table 7.15, which identifies the selection basis for the event tree probabilities lists the following information:

- Event I.D.
  This relates the event to the event tree identification number
- Event Description
  This briefly describes the event
- FPS Functional Requirement
  This briefly describes the functional requirement of the FPS based on the:
  - Scenario-specific input
  - Risk tolerance objectives
  - The event tree time line
- Selected Frequency (F) or Probability (P)
  This is the selected frequency (events/year) or conditional probability (a number between 0 → 1) which was selected as input for the specific event tree branch line
- Probability Selection Basis
  This is the approach or approaches used to support the probability selection and includes:
  - FTA or performance success tree analysis (STA)
    The reference would include the related reference identification number
  - PIM (performance integrity measures) worksheet
    The reference would include the related worksheet number

Providing a table that documents the probability selection basis is very important as it provides a tool for review, repeatability, consistency, and updating if new or better information becomes available.

Fig. 7.18: Example Event Tree Documentation Items

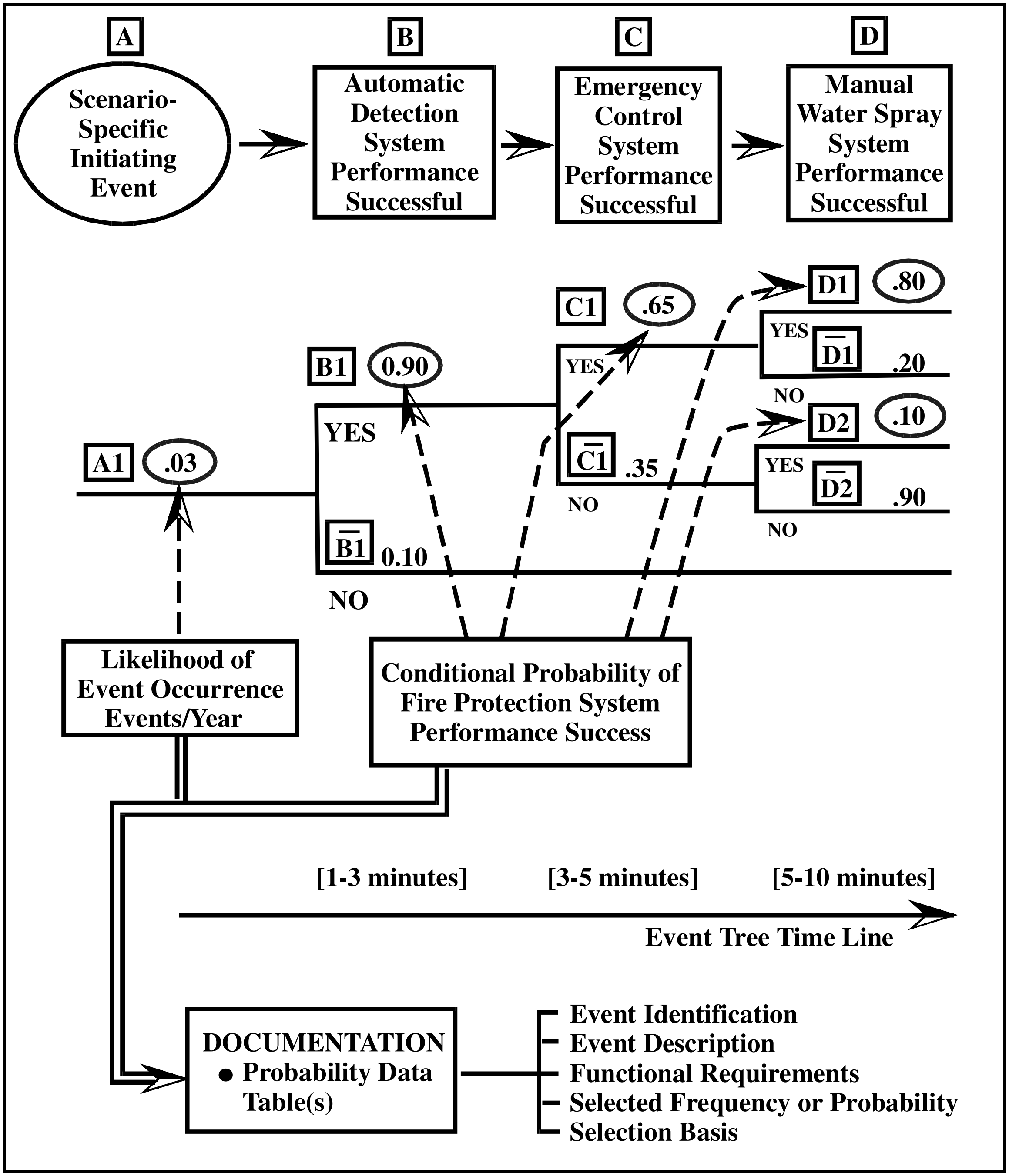


Table 7.15 Example Event Tree Probability Data Table

EVENT ID	EVENT DESCRIPTION	FPS FUNCTIONAL REQUIREMENTS	SELECTED FREQUENCY (F) OR PROBABILITY (P)	PROBABILITY SELECTION BASIS	REMARKS/ REFERENCES
A1	Scenario-specific initiating event flammable liquid release and fire	————	———— .03 (F) events/year	Fault Tree Analysis; FTA Reference A1	
B1	Automatic detection system performance success	Detect fire within 1 – 3 min, initiate alarms, transmit signal to control room	0.90 (P)	Performance Success Tree; STA Reference B1	
C1	Emergency control system (ECS) performance success given detection system is successful	Following detection input, shutdown flammable liquid pumps within 3 – 5 min	0.65 (P)	Performance Success Tree STA Reference C1	
D1	Manual water spray system performance success given ECS is successful	Following fire detection input, activate deluge water spray cooling of process equipment within 5 – 10 min	0.80 (P)	Engineering Design Review. PIM Worksheet Ref. PIM D1, D2	
D2	Automatic suppression system performance success given ECS is not successful	Same as D1	0.10 (P)	Same as D1	

Remarks:
PIM = Performance integrity measure
FPS = Fire protection system
ECS = Emergency control system
FTA = Fault tree analysis
STA = Success tree analysis

7.4.1 Computer Spreadsheet Modeling

Use of a computer spreadsheet program such as Excel by Microsoft to develop event tree analysis (ETA) models and documentation tables provides an efficient means to conduct:

- What-If sensitivity analysis
- Monte Carlo simulation

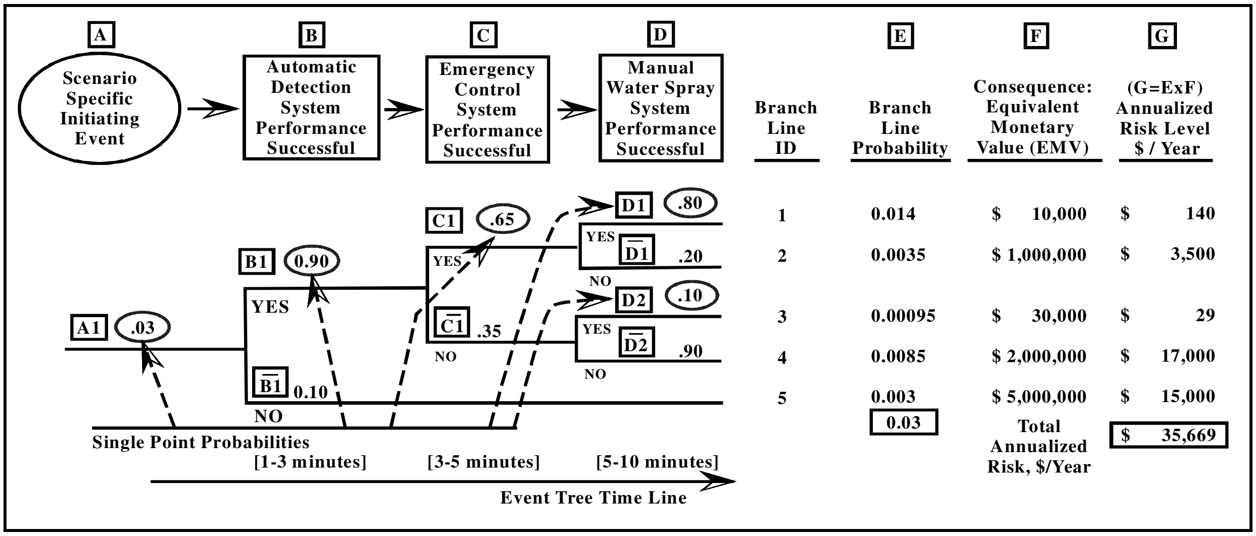
What-If Analysis Versus Monte Carlo Simulation

As presented in Fig. 7.19, the frequency of the initiating events and FPS performance success probabilities are single point values. Single point probability selection within an event tree model involves using a “best selection choice” estimate of variables within a range to determine the risk outcome(s) or levels. The best selection choice or value with the highest likelihood is determined using the methods and criteria discussed in previous chapters with the selection being made by a risk evaluation team and consensus opinion. Therefore the point estimates have a level of technical justification, credibility, informed judgement and consistency. In general, doing a first-order evaluation with point estimates will produce results within an order-of-magnitude bandwith of uncertainty.

In some cases sensitivity analysis of selected variables may be performed to evaluate how much the risk level outcome may vary with changes in variables which have a degree of uncertainty. This is usually performed by selecting various combinations for each variable of interest. These various combinations are commonly known as “what-if” scenarios.

Figure 7.19 presents an event tree with an annualized risk level calculated. Table 7.16 provides an example of value ranges in terms of minimum, most likely, and maximum. With 5 events (A1 → D2) and 3 values per event, this would equate to $3^5 = 243$ possible what-if scenarios.

Fig. 7.19: Abbreviated Event Tree Example



Branch Line ID	Branch Line Probability	Consequence: Equivalent Monetary Value (EMV)	(G=ExF) Annualized Risk Level $ / Year
1	0.014	$ 10,000	$ 140
2	0.0035	$ 1,000,000	$ 3,500
3	0.00095	$ 30,000	$ 29
4	0.0085	$ 2,000,000	$ 17,000
5	0.003	$ 5,000,000	$ 15,000
	0.03	Total Annualized Risk, $/Year	$ 35,669

Table 7.16: Example of Likelihood and Probability Value Ranges

VALUE RANGES	**A1** INITIATING EVENT	**B1** DETECTION SYSTEM SUCCESS	**C1** EMERGENCY SYSTEM (ECS) SUCCESS CONTROL	**D1** WATER SPRAY SUCCESS WITH ECS SUCCESSFUL	**D2** WATER SPRAY SUCCESS WITH ECS NOT SUCCESSFUL
Minimum	0.10 1 occurrence/10 years	0.70	.50	0.70	0.05
Best choice; most likely	0.03* 1 occurrence/33 years	0.90*	0.65*	0.80*	0.10*
Maximum	0.01 1 occurrence/100 years	0.95	0.70	0.85	0.20
* Used as point estimates in Fig. 7.19					

The major drawbacks of what-if analysis include:

- Only three values are being used for each variable (minimum, most likely, maximum), where there could be any number of values
- No recognition is being given to the fact that the "best selection choice" is much more likely to occur than the minimum and maximum values (it is not weighted more heavily)

Monte Carlo simulation is similar to "what-if" scenario analysis in that it generates a number of possible scenarios; however, Monte Carlo accounts for other possible values that each variable could take and weights possible scenarios by the probability of its occurrence.

With Monte Carlo Simulation, uncertain variables within a model (i.e., fault tree or event tree) are addressed by a probability distribution.

There are numerous definitions and references for probability distributions, probability theory and concepts, and probability and statistics calculation methods. Description of these subjects is beyond the scope of this book. Information in the following two boxes is provided for the reader's reference.

Definitions of Some Common Probability Distribution Terms

Discrete random variable: A discrete random variable can have only a discrete number of states or a countable number of values. For example, the outcome of a toss of a coin is a discrete variable since there are only two discrete states that can occur, heads and tails. Similarly, the outcome of a throw of a die is a discrete variable as only six discrete outcome states are possible.

Continuous random variable: A continuous random variable can have an infinite number of values. This does not mean that the range must extend from – ∞ + ∞, only that there are an infinite number of possibilities of the value. For example, if an electric current can have any value between 5 and 10 A but no other, it is a continuous random variable.

Discrete distributions: Discrete distributions are sets of discrete numbers, each having a one-to-one functional relationship to the set of discrete random variables used to develop the distributions.

Continuous distributions: Continuous distributions represent a continuum of numbers each having a one-to-one functional relationship to the continuous random variables used to develop the distributions.

Cumulative distributions: Distributions of ordered (ascending or descending) values of discrete or continuous random variables, where each cumulative functional value is the cumulative representation of all previous functional values in the ordered distribution added to the functional value for the corresponding variable.

Probability: A number between 0 and 1 (inclusive) representing the chance that a given event will occur.

Point estimate: A single value that summarizes a probability distribution e.g., the mean, median, and mode of the distribution.

Probability distribution function: A cumulative discrete or continuous distribution where each functional value represents the probability that a given event will occur at or before the corresponding value of the discrete or continuous random variable.

Probability density function: A discrete or continuous distribution derived from the probability distribution function, describing the relative likelihoods of the occurrence of the possible values of an uncertain quantity.

Variance: The mean of the squares of the variations from the mean of the distribution.

Confidence interval: A range of values of a variable with a specific probability that the value of the variable lies within the range.

Confidence limit: One of the two values — upper and lower — that specify the endpoints or range of a confidence interval.

Standard deviation: The square root of the variance, used as a measure of dispersion or spread in a distribution.

Some References

- Hall, John R., *Probability Concepts*, Sect.1/Chap.11, 2nd Edition of the SFPE Fire Protection Engineering Handbook.

  This handbook chapter introduces the basic definitions and methods of probability theory. Additional references are listed at the end of this chapter.

- Gonick, Larry & Woollcott Smith, *The Cartoon Guide to Statistics*, Harper Perennial, N.Y., 1993

  This book covers probability and statistics in a simple, clear manner with humourous illustrations.

- Vos, David, *Quantitative Risk Analysis, A Guide to Monte Carlo Simulation Modelling*, John Wiley & Sons, England, 1997.

  This book describes risk and probability modeling and the use of Monte Carlo simulation techniques in detail.

7.4.2 Monte Carlo Simulation

A quantitative uncertainty analysis can be performed within a computer spreadsheet such as Microsoft Excel using Monte Carlo simulations.[2] To provide a more reasonable estimate of the probable range of exposures, instead of varying input parameters one at a time, all parameters are assumed to be random or uncertain, and a probability density distribution function for each variable is generated. Spreadsheet add-in computer software such as @Risk or Crystal Ball can now perform thousands of simulations in a matter of minutes. The computer program selects randomly from each distribution every time the model equations are solved, and the procedure is repeated many times resulting in a probability distribution of risk values.

Example of Some Monte Carlo Simulation Software

- **@Risk** — Probabilistic risk analysis and forecasting program can quantify and graphically portray uncertainty levels using Monte Carlo simulations. Works with Lotus 1-2-3 or Microsoft Excel.

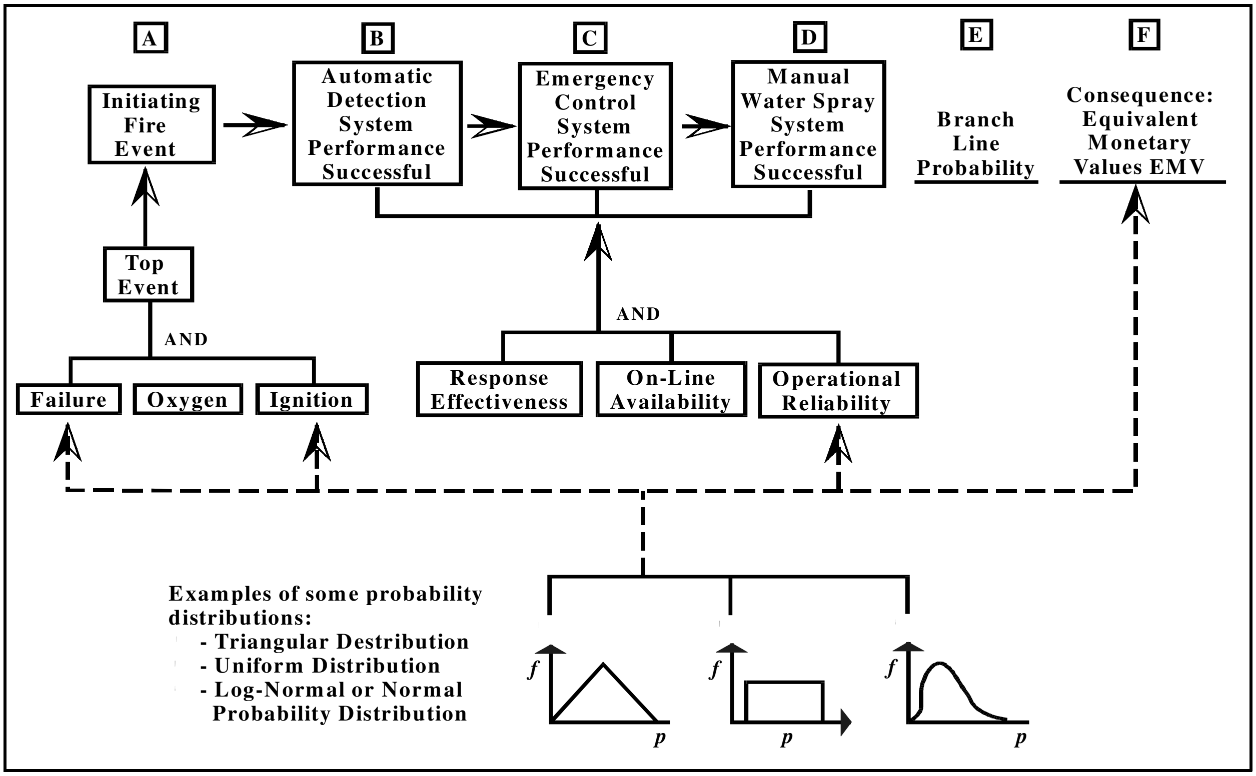
  Palisade Corporation
  31 Decker Road
  Newfield, New York 14867
  Web Site: www.palisade.com

- **Crystal Ball** — Forecasting and probabilistic risk analysis program for spreadsheet users. By specifying probability distributions for variables, can quantify and graphically illustrate uncertainty/confidence levels by Monte Carlo simulations. Works with Microsoft Windows and either Microsoft Excel or Lotus 1-2-3.

  Decisioneering Inc.
  1380 Lawrence Street
  Denver, Colorado 80204
  Web Site: www.decisioneering.com

With Monte Carlo simulation software, probability distributions can be used in the initiating event likelihood analysis (for example if there is uncertainty in failure rates or ignition probabilities), FPS performance STA, or directly within the ETA model. Figure 7.20 presents an example of some areas within a fire risk model where probability distributions can be used to supplement point estimates when uncertainty is present.

Fig. 7.20: Integrating Probability Distributions to Supplement Point Estimates



Random Variables and Probability Distribution

In order to compute a value for the total annualized risk in an ETA model, each ETA event input must be assigned a specific value so that all the related calculations can be performed. However, some uncertainty may exist regarding the value that should be assumed by one or more independent input variables in the ETA model, such as the initiating event likelihood, protection system performance probability, or consequence equivalent monetary values.

A random variable is any variable whose value cannot be predicted or set with certainty. Thus, some input variables in an ETA model represent random variables whose actual values may be difficult to predict with certainty.

Use of computer spreadsheets such as Excel and add-in simulation software such as @RISK allows the use of a number of different types of probability distributions, which provide the random number generation (RNG) functions for performing ETA simulations. @Risk lists the following probability distributions[3]:

Beta
Beta-Subjective
Binomial
Shi-Square
Correlations
Cumulative
Discrete
Discrete Uniform
Error Function
Erlang
Exponential
Extreme Value
Gamma
General
Geometric
Histogram
Hypergeometric
Inverse Gaussian
Logistic
Log-Logistic
Lognormal
Lognormal2
Negative Binomial
Normal
Pareto
Pearson V
Pearson VI
PERT
Poisson
Rayleigh
Student's t
Triangular
Uniform
Weibull

In @RISK, probability distributions are entered directly into worksheet formulas using custom distribution functions. These new functions, each of which represents a type of probability distribution (such as TRIANGULAR or NORMAL), are added to a spreadsheet's function set by @RISK. Both the function name, such as **RiskTriang** — a triangular distribution — and the arguments that describe the shape and range of the distribution, such as **RiskTriang** (10,20,30), where 10 is the minimum value, 20 the most likely value and 30 the maximum value, must be entered when entering a distribution function.[3]

Simulation add-in models such as @RISK have sophisticated capabilities for specifying and executing simulations of ETA spreadsheet models. Both Monte Carlo and Latin Hypercube modeling techniques are supported, and probability distributions of possible results may be generated for any cell or range of cells in the spreadsheet model.

Monte Carlo simulation involves the random sampling of each probability distribution inserted within the ETA spreadsheet model to produce hundreds or even thousands of scenarios (also called iterations or trials). Each probability distribution is sampled in a manner that reproduces the distribution's shape. The distribution of the values calculated for the model outcome therefore reflects the probability of the values that could occur. Monte Carlo simulation offers many advantages, which include:[2, 3]

- The distributions of the model's variables do not have to be approximated in any way.
- Correlations and other interdependencies can be modeled.
- The level of mathematics required to perform a Monte Carlo simulation is quite basic.
- The computer does all of the work required in determining the outcome distribution.
- Software is commercially available to automate the tasks involved in the simulation.
- Greater levels of precision can be achieved by simply increasing the number of iterations that are calculated.
- Complex mathematics can be included (e.g., power functions, logs, IF statements, etc.) with no extra difficulty.
- Monte Carlo simulation is widely recognized as a valid technique so its results are more likely to be accepted.
- The behavior of the model can be investigated with great ease.
- Changes to the model can be made very quickly and the results compared with previous models.

A Short Example

Figure 7.21 provides an example of a fire risk event tree developed in Excel. In this example it is assumed that there is some uncertainty associated with the evaluation of:

- Initiating fire event (event A1)
- Automation detection system performance (event B1)
- Consequence, EMV (for Branch Line 5)

The risk evaluation team wishes to perform an uncertainty analysis applying Monte Carlo simulation. This involves the following steps:

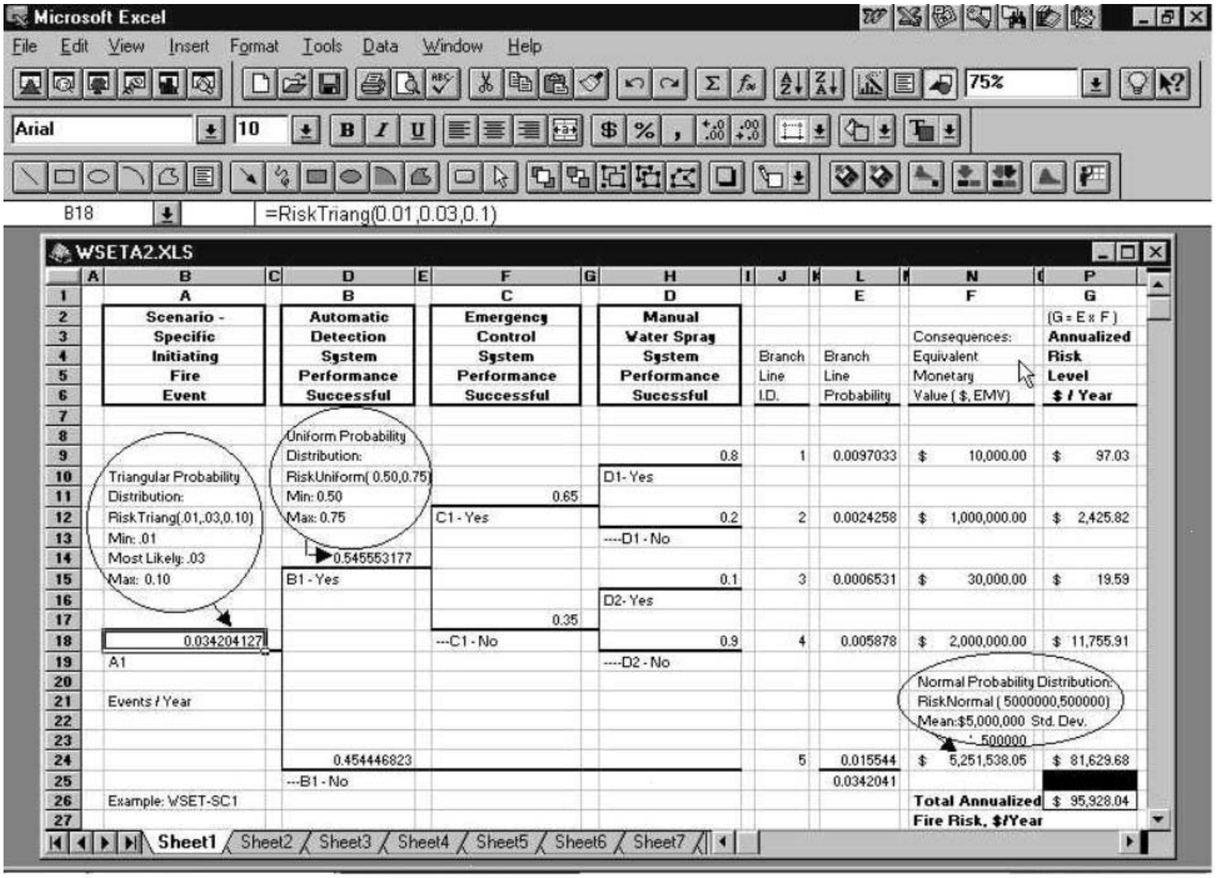
1. Assign RNG probability distribution formulas in each spreadsheet cell that contains an uncertain value
2. Define the simulation settings and output cells
3. Run the simulation and review the outputs
4. Graph the primary outputs

Assigning RNG Probability Distributions

In Fig. 7.21, the following distributions were entered into the spreadsheet:

EVENT	DISTRIBUTION RNG	DESCRIPTION
Initiating Fire Event (A1)	Triangular: Risk Triang (min, most likely, Max) Risk Triang (0.01, 0.03, 0.10)	Returns a value from a triangular distribution covering the range specified by a minimum (min) and a maximum (max). The shape of the distribution is then determined by the size of the most likely value relative to min and max.
Automatic Detection System Performance (B1)	Continuous: Risk Uniform (min, max) Risk Uniform (0.50, 0.75)	Returns a value in the range from a minimum (min) to a maximum (max). Each value in this range is equally likely to occur.
Consequence; EMV (for Branch Line 5)	Normal: Risk Normal (μ,σ) Risk Normal (5,000,000, 500,000)	Returns a value from a normal distribution with mean μ and standard deviation σ.

Fig. 7.21: **Inserting Probability Distributions**



B18 =RiskTriang(0.01,0.03,0.1)

	B	D	F	H	J	L	N	P
1	A	B	C	D		E	F	G
2	Scenario -	Automatic	Emergency	Manual				(G = E x F)
3	Specific	Detection	Control	Water Spray			Consequences:	Annualized
4	Initiating	System	System	System	Branch	Branch	Equivalent	Risk
5	Fire	Performance	Performance	Performance	Line	Line	Monetary	Level
6	Event	Successful	Successful	Successful	I.D.	Probability	Value ($, EMV)	$ / Year
7								
8		Uniform Probability						
9		Distribution:		0.8	1	0.0097033	$ 10,000.00	$ 97.03
10	Triangular Probability	RiskUniform(0.50,0.75)		D1- Yes				
11	Distribution:	Min: 0.50	0.65					
12	RiskTriang(.01,.03,0.10)	Max: 0.75	C1 - Yes	0.2	2	0.0024258	$ 1,000,000.00	$ 2,425.82
13	Min: .01			----D1 - No				
14	Most Likely: .03	0.545553177						
15	Max: 0.10	B1 - Yes		0.1	3	0.0006531	$ 30,000.00	$ 19.59
16				D2- Yes				
17			0.35					
18	0.034204127		---C1 - No	0.9	4	0.005878	$ 2,000,000.00	$ 11,755.91
19	A1			----D2 - No				
20							Normal Probability Distribution:	
21	Events / Year						RiskNormal (5000000,500000)	
22							Mean:$5,000,000 Std. Dev.	
23							500000	
24		0.454446823			5	0.015544	$ 5,251,538.05	$ 81,629.68
25		---B1 - No				0.0342041		
26	Example: WSET-SC1						Total Annualized	$ 95,928.04
27							Fire Risk, $/Year	

The Triangular distribution can be used as a rough modeling tool where the range (*a* to *c*) and the most likely value within the range (*b*) can be estimated. The Triangular distribution offers considerable flexibility in its shape and coupled with its speed of use it has achieved a great deal of popularity among risk analysts. However, *a* and *c* are the *absolute* minimum and maximum estimated values for the variable, and it may be difficult to make estimates of these values. @RISK offers a Trigen distribution that attempts to reduce this problem. It requires “practical” minimum and maximum values and estimates of how likely these values are to be exceeded, as well as the most likely value.[3]

The Triangular distribution is the most commonly used distribution for modeling expert opinion and is a useful distribution for evaluating initiating fire or explosion events. Figure 7.22 provides a summary of the Tringular distribution.[3]

Fig. 7.22: Triangular Distribution[3]

TRIANG(min,most likely,max)

Applications

Rough modeling when actual data is absent.

Density

$$f(x) = \frac{2(x-a)}{(b-a)(c-a)} \qquad \text{if } a \le x \le b$$

$$f(x) = \frac{2(c-x)}{(c-a)(c-b)} \qquad \text{if } b < x \le c$$

where a = min, b = most likely, c = max

Distribution

$$F(x) = 0 \qquad \text{if } x < a$$

$$F(x) = \frac{(x-a)^2}{(b-a)(c-a)} \qquad \text{if } a \le x \le b$$

$$F(x) = 1 - \frac{(c-x)^2}{(c-a)(c-b)} \qquad \text{if } b < x \le c$$

$$F(x) = 1 \qquad \text{if } c < x$$

Parameters

$a \le b \le c$

Domain

$a \le x \le b$

Mean

$$\frac{a+b+c}{3}$$

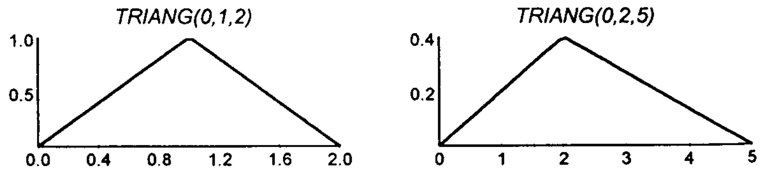
Mode

b

Variance

$$\frac{a^2+b^2+c^2-ab-ac-bc}{18}$$

Triangular Graphs



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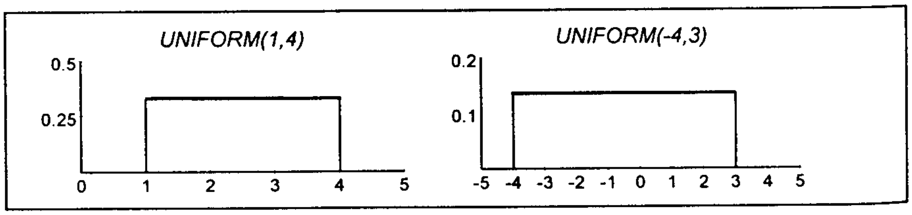
The uniform distribution, Fig. 7.23, is used as a very approximate model. It is rarely a good reflection of the perceived uncertainty of a parameter since all values within the allowed range have the same constant probability density (i.e., same weighting or likelihood). However, it is sometimes useful for evaluating a range of FPS performance success probabilities where a most likely value has not been estimated.

Fig. 7.23: Uniform Probability Distribution[3]

UNIFORM(min,max)

Applications	*Quantities that variy uniformly between two values.*
Density	$f(x) = \frac{1}{max - min}$
Distribution	$F(x) = \frac{x - min}{max - min}$
Parameters	$min \le max$
Domain	$min \le x \le max$
Mean	$\frac{min + max}{2}$
Mode	*No unique mode*
Variance	$\frac{(max - min)^2}{12}$
Uniform Graphs	

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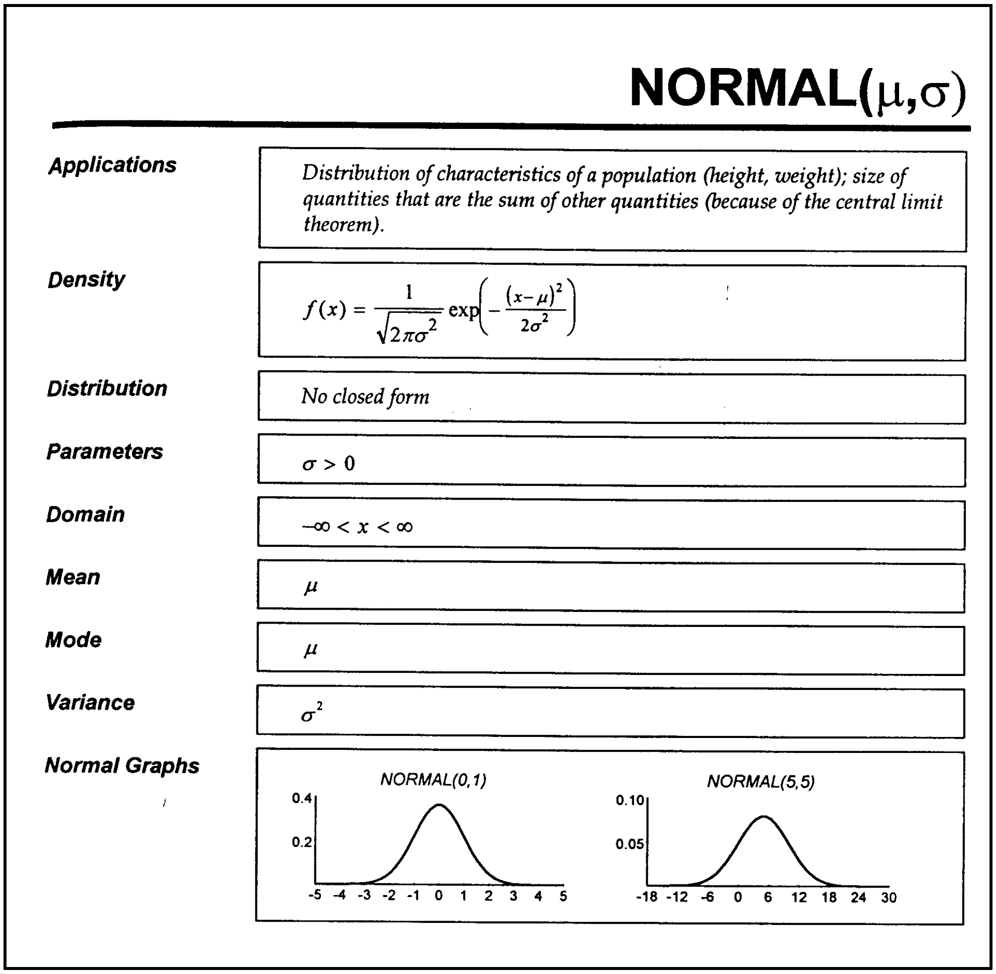
The Normal, or *Gaussian*, distribution, Fig. 7.24, occurs in a wide variety of applications due, in part, to the central limit theorem. It is also frequently observed that variations of a naturally occurring variable will describe a Normal distribution. A Normal distribution is also used in statistical theory for the distribution of errors (for example, in least squares regression analysis) and in finance theory for the distribution of cashflows and returns. It is a particularly useful distribution in finance theory because the sum of and difference between two normal distributions are themselves normally distributed with parameters that can be determined from the central limit theorem.[2,3]

Several other distribution types converge to a Normal distribution as their coefficient of variability (i.e., the standard deviation divided by the mean) approaches zero; Lognormal ($\sigma<\mu/4$), Student's *t*, and Binomial, as well as Poisson and Chi squared. Logistic (*O, β*) and Weibull (α, 3.25) are very close to a Normal distribution, too.

The normal distribution is sometimes useful in evaluating EMV associated with consequence levels.

Fig. 7.24: Normal Probability Distribution[3]



NORMAL(μ,σ)

Applications	*Distribution of characteristics of a population (height, weight); size of quantities that are the sum of other quantities (because of the central limit theorem).*
Density	$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$
Distribution	*No closed form*
Parameters	$\sigma > 0$
Domain	$-\infty < x < \infty$
Mean	μ
Mode	μ
Variance	σ^2
Normal Graphs	

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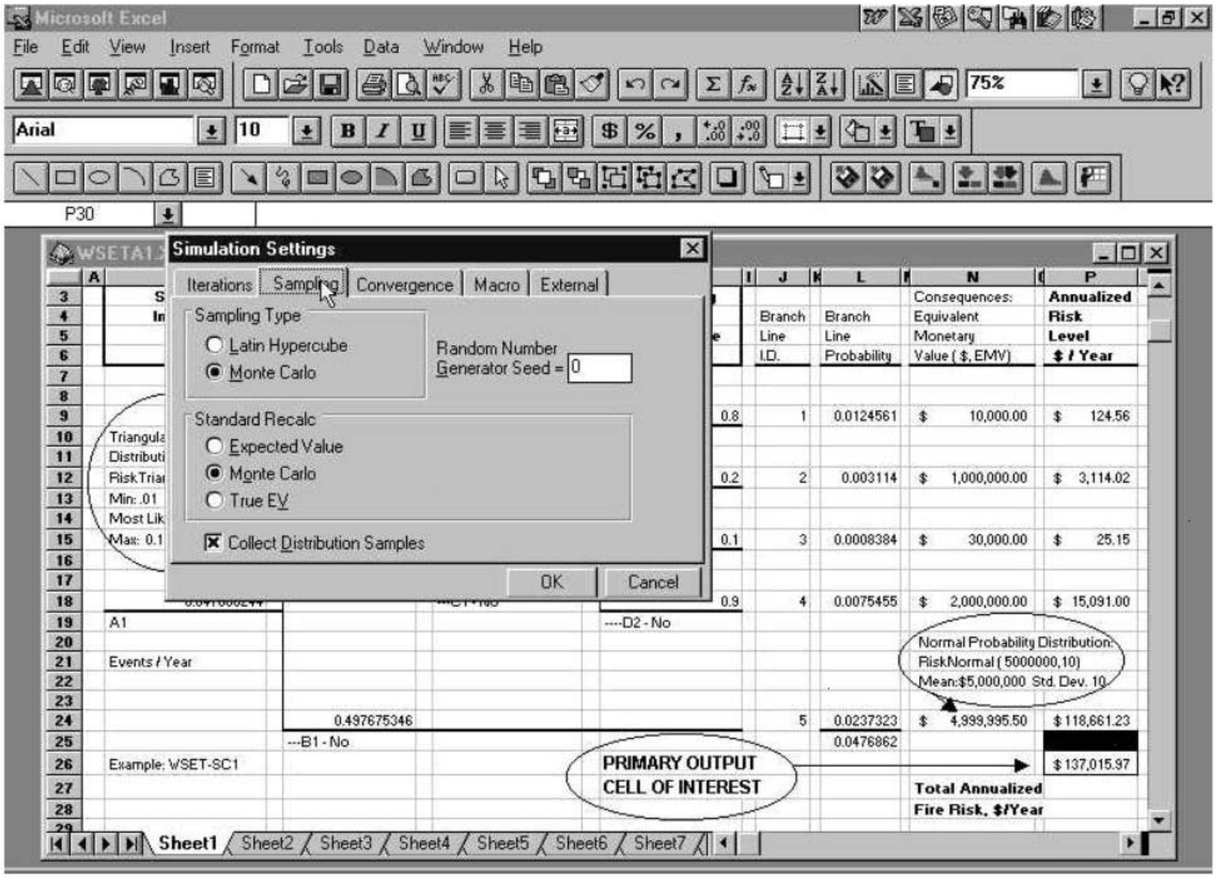
Figure 7.25 provides an example of @RISK Simulation Settings pop-up menu within the Excel™ Spreadsheet. The # Iterations option in @RISK Simulation allows one to specify the number of iterations (or replications) to include in our simulation. For this example, 300 replications were selected. Why not 200, or 1000? Unfortunately there is no easy answer to this question. Remember that the goal in simulation is to estimate various characteristics about the bottom-line performance measure(s) under consideration. For example, we might want to estimate the mean value of the performance measure and the shape of its probability distribution. However, a different value of the bottom-line performance measure occurs each time we manually recalculate the model. Thus, there is an infinite number of possibilities. We cannot analyze all of these infinite possibilities. But by taking a large enough sample from this infinite population, we can make reasonably accurate estimates about the characteristics of the underlying infinite population of values. The larger the sample we take (that is, the more replications we do), the more accurate our final results will be. But, performing many replications takes time, so we must make a trade-off in terms of estimation accuracy versus convenience. Thus, there is no simple answer to the question of how many replications to perform, but, at a bare minimum, you should always perform at least 100 replications, and more as time permits or accuracy demands.[3]

Fig. 7.25: Simulation Settings



Simulation Settings

Sampling Type
○ Latin Hypercube
● Monte Carlo

Random Number Generator Seed = 0

Standard Recalc
○ Expected Value
● Monte Carlo
○ True EV

☒ Collect Distribution Samples

	J	L	N	P
	Branch Line I.D.	Branch Line Probability	Consequences: Equivalent Monetary Value ($, EMV)	Annualized Risk Level $ / Year
0.8	1	0.0124561	$ 10,000.00	$ 124.56
0.2	2	0.003114	$ 1,000,000.00	$ 3,114.02
0.1	3	0.0008384	$ 30,000.00	$ 25.15
0.9	4	0.0075455	$ 2,000,000.00	$ 15,091.00
	5	0.0237323	$ 4,999,995.50	$ 118,661.23
		0.0476862		
				$ 137,015.97
			Total Annualized Fire Risk, $/Year	

Triangula
Distributi
RiskTria
Min: .01
Most Lik
Max: 0.1

A1
Events / Year
0.497675346
---B1 - No
----D2 - No
Example: WSET-SC1

Normal Probability Distribution:
RiskNormal (5000000,10)
Mean:$5,000,000 Std. Dev. 10

PRIMARY OUTPUT
CELL OF INTEREST

Having identified the output cells to track and the number of replications to perform, we now need to instruct @RISK to perform the simulation by clicking the Simulate button on the @RISK toolbar. @RISK then begins to perform the specified number of replications. Depending on the number of iterations selected, the size of the model, and the speed of your computer, it could take anywhere from several seconds to several minutes for these computations to be carried out.

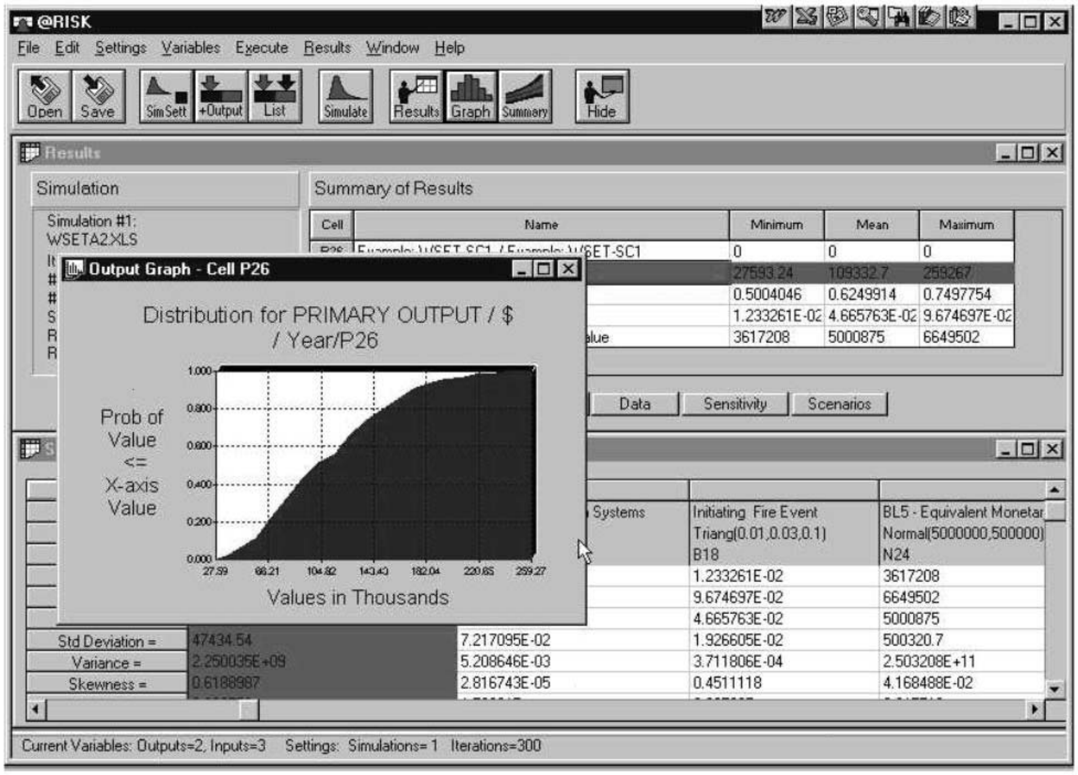
For our example problem, @RISK performs 300 recalculations of the model, keeping track of the value in cell P26 (total annualized fire risk, $/Year) for each replication. The objective of performing a simulation is to estimate various characteristics of the performance measure resulting from uncertainty in some or all of the input variables.

The results indicate an average (or mean) value for cell P26, which is the Total Annualized Fire Risk, $/Year, of $109,333.00. The maximum value is $259,267.00.

@RISK simulation results include distributions of possible results for your outputs. In addition, @RISK generates sensitivity and scenario analysis reports, which identify the input distribution most critical to your results. These results are best presented graphically. Available graphs include frequency distributions of possible output variable values, cumulative probability curves, and summary graphs which summarize changing risk across a range of output cells.

The cumulative probability distribution graph is very useful for evaluating the uncertainty of a variable as shown in Fig. 7.26. One can assess the probability of exceeding any value and can also find the probability of that value lying between any two *x*-axis values: it is simply the difference between their cumulative probabilities.

Fig. 7.26: Accumulative Probability Distribution



Simulation #1:
WSETA2.XLS

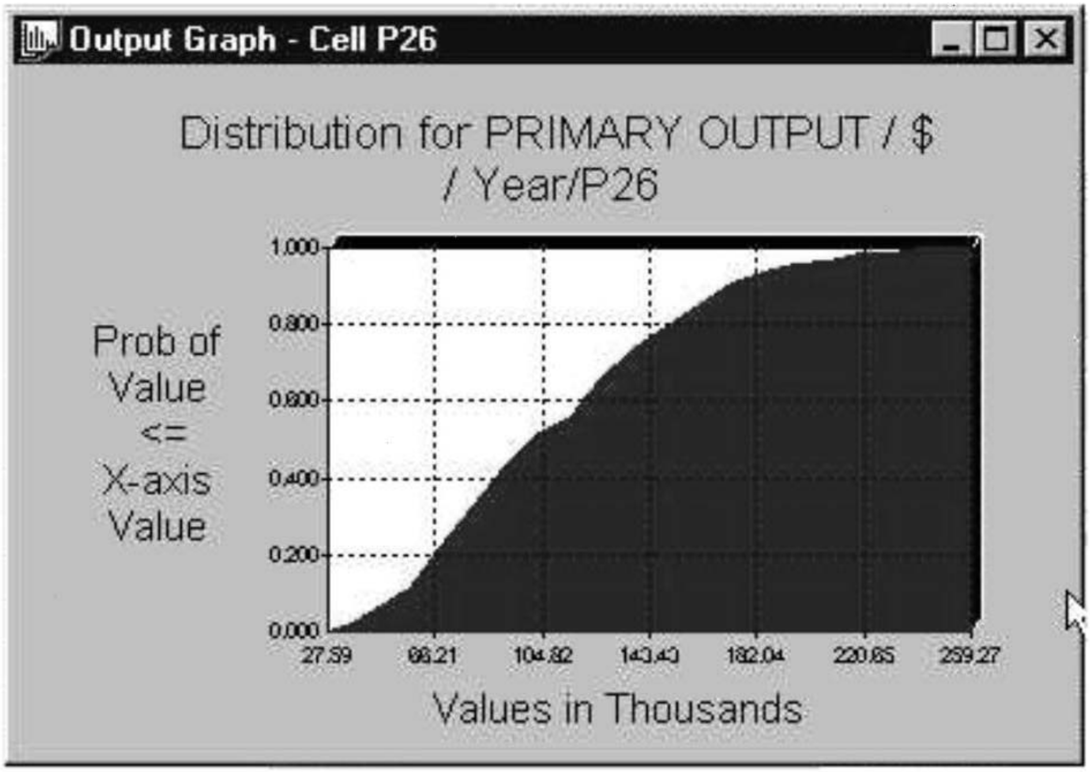
Cell	Name	Minimum	Mean	Maximum
P26	Example:\WSET-SC1 / Example:\WSET-SC1	0	0	0
		27593.24	109332.7	259267
		0.5004046	0.6249914	0.7497754
		1.233261E-02	4.665763E-02	9.674697E-02
	...lue	3617208	5000875	6649502

		Systems	Initiating Fire Event Triang(0.01,0.03,0.1) B18	BL5 - Equivalent Monetar Normal(5000000,500000) N24
			1.233261E-02	3617208
			9.674697E-02	6649502
			4.665763E-02	5000875
Std Deviation =	47434.54	7.217095E-02	1.926605E-02	500320.7
Variance =	2.250035E+09	5.208646E-03	3.711806E-04	2.503208E+11
Skewness =	0.6188987	2.816743E-05	0.4511118	4.168488E-02

Current Variables: Outputs=2, Inputs=3 Settings: Simulations= 1 Iterations=300

Figure 7.27 provides an enlarged view of the example accumulative probability distribution for total annualized fire risk. The decision makers can use a graph of this type for various analysis. For example, this graph indicates that a 95% probability exists that the annualized fire risk will be approximately $225,000 or less.

Fig. 7.27: Enlarged View – Example Accumulative Probability Distribution of Total Annualized Fire Risk



The results of the Monte Carlo simulation analysis give us greater insight into the problem, having some idea of the best- and worst-case total annualized risk outcomes for a company. We have a better idea of the distribution and variability of the possible outcomes, and a more precise idea about where the mean of the distribution is located. We also now have a way of determining how likely it is for the actual outcome to fall above or below some value. Thus, in addition to our greater insight and understanding of the problem, we also have some additional empirical evidence (the facts and figures) to support our risk evaluation and risk reduction recommendations.

Lees notes that many practical problems in reliability and/or availability of complex systems cannot be solved by analytical methods but require numerical simulation. Thus, rather than attempt to analyze the effects of inputs described with probabilistic distributions (e.g., equipment failure rates), Monte Carlo techniques represent the distributions as sequences of discrete random values. A sufficiently large number of these discrete values approximates the original continuous distribution.[4]

Summary

The results of the risk estimation and risk comparison must be communicated to the decision maker(s). The project quality controls, team experience, documentation, and uncertainties must be included within this communication to support the credibility and confidence in the results.

In each of the steps described in this book, measures have been taken to control uncertainties. However, in many cases it would be very costly or near impossible to eliminate all uncertainties. Many decision makers will consider the uncertainty informally while other decision makers may want explicit quantification of uncertainties (i.e., such as Monte Carlo Simulation and accumulative probability distributions of annualized risk estimations).

If the estimated annualized fire or explosion risk exceeds the decision maker(s) risk tolerance criteria, then the evaluation of risk reduction alternatives must be performed. This involves quantification of risk reduction benefit and costs associated with risk reduction opportunities, which is Step 8 in the Risk-Informed, Performance-Based Fire Protection method.

7.5 REFERENCES

1. *Tools For Making Acute Risk Decisions with Chemical Process Safety Applications*, Center for Chemical Process Safety of the American Institute of Chemical Engineers, N.Y., N.Y., 1995.

2. Vose, David. *Quantitative Risk Analysis: A Guide to Monte Carlo Simulation Modelling*. John Wiley & Sons, Chichester, England, 1997.

3. *Guide to Using @ Risk; Risk Analysis and Simulation Add-In for Microsoft Excel or Lotus 1-2-3*. Palisade Corporation, Newfield, NY, 1996.

4. Lees, Frank P., *Loss Prevention in the Process Industries*, Two volumes. Butterworths, London and Boston, 1989.