prioritized risks, (3) probability of exceeding project cost and/or schedule, (4) probability of not achieving project performance requirements, (5) decision analysis results, (6) failure modes and effects (reliability), (7) fault paths (reliability), and (8) probability of failure (reliability).

17.9 QUALITATIVE RISK ANALYSIS

PMBOK® Guide 6th Edition
11.3 Perform Qualitative Risk Analysis

A commonly used qualitative risk analysis methodology involves risk scales (templates) for estimating probability of occurrence and consequence of occurrence, coupled with a risk mapping matrix. The risk is evaluated using expert opinion against all relevant probability-of-occurrence scales as well as the three consequence-of-occurrence scales (cost, technical performance, and schedule) and the results are then transferred onto a risk mapping matrix to convert these values to a corresponding risk level. The risk is included in a prioritized list based upon the risk level as well as other considerations (e.g., frequency of occurrence, the time to impact, and interrelationships with other risks).

Several different classes of risk scales exist.[2] The first type of scale is a nominal scale. Nominal scales have coefficients with no mathematical meaning, and the values are generally placeholders (e.g., freeway numbers). Nominal scales are not used in risk analyses.

The second type of scale is an interval scale. Interval scales, such as Fahrenheit and Celsius temperature, are cardinal in nature. However, the scales have no meaningful zero point, and ratios between similar scales are not equivalent. Interval scales are not commonly used in risk analyses.

The third type of scale is an ordinal scale. Ordinal scales have levels that are only rank-ordered—they have no cardinal meaning *because the true scale interval values are unknown*. There is no probabilistic or mathematical justification to perform math operations (e.g., addition, multiplication, averaging) on results obtained from ordinal-scale values, and any such results may have large errors. For example, relatively simple examples have been developed that contain errors of 600 percent or more when comparing actual versus assumed ordinal-scale coefficients.[3] These scales may be used to represent different aspects of the probability of occurrence (e.g., technology, design, manufacturing) and consequence of occurrence (e.g., cost, schedule, and technical). Ordinal scales are commonly used in risk analyses. Such scales and a corresponding risk mapping matrix can be a helpful methodology for estimating risk. However, for the reasons discussed above great care must be taken in using this approach.

The fourth type of scale is a calibrated ordinal scale. Calibrated ordinal scales are ordinal scales whose scale-level coefficients are estimated by evaluating an additive utility function (or similar approach). These estimated cardinal coefficients replace the ordinal placeholder values. Limited mathematical operations are possible that yield valid results.

2. This section is derived from Conrow, 2003, note 1, pp. 237–245. Copyright © 2003, Edmund H. Conrow. Used with permission of the author.
3. See Conrow, 2003, note 1, pp. 258–268.

However, the values are often relative rather than absolute and the zero point may not be meaningful. Calibrated ordinal scales are not commonly used in risk analysis, in part because of the difficulty in accurately estimating the associated coefficients.

The fifth type of scale is a ratio scale. Ratio scales, such as Kelvin and Rankine temperature, have cardinal coefficients, indicate absolute position and importance, and the zero point is meaningful. In addition, intervals between scales are consistent, and ratio values between scales are meaningful. Mathematical operations can be performed on ratio scales and yield valid results. Although ratio scales are the ideal scales for use in risk analyses, they rarely exist or are used.

The sixth type of scale is based on subjective estimates assigned to different probability statements (e.g., high), termed here "estimative probability." Estimative probability scales can either be ordinal (more common) or cardinal (less common) in nature depending upon the source of the underlying data and the structure of the scale. In the worst case the probability estimates are point estimates or ranges developed by the scale's author with no rigorous basis to substantiate the values. In the best case the probability estimates are derived from a statistical analysis of survey data from a substantial number of respondents and include point estimates and ranges around the estimate for each probability statement. Estimative probability scales are sometimes used in risk analyses. However, this type of scale should never be the first choice when performing a risk analysis because different people may assign different probability values to the same subjective word (e.g., high). This can lead to nontrivial errors in both the estimated probability value and the resulting risk level.

A risk mapping matrix is typically used to convert ordinal probability of occurrence and consequence of occurrence scale values to a corresponding risk level. While there is no preset size for such a matrix, its dimensions must be less than or equal to the number of scale levels used in both the probability and consequence dimensions. With five-level probability-of-occurrence and consequence-of- occurrence scales this corresponds to a 5 × 5 or smaller matrix. As previously mentioned, risk and opportunity are not the mirror images or dual of each other. Hence, it is incorrect to simply assume that a decision maker will have a neutral position towards both risks and opportunities, then claim that a mirror image mapping matrix (sometimes called a "butterfly matrix") can be used to illustrate the level of risks and opportunities.

17.10 QUANTITATIVE RISK ANALYSIS

PMBOK® Guide 6th Edition
11.4 Perform Quantitative Risk Analysis

Several methodologies are commonly used in quantitative risk analyses. These include but are not limited to payoff matrices, decision analysis (typically decision trees), expected value, and a Monte Carlo process. If the potential probabilities of the states of nature can be represented by a point value, as in Figures 17–3 and 17–4, then the decision tree approach (which relies on expected value calculations assuming risk-neutral participants) is often appropriate. On the other hand, if the states of nature cannot be represented by one or more point values, then probability distributions should be used instead. A common methodology that incorporates a model structure and probability distributions is a Monte Carlo process (commonly called a Monte Carlo simulation).

Two keys to producing accurate quantitative risk analysis results include developing an accurate model structure and incorporating accurate probability information. In project risk management there is often insufficient attention paid to each of these items, and the outcome can be inaccurate results. The model structure should be carefully developed and validated before any output is used for decision-making purposes. While this is easy to do for simple decision trees (e.g., those in Figures 17–3 and 17–4), it can be much more complex when scores or hundreds of branches and potential outcomes are involved.

Quantitative risk analysis outputs can be used in a variety of ways, including but not limited to developing (1) prioritized risk lists (similar to that for calibrated ordinal scales), (2) probabilistic cost estimates at completion per project phase and probabilistic schedule estimates for key milestones to help the project manager allocate reserves accordingly, (3) probabilistic estimates of meeting desired technical performance parameters (e.g., missile accuracy) and validating technical performance of key components (e.g., real-time integrated circuit operation), and (4) estimates of the probability of meeting cost, technical performance, and schedule objectives (e.g., determining the probability of achieving the planned estimate at completion, a key schedule milestone, or key technical performance characteristics.) Trends versus time can also be developed from the above outputs by repeating the quantitative risk analyses during the course of the project phase. (Note, however, that the actual trend information will often be masked by uncertainties in the analysis that should reduce as a function of time [holding all else constant]).

Monte Carlo Process

The Monte Carlo process, as applied to risk management, is an attempt to create a series of probability distributions for potential risks, randomly sample these distributions, and then transform these numbers into useful information that reflects quantification of the associated cost, technical performance, or schedule risks. While often used in technical applications (e.g., integrated circuit performance, structural response to an earthquake), Monte Carlo simulations have also been used to estimate risk in the design of service centers; time to complete key milestones in a project; the cost of developing, fabricating, and maintaining an item; inventory management; and thousands of other applications.

A summary of the steps used in performing a Monte Carlo simulation for cost and schedule follows. (Technical performance simulations can have a widely varying model structure and hence may not fit into the outline below.) Although the details of implementing the Monte Carlo simulation will vary between applications, many cases use a procedure similar to this:

1. Develop and validate a suitable cost or schedule deterministic model without risk and/or uncertainty.
2. Develop the reference point estimate (e.g., cost or schedule duration) for each WBS element or activity contained within the model.
3. Check and recheck the model logic (cost and schedule) and constraints (schedule), as incorrect model logic and constraints are surprisingly common and will lead to erroneous simulation results. For example, the percentage of time spent validating the

deterministic schedule logic and constraints should increase with the number of tasks present. For schedules with several thousand tasks more than half of the time should be spent validating the schedule and less than half the time spent obtaining the probability distributions and interpreting the output.

4. Identify the lowest WBS or activity level for which probability distributions will be constructed. The level selected will depend on the program phase—often lower levels as the project matures.
5. Identify which WBS elements or activities contain estimating uncertainty and/or risk. (For example, technical risk can be present in some cost estimate WBS elements and schedule activities.)
6. Develop suitable probability distributions for each WBS element or activity with estimating uncertainty and/or risk. For cost risk analyses cost estimating uncertainty, schedule risk, and technical risk should be considered as separate distributions. For schedule risk analyses schedule estimating uncertainty, technical risk, and possibly cost risk should be considered as separate distributions. With some tools (e.g., some project scheduling software) only a single probability distribution can be used for a given WBS element or activity. In such cases expert judgement will be needed to develop a single probability distribution from multiple data samples.
7. Aggregate the WBS element or activity probability distributions functions using a Monte Carlo simulation. When performed for cost, the results of this step will typically be a WBS level 1 probabilistic cost estimate at completion at the desired probability level and a cumulative distribution function (CDF) of cost versus probability. These outputs are then analyzed to determine the level of cost risk and to identify the specific cost drivers. When performed for schedule, the results of this step will be CDFs of schedule finish dates (and possibly durations) for selected tasks. These outputs are then analyzed to determine the level of schedule risk at the desired probability level and to identify the specific schedule drivers.
8. Sensitivity and scenario analyses should also be considered for cost and schedule risk analyses. However, they should be performed on the probabilistic (simulation) model, not the deterministic model. If the deterministic model is used, probabilistic considerations will not be taken into consideration. For cost risk analysis the sensitivity analysis identifies which elements with probability distributions affect the results (e.g., total program cost, cost by program phase) the most. For schedule risk analyses the percent of time a task is on the probabilistic critical path (e.g., criticality, critical index) coupled with the influence the probability distribution associated with that task has on the specified output (sensitivity, usually derived from correlation or regression) is of considerable value since neither type of information can be obtained from a deterministic analysis. Furthermore, the product of the criticality times sensitivity yields cruciality, which is a measure of the sensitivity times the percent of time the task is on the probabilistic critical path.

Note: It should be recognized that the quality of Monte Carlo simulation results are only as good as the structure of the model, the quality of the reference point estimates, the selection of probability distributions used in the simulation, and how the simulation is implemented.

17.11 PLAN RISK RESPONSE

PMBOK® Guide 6th Edition
11.5 Plan Risk Response
11.6 Implementing Risk Response

Planning risk responses (risk handling) includes specific methods and techniques to deal with known risks and opportunities, identifies who is responsible for the risk or opportunity, and provides an estimate of the resources associated with handling the risk or opportunity, if any. It involves planning and execution with the objective of reducing risks to an acceptable level and exploiting potential opportunities. There are several factors that can influence our response to a risk or opportunity, including but not limited to:

- Amount and quality of information on the event or situation that caused the risk (descriptive uncertainty)
- Amount and quality of information on the magnitude of the damage (measurement uncertainty)
- Personal benefit to the project manager for accepting the risk or opportunity (voluntary risk or opportunity)
- Risk or opportunity forced upon the project manager (involuntary risk or opportunity)
- The existence of cost-effective alternatives (equitable risks or opportunities)
- The existence of high-cost alternatives or possibly lack of options (inequitable risks or opportunities)
- Length of exposure to the risk or time available for the opportunity

Risk response planning must be compatible with the RMP and any additional guidance the project manager provides. A critical part of risk response planning involves refining and selecting the most appropriate response option(s) and specific implementation approach(es) for selected risks (often those with medium or higher risk levels) and opportunities. The selected risk response option coupled with the specific implementation approach is known as the risk response (handling) strategy, which is documented in the risk response (handling) plan. The procedure to develop a risk response strategy is straightforward. First, the most desirable risk response option (of acceptance, avoidance, control [mitigation], and transfer for risks, and acceptance, enhance, exploit, and share for opportunities) is selected based upon cost, performance, schedule, and risk trade studies, then the best implementation approach is chosen for the selected option. In cases where one or more backup strategies may be warranted (e.g., high risks), the above procedure is repeated. (While the selected option for a backup strategy may be the same as for the primary strategy, the implementation approach will always be different; otherwise, the primary and backup strategy would be identical.) Similarly, contingent responses can be developed for risks and opportunities where action is taken only if certain predefined conditions occur. Finally, handling strategies can be developed using a hybrid of up to all four risk or opportunity options coupled with a suitable implementation approach.

Personnel that evaluate candidate risk response strategies may use the following criteria as a starting point for evaluation:

- Can the strategy be feasibly implemented and still meet the user's needs?
- What is the expected effectiveness of the response strategy in reducing program risk to an acceptable level?

- Is the strategy affordable in terms of dollars and other resources (e.g., use of critical materials, personnel, and test facilities and equipment)?
- Is time available to develop and implement the strategy, and what effect does that have on the overall program schedule?
- What effect does the strategy have on the system's technical performance?

A summary of risk response options for risks and opportunities is given in Table 17–6. For risks this includes acceptance, avoidance, mitigation (control), and transfer while for opportunities this includes acceptance, enhance, exploit, and share. In addition, contingent responses are possible for both risks and opportunities.

A brief discussion of the four response options for risks follows:

- *Acceptance* (i.e., retention): The project manager says, "I know the risk exists and am aware of the possible consequences. I am willing to wait and see what happens. I accept the risk should it occur and have allocated sufficient budget, schedule, and other resources to deal with it."
- *Avoidance*: The project manager says, "I will not accept this design because of the potentially unfavorable results. I will change either the design to preclude the risk or the requirements that lead to the risk."
- *Control* (e.g., mitigation): The project manager says, "I will take the necessary measures required to actively mitigate this risk. I will do what is expected."
- *Transfer*: The project manager says, "I will share this risk with others through insurance or a warranty or transfer the entire risk to them. I may also consider

TABLE 17–6. SUMMARY OF RESPONSE OPTIONS FOR RISKS AND OPPORTUNITIES

Type of Response	Use for Risk or Opportunity	Description
Avoidance	Risk	Eliminate risk by accepting another alternative, changing the design, or changing a requirement. Can affect the probability and/or impact.
Mitigation (control)	Risk	Reduce probability and/or impact through active measures.
Transfer	Risk	Reduce probability and/or impact by transferring ownership of all or part of the risk to another party, use of insurance and warranties, by redesign across hardware/software or other interfaces, etc.
Exploit	Opportunity	Take advantage of opportunities.
Share	Opportunity	Share with another party who can increase the probability and/or impact of opportunities.
Enhance	Opportunity	Increase probability and/or impact of opportunity.
Acceptance	Risk and opportunity	Assume the associated level of risk or opportunity without engaging in any special efforts to control it. Budget, schedule, and other resources must be held in reserve in case the risk occurs or opportunity is selected.

partitioning the risk across hardware and/or software interfaces or using other approaches that share the risk."

A brief discussion of the four response options for opportunities follows:

- *Acceptance* (i.e., retention): The project manager says, "I know an opportunity exists and am aware of the possible benefits. I am willing to wait and see what happens. I will accept the opportunity should it occur."
- *Enhance:* The project manager says, "This is an opportunity. What can we do to increase the probability of occurrence of the opportunity, such as by using more aggressive advertising?"
- *Exploit:* The project manager says, "This is an opportunity. How can we make the most of it? Will assigning more talented resources allow us to get to the marketplace quicker?"
- *Share:* The project manager says, "This is an opportunity but we cannot maximize the benefits alone. We should consider sharing the opportunity with a partner."

Finally, while risks and the responses developed to address them may identify potential opportunities, pursuing opportunities will often lead to unanticipated risks. This outcome is rarely if ever discussed by opportunity proponents, yet it can lead to adverse program impacts if the resulting unexpected risks occur.

17.12 MONITOR AND CONTROL RISKS

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11.7 Monitor Risks

The monitoring and control process systematically tracks and evaluates the effectiveness of risk response actions against established metrics.[4] Monitoring results should also be fed back to the prior risk management process steps and may also provide a basis for developing additional risk response strategies or updating existing risk response strategies and reanalyzing known risks. In some cases monitoring results may also be used to identify new facets of an existing risk (or new risks) and revise some aspects of risk planning. The key to the risk monitoring and control process is to establish a cost, technical performance, and schedule management indicator system that the project manager and other key personnel use to evaluate the status of the project. The indicator system should be designed to provide early warning of potential problems to allow management actions.

Risk monitoring and control is not a problem-solving technique, but rather a proactive technique to obtain objective information on the progress to date in reducing risks to

4. Material discussing risk monitoring and control was derived in part from *Risk Management Guide for DoD Acquisition*, note 20, pp. 23–24.

acceptable levels. Some techniques suitable for risk monitoring and control that can be used in a program-wide indicator system include:

- Earned Value (EV). This uses standard cost/schedule data to evaluate a program's cost performance (and provide an indicator of schedule performance) in an integrated fashion. As such, it provides a basis to determine if risk response actions are achieving their forecasted results.
- Program Metrics. These are formal, periodic performance assessments of the selected development processes, evaluating how well the development process is achieving its objective. This technique can be used to monitor corrective actions that emerged from an assessment of critical program processes.
- Schedule Performance Monitoring. This is the use of program schedule data to evaluate how well the program is progressing to completion.
- Technical Performance Measurement (TPM). TPM is a product design assessment which estimates, through engineering analysis and tests, the values of essential technical performance parameters of the current design as effected by risk response actions.

The indicator system and periodic reassessments of program risk should provide the program with the means to incorporate risk management into the overall project management structure. Finally, a well-defined test and evaluation program is often a key element in monitoring the performance of selected risk response strategies and updating risk analyses, and identifying candidate risks.

17.13 SOME IMPLEMENTATION CONSIDERATIONS

While it is important to emphasize a comprehensive, structured risk management process, it is equally important that that suitable organizational and behavioral considerations exist so that the process will be properly implemented. While no single set of guidelines will suffice, because implementation considerations vary on a project-by-project basis, it is important that risk management roles and responsibilities be defined in the RMP and carried out in the program. For example, you need to decide (in advance) within the project:

- Which group of managers have responsibility for risk management decision making?
- Which group "owns" and maintains the risk management process?
- Which group or individual is responsible for risk management training and assisting others in risk management implementation?
- Who identifies candidate risks? (Everyone should!)
- How are focal points (sometimes termed "owners") assigned for a particular approved risk?
- How are risk analyses performed and approved?
- How are risk response plans developed and approved, including the necessary resources for their implementation?