Chapter 5
Schedule Risk Analysis

Abstract The interest in activity sensitivity from both the academics and the practitioners lies in the need to focus a project manager's attention on those activities that influence the performance of the project. When management has a certain feeling of the relative sensitivity of the various activities on the project objective, a better management focus and a more accurate response during project tracking or control should positively contribute to the overall performance of the project.

The technique known as Schedule Risk Analysis (SRA) connects the risk information of project activities to the baseline schedule and provides sensitivity information of individual project activities as a way to assess the potential impact of uncertainty on the final project duration and cost.

5.1 Introduction

Since the introduction of the well-known PERT and CPM techniques in the late 1950s in project scheduling, research on measuring a project's sensitivity has increasingly received attention from both practitioners and academics. This interest is inspired by the observation that a schedule obtained by the PERT/CPM principles assumes that the durations and precedence relations of the project activities are known with certainty. Reality, however, is flavored with uncertainty, which renders the critical path method inapplicable for many real life projects. Consequently, despite its relevance in practice, the PERT/CPM approach often leads to underestimating the total project duration, which obviously results in time overruns in practice. This occurs for the following reasons:

- The activity durations in the critical path method are single point estimates that do not adequately address the uncertainty inherent to activities. The PERT method extends this to a three point estimate, but still relies on a strict predefined way of analyzing the critical path.

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- Estimates about time and cost are predictions for the future, and human beings often tend to be optimistic about it or, on the contrary, often add some reserve safety to protect themselves against unexpected events.
- The topological structure of a network often implies extra risk at points where parallel activities merge into a single successor activity.

Motivated by the common knowledge that the traditional critical path analysis gives an optimistic project duration estimate, measuring the project sensitivity and the ability to forecast the final duration during its execution have become key parameters for project managers. The remainder of this chapter puts a strong focus on the sensitivity of a project's duration as a result of variability in the individual activity durations and not on the cost sensitivity of project activities. Obviously, a risk analysis can also be performed on the cost dimension of a project in order to detect the cost sensitivity of individual project activities on the total cost outline of a project. Since the total activity cost is mostly a weighted sum of its required resources, Sect. 7.6 elaborates on the cost calculations of project activities. Using the cost calculations presented there, the variations of activity durations discussed in the current chapter have an immediate effect on the total activity cost, resulting in cost sensitivity information of the project activities.

Measuring the duration sensitivity of project activities is referred to as *Schedule Risk Analysis* (SRA, Hulett (1996)), which can be considered as an extended version of the PERT/CPM scheduling principles towards a higher degree of uncertainty. Consequently, throughout this chapter, it is assumed that project scheduling and risk analysis need to be integrated for projects lying in quadrant 2 of the project mapping Fig. 1.4.

The outline of this chapter can be summarized as follows. Section 5.2 reviews the four basic steps of a schedule risk analysis study and highlights the central role of the baseline project schedule. In Sect. 5.3, four different sensitivity measures to calculate the duration sensitivity of project activities are discussed. Section 5.4 shows an illustrative example and discusses strengths and weaknesses of these activity sensitivity measures. In Sect. 5.5, the relevance of SRA is put in a practical project tracking and performance measurement setting, and general conclusions of a research study are drawn. Section 5.6 gives a chapter summary and draws general conclusions.

5.2 Schedule Risk Analysis

In this section, the four steps of a successful schedule risk analysis are described. Figure 5.1 gives a graphical overview of an SRA study, which will be outlined into detail along the following paragraphs.

The first step requires a scheduling phase to construct a baseline schedule that serves as a point of reference during the three remaining steps. In a second step,

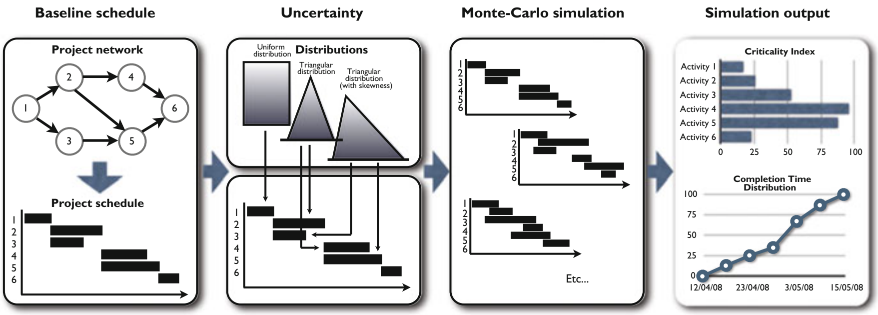

Fig. 5.1 The four steps of a schedule risk analysis

uncertainty needs to be defined resulting in activity duration range estimates. The third step requires an extensive Monte-Carlo simulation run to simulate project progress based on the uncertainty estimates. In a final step, results are reported through sensitivity measures, which require knowledge and understanding of their meaning as well as interpretation for the specific project. This is an important step since metrics without understanding lead to useless results. Beware to always interpret the results of a schedule risk analysis in the light of the characteristics of the project under study.

In the following four subsections, these four steps will be discussed in detail.

5.2.1 Step 1. Baseline Scheduling

When appropriate methods are chosen and the uncertainty of their result is estimated, then the result may be compared to some expected outcome, or to a guideline, standard or baseline level. Both the PERT and CPM methods calculate the shortest path of a project network, the critical path, based on the network logic and the activity duration estimates made by the project manager. However, since estimates are often, if not always, subject to a margin of error, people feel more comfortable with a range of possible project outcomes rather than with a single point estimate like the critical path length. Moreover, the black-and-white view of the CPM methods on the critical activities should be more refined since noncritical (critical) activities have the potential to become critical (noncritical) during the progress of the project.

Consequently, the project baseline schedule serves as a point of reference to which the simulated real project progress of step 3 is compared to. Although it is generally accepted that it is very unlikely that everything will go according to plan, the baseline schedule plays a central role in a schedule risk analysis and the lack of it would lead to incomparable data or even biased results. The construction of a baseline schedule is the topic of Chap. 2 (without renewable resources) and Chaps. 7 and 8 (with renewable resources).

5.2.2 Step 2. Risk and Uncertainty

Risk management requires analytical skills and basic knowledge of statistics, which is often perceived as mathematically complex and sometimes theoretical and far from practice. However, a basic understanding of probability and distribution functions allows the project manager to better estimate the effects of unexpected events on the project outcome. The level of detail of an SRA can be varied according to the level of expertise in mathematics and statistics, as described along the following lines.

- Statistical expert: Formulas for statistical distribution functions and their cumulative counterparts need to be known and understood.
- Basic knowledge of statistics: A basic knowledge about the statistical terminology and the willingness to rely on easy-to-use software tools like Microsoft Excel or graphical supported risk distribution tools allow the project manager to easily set up a schedule risk analysis. The use of basic three-point estimates for risk as an easy approximate alternative for the complex statistical distributions makes schedule risk analysis understandable to a broad audience.
- Statistics for dummies: The classification of project activities in easy-to-understand and well-defined risk classes brings the schedule risk analysis technique to the work floor accessible for people who have never heard about any statistical analysis.

These three levels of statistical expertise, and their impact on the way SRA is done, are briefly outlined in the following three paragraphs.

Statistical Expertise: An expert in statistics is expected to have a profound knowledge of the formulas and characteristics of statistical distribution functions. Once the parameters of these functions are known, one can easily transform any distribution function into a cumulative distribution function (CDF), which allows the generation of a random number from this function. Consider, as an example, the use of an exponential distribution. The cumulative distribution function of a random variable X that follows an exponential distribution can be given by $\mathrm{P}(X \leq x) = 1 - e^{-\lambda x}$ with $\frac{1}{\lambda}$ the mean of the exponential distribution. When u is used as a parameter to denote the cumulative probability $\mathrm{P}(X \leq x)$, which obviously lies between 0 and 1, one can have:

$$u = 1 - e^{-\lambda x} \rightarrow x = -\frac{1}{\lambda} ln(1 - u)$$

u can be replaced by a random generated number from the interval [0,1[, obtained by e.g. the RAND() function in Microsoft Excel, which leads to a randomly generated number from an exponential distribution with an average equal to $\frac{1}{\lambda}$ (see Sect. 5.2.3).

The validity of this exact distribution approach in reality is often questionable due to uniqueness of the project or lack of data about the specific probability distributions. However, the method can be used in research environments where the influence of various project parameters on the project outcome is measured under different scenarios by varying the parameters of well-known statistical probability distributions.

Basic Statistical Knowledge: Risk is often measured through a degree of skewness as a measure of the asymmetry of the probability distribution of a real-valued random variable. The skewness measures can be easily used to express risk as follows:

- No risk: the activity entails no risk and the duration is a single point estimate (i.e. the estimate used in the baseline schedule).
- Triangular distribution
  - Symmetric: The activity is subject to risk within a certain range, with worst case and best case scenarios symmetric above and below the average.
  - Skewed to the right: The activity is subject to risk within a certain range, where activity delays are more likely than early activity durations.
  - Skewed to the left: The activity is subject to risk within a certain range, where early activity durations are more likely than activity delays.

Dummy in Statistics: When statistical knowledge is not available by risk analysts, a simple risk classification to classify project activities into a small set of predefined risk categories representing relative distributions often is a valuable alternative. Each distribution has a certain class name and a well-defined meaning of risk, and each activity can be assigned to each of these classes while a software simulation engine does the rest and provides risk measures for each individual activity.

An example of a risk classification is given below. The reader should note that both the names and the meaning of each risk class are only for illustrative purposes, and can vary along the characteristics of the project, the culture of the company, the wishes and needs of the project team, and many more. Moreover, each risk class is linked to a certain probability distribution, and consequently, these risk classes serve as easy-to-understand tools to define probability distributions that will be used during the Monte-Carlo simulation runs.

- Variation: The activity time estimate is quite reliable, but might be subject to little unexpected changes.
- Foreseen Uncertainty: The activity time estimate is quite reliable, unless a known risk factor shows up. A typical example is a quite reliable time estimate of the project activity, which can be subject to a delay if weather conditions (i.e. the known risk factor) are worse than expected.

- Unforeseen Uncertainty: The activity time estimate is not very reliable and might vary between two extremes.
- Chaos: The activity time estimate is a rough average prediction, and can differ very much from the original prediction in two extremes: much lower or much higher than expected.

5.2.3 Step 3. Monte-Carlo Simulation

Figure 5.2 shows the basic underlying principle of a Monte-Carlo simulation run used in a schedule risk analysis. A simulation run generates a duration for each project activity given its predefined uncertainty profile, as follows:

1. Generate a continuous uniform random number from the interval [0,1[.
2. Add the number as the *u* parameter in the CDF function and search for the corresponding real activity duration.
3. Replace the baseline duration by the newly generated number and recalculate the critical path.

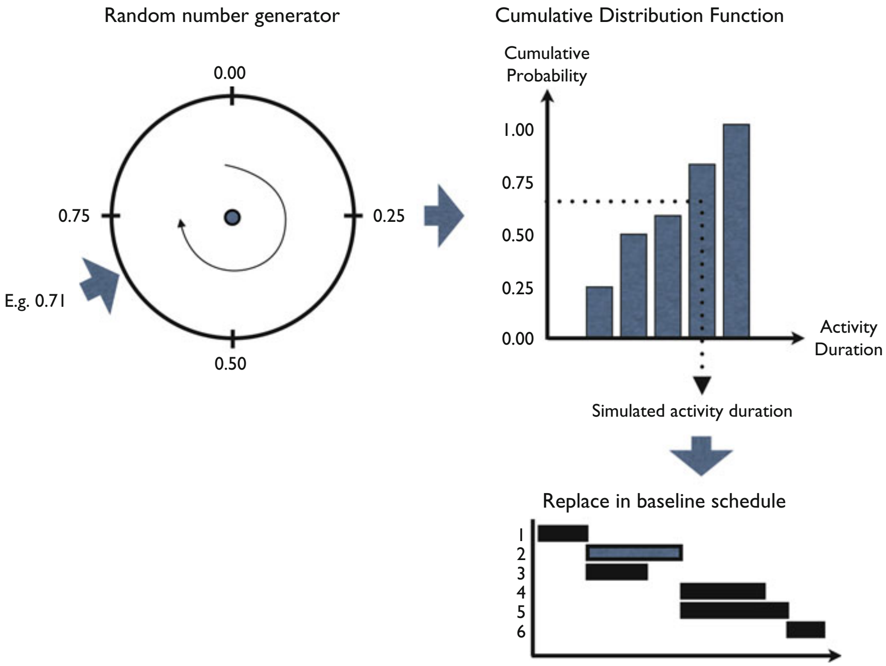

Fig. 5.2 Monte-Carlo simulation principle

This Monte-Carlo approach is used to generate activity durations that might differ from their original baseline values, leading to a change in the set of critical activities and a total real project duration that might differ from its baseline planned duration. The effect of these changes is measured in the next and last step of an SRA run.

5.2.4 Step 4. Results

During each simulation run, the simulation engine has recorded all project schedules and critical paths during the simulated project progress in order to be able to measure the degree of activity sensitivity on the project objective. The output of a schedule risk analysis is a set of measures that define this degree of activity criticality and sensitivity. These measures refine the black-and-white view of the critical path (which defines that an activity is either critical or not) to a degree of sensitivity, as follows:

- Criticality Index (CI): Measures the probability that an activity is on the critical path.
- Significance Index (SI): Measures the relative importance of an activity.
- Schedule Sensitivity Index (SSI): Measures the relative importance of an activity taking the CI into account.
- Cruciality Index (CRI): Measures the correlation between the activity duration and the total project duration, in three different ways:
  - CRI(r): Pearson's product-moment correlation coefficient.
  - CRI(ρ): Spearman's rank correlation coefficient.
  - CRI(τ): Kendall's tau rank correlation coefficient.

Each measure gives the manager an indication of how sensitive the activity is towards the final project duration. Next to the sensitivity measures, an SRA simulation also provides the probability of the project finish over time, expressed in a "cumulative project duration" graph as shown in Fig. 5.3. The values for the sensitivity measures are available upon completion of the simulation run and are used as triggers to focus on the risky activities, which probably require higher attention in order to achieve successful project fulfillment. The specific calculations of each sensitivity measure are discussed in the next section.

5.3 Sensitivity Measures

In this section, the four activity based sensitivity measures are reviewed. The first three measures are originally discussed in Williams (1992) while the last one is published in PMBOK (2004). More detailed information can be found in

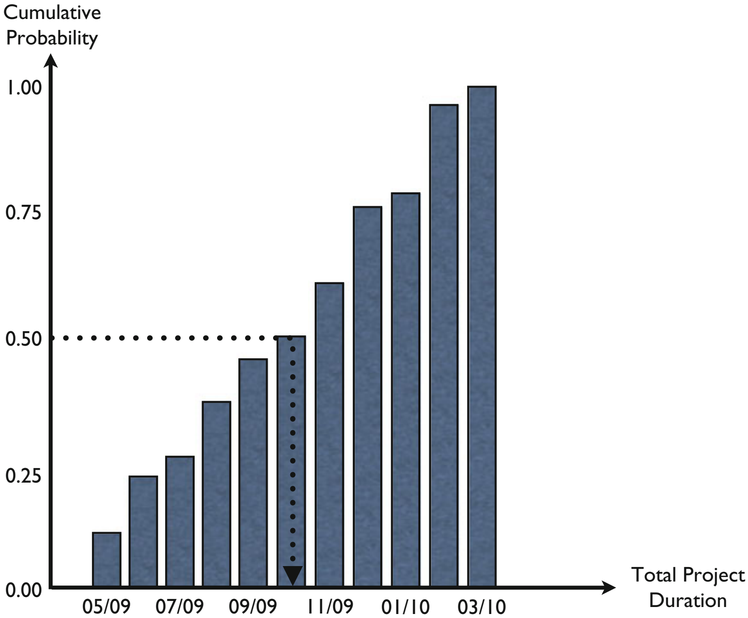

Fig. 5.3 Cumulative project duration graph

Vanhoucke (2010b). The following notation will be used throughout the presentation of the sensitivity measure formulas:

nrs	Number of Monte-Carlo simulation runs (index k)
d_i	Duration of activity i
	(superscript k will be used to refer to the d_i of simulation run k)
tf_i	Total float of activity i
	(superscript k will used to refer to the tf_i of simulation run k)
RD	Total real project duration (as a result of a simulation run)
	(superscript k will used to refer to the RD of simulation run k)

5.3.1 Criticality Index CI

The criticality index measures the probability that an activity lies on the critical path. It is a simple measure obtained by Monte-Carlo simulations, and is expressed as a percentage denoting the likelihood of being critical. The CI of activity i can be given as follows:

$$\text{CI} = \Pr(\text{tf}_i = 0). \tag{5.1}$$

with $\Pr(x)$ the abbreviation used to denote the probability of x.

Although the criticality index has been used throughout various studies and implemented in many software packages, the CI often fails in adequately measuring the project risk. The main drawback of the CI is that its focus is restricted to measuring probability, which does not necessarily mean that high CI activities have a high impact on the total project duration. As an example, it is perfectly possible that an activity with a very low duration always lies on the critical path (i.e. CI = 100%), although it will have a low impact on the total project duration due to its negligible duration.

A simulation-based estimator of CI, denoted by $\widehat{\mathrm{CI}}$, can be calculated easily as the frequency of an activity i being critical over all simulation runs $k = 1, \ldots, nrs$, as follows:

$$\widehat{\mathrm{CI}} = \frac{1}{\mathrm{nrs}} \sum_{k=1}^{\mathrm{nrs}} \mathbf{1}(\mathrm{tf}_i^k = 0), \tag{5.2}$$

where in general the indicator function $\mathbf{1}(.)$ is defined by

$$\mathbf{1}(G) \equiv \begin{cases} 1, \text{ if } G \text{ is true,} \\ 0, \text{ if } G \text{ is false.} \end{cases} \tag{5.3}$$

5.3.2 Significance Index SI

In order to better reflect the relative importance between project activities, the sensitivity index of activity i has been formulated as follows:

$$\mathrm{SI} = E\left(\frac{d_i}{d_i + \mathrm{tf}_i} \cdot \frac{\mathrm{RD}}{E(\mathrm{RD})}\right) \tag{5.4}$$

with $E(x)$ used to denote the expected value of x. The SI has been defined as a partial answer to the criticism on the CI. Rather than expressing an activity's criticality by the probability concept, the SI aims at exposing the significance of individual activities on the total project duration. In some examples, the SI seems to provide more acceptable information on the relative importance of activities. Despite this, there are still examples where counterintuitive results are reported.

A simulation-based estimator of SI is given by

$$\widehat{\mathrm{SI}} = \frac{1}{\mathrm{nrs}} \sum_{k=1}^{\mathrm{nrs}} \left(\frac{d_i^k}{d_i^k + \mathrm{tf}_i^k}\right) \left(\frac{\mathrm{RD}^k}{\overline{\mathrm{RD}}}\right). \tag{5.5}$$

with $\overline{\mathrm{RD}}$ the average of all RD values over all simulation runs, i.e. $\frac{1}{\mathrm{nrs}} \sum_{k=1}^{\mathrm{nrs}} \mathrm{RD}^k$.

5.3.3 Cruciality Index CRI

A third measure to indicate the duration sensitivity of individual activities on the total project duration is given by the *correlation* between the activity duration and total project duration. This measure reflects the relative importance of an activity in a more intuitive way and measures the portion of total project duration uncertainty that can be explained by the uncertainty of an activity.

This measure can be calculated by using the Pearson's product-moment, the Spearman's rank correlation or Kendall's tau rank correlation, as described along the following lines.

(a) A simulation-based estimator of *Pearson's product-moment* of activity i can be calculated as follows:

$$\widehat{\text{CRI}}(r) = \frac{\sum_{k=1}^{\text{nrs}} (d_i^k - \bar{d}_i)(\text{RD}^k - \overline{\text{RD}})}{\text{nrs}\ \sigma_{d_i} \sigma_{\text{RD}}} \tag{5.6}$$

with σ_{d_i} and σ_{RD} the population standard deviations of variables d_i and RD,[1] given by

$$\sigma_{d_i} = \sqrt{\frac{\sum_{k=1}^{\text{nrs}} (d_i^k - \bar{d}_i)^2}{\text{nrs}}} \text{ and } \sigma_{\text{RD}} = \sqrt{\frac{\sum_{k=1}^{\text{nrs}} (\text{RD}^k - \overline{\text{RD}})^2}{\text{nrs}}}. \tag{5.7}$$

This correlation metric is a measure of the degree of linear relationship between two variables. However, the relation between an activity duration and the total project duration often follows a nonlinear relation. Therefore, Cho and Yum (1997) propose to use nonlinear correlation measures such as the Spearman Rank correlation coefficient or Kendall's tau measure. These nonlinear measures can be calculated as follows:

(b) The *Spearman's Rank Correlation* assumes that the values for the variables are converted to ranks and the differences between the ranks of each observation on the two variables are then calculated. A simulation-based estimator is given by

$$\widehat{\text{CRI}}(\rho) = 1 - \frac{6 \sum_{k=1}^{\text{nrs}} \delta_k^2}{\text{nrs}(\text{nrs}^2 - 1)} \tag{5.8}$$

where δ_k is the difference between the ranking values of d_i and RD during simulation run k, i.e. $\delta_k \equiv rank(d_i^k) - rank(\text{RD}^k)$ for $k = 1, \ldots, \text{nrs}$.

(c) *Kendall's tau rank correlation* index measures the degree of correspondence between two rankings as follows:

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[1] Alternatively, the sample standard deviations can be used, given by $s_{d_i} = \sqrt{\frac{\sum_{k=1}^{\text{nrs}} (d_i^k - \bar{d}_i)^2}{\text{nrs}-1}}$ and $s_{\text{RD}} = \sqrt{\frac{\sum_{k=1}^{\text{nrs}} (\text{RD}^k - \overline{\text{RD}})^2}{\text{nrs}-1}}$.

$$CRI(\tau) = \frac{4P}{\text{nrs}(\text{nrs}-1)} - 1 \tag{5.9}$$

where P is used to represent the number of concordant pairs[2] of the d_i and RD variables.

A simulation-based estimator is given as follows:

$$\widehat{\text{CRI}}(\tau) = \left[\frac{4}{\text{nrs}(\text{nrs}-1)} \sum_{k=1}^{\text{nrs}-1} \sum_{\ell=k+1}^{\text{nrs}} \mathbf{1}\left\{(d_i^\ell - d_i^k)(\text{RD}^\ell - \text{RD}^k) > 0\right\} \right] - 1. \tag{5.10}$$

5.3.4 Schedule Sensitivity Index SSI

The Project Management Body Of Knowledge (PMBOK 2004) mentions quantitative risk analysis as one of many risk assessment methods and proposes to combine the activity duration and project duration standard deviations (σ_{d_i} and σ_{RD}) with the criticality index. It is referred to as the Schedule Sensitivity Index (SSI). The measure is equal to

$$\text{SSI} = \left[\sqrt{\frac{\text{Var}(d_i)}{Var(\text{RD})}} \right] \cdot \text{CI} \tag{5.11}$$

and its corresponding simulation-based estimator is given by

$$\widehat{\text{SSI}} = \frac{\sigma_{d_i} \cdot \widehat{\text{CI}}}{\sigma_{\text{RD}}}. \tag{5.12}$$

5.4 Sensitivity Examples

5.4.1 A Fictitious Project Example

This section discusses the use of the sensitivity measures on a fictitious project example displayed in Fig. 5.4. The numbers above each node are used to refer to the activity duration estimates. Table 5.1 shows five fictitious simulated scenarios for the example project network. Each scenario is characterized by a set of activity

[2]Let (x_i, y_i) and (x_j, y_j) be a pair of (bivariate) observations. If $x_j - x_i$ and $y_j - y_i$ have the same sign, the pair is *concordant*, if they have opposite signs, the pair is *discordant*.

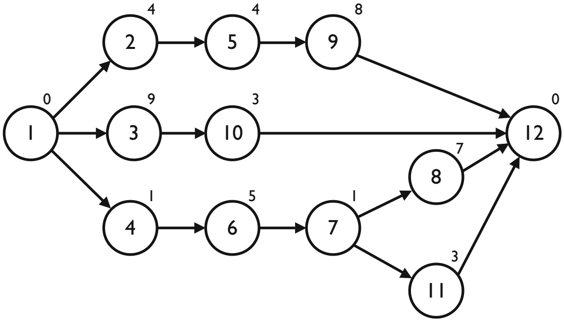


Fig. 5.4 An example project (Source: Vanhoucke 2010a)

Table 5.1 Five simulation scenarios to perform a schedule risk analysis

Scenario	2	3	4	5	6	7	8	9	10	11	RD
1	6	11	1	4	3	2	8	8	5	4	18
2	7	14	1	4	5	1	8	11	5	5	22
3	6	16	1	7	8	1	11	14	6	5	27
4	4	14	1	7	5	1	9	9	5	3	20
5	6	17	2	6	9	2	13	12	4	4	26
Average	5.8	14.4	1.2	5.6	6	1.4	9.8	10.8	5	4.2	22.6
StDev.	0.98	2.06	0.40	1.36	2.19	0.49	1.94	2.14	0.63	0.75	3.44

Table 5.2 The sensitivity measures for all activities obtained through a schedule risk analysis

	2	3	4	5	6	7	8	9	10	11
CI	0.80	0.00	0.20	0.80	0.20	0.20	0.20	0.80	0.00	0.00
SI	0.94	0.82	0.36	0.94	0.61	0.38	0.72	0.97	0.62	0.30
CRI (r)	0.27	0.93	0.49	0.52	0.96	0.14	0.83	0.97	0.09	0.50
CRI (ρ)	0.30	0.88	0.50	0.50	0.88	0.13	0.73	1.00	0.30	0.60
CRI (τ)	0.20	0.60	0.40	0.20	0.60	0.60	0.40	1.00	0.20	0.20
SSI	0.23	0.00	0.02	0.32	0.13	0.03	0.11	0.50	0.00	0.00

durations and a total real project duration RD. Note that scenario 1 corresponds to the Gantt chart presented later in Fig. 12.13.

Table 5.2 displays the values for all sensitivity measures and Table 5.3 displays the intermediate calculations required to calculate the sensitivity measures.

The sensitivity measures are calculated for illustrative purposes for activity 2 of the example network.

Criticality Index CI: The rows of Table 5.3 with label "critical (yes/no)" display for each scenario whether the activity is critical or not, and are used to calculate the criticality index. As an example, the CI for activity 2 is equal to $\mathrm{CI} = \frac{4}{5} = 0.80$.

Significance Index SI: The activity float (row "Total Float") is necessary to calculate the significance index as $\mathrm{SI} = \left(\frac{6}{6+0} * \frac{18}{22.6} + \frac{7}{7+0} * \frac{22}{22.6} + \frac{6}{6+0} * \frac{27}{22.6} + \frac{4}{4+0} * \frac{20}{22.6} + \frac{6}{6+2} * \frac{26}{22.6}\right)/5 = 0.94$.

Cruciality Index CRI: The cruciality index CRI can be calculated using the three formulas:.

- **CRI (r):** The CRI (r) measure is calculated as CRI $(r) = \frac{1}{5*0.98*3.44} * (6-5.8) * (18-22.6) + (7-5.8) * (22-22.6) + (6-5.8) * (27-22.6) + (4-5.8) * (20-22.6) + (6-5.8) * (26-22.6) = 0.27$.
- **CRI (ρ):** In order to avoid errors resulting from nonlinearities, the CRI (ρ) and CRI (τ) require a transformation of the original data into a ranking. In case of tied ranks, the same rank is given to each of the equal values as the average of their positions in the ranking. As an example, placing the activity durations of activity 2 in increasing order for all scenarios results in the following scenario sequence $4 - \overbrace{1 - 3 - 5}^{\textit{tie break}} - 2$ corresponding to a ranking [2,5,3,1,4] for scenarios [1,2,3,4,5]. However, tie breaks occur for scenarios 1, 3 and 5. In this case, the average is taken of their ranking values as $\frac{2+3+4}{3} = 3$, resulting in the ranking [3,5,3,1,3] as shown in the rows with label "ranking (tie breaks)" of Table 5.3. Consequently, the CRI (ρ) measure uses these rankings to calculate the δ values and is equal to CRI $(\rho) = 1 - 6 * \frac{(3-1)^2+(5-3)^2+(3-5)^2+(1-2)^2+(3-4)^2}{5*(5^2-1)} = 0.30$.
- **CRI (τ):** The CRI (τ) measure relies on the Kendall τ coefficient in which the P value can be calculated rather easily by re-ordering the ranks in increasing

Table 5.3 Intermediate calculations for the sensitivity measures

	Scenario	2	3	4	5	6	7	8	9	10	11	RD
Critical	1	Yes	No	No	Yes	No	No	No	Yes	No	No	–
(yes/no)	2	Yes	No	No	Yes	No	No	No	Yes	No	No	–
	3	Yes	No	No	Yes	No	No	No	Yes	No	No	–
	4	Yes	No	No	Yes	No	No	No	Yes	No	No	–
	5	No	No	Yes	No	Yes	Yes	Yes	No	No	No	–
Total	1	0	2	4	0	4	4	4	0	2	8	–
float	2	0	3	7	0	7	7	7	0	3	10	–
	3	0	5	6	0	6	6	6	0	5	12	–
	4	0	1	4	0	4	4	4	0	1	10	–
	5	2	5	0	2	0	0	0	2	5	9	–
Ranking	1	3	1	2.5	1.5	1	4.5	1.5	1	3	2.5	1
(tie breaks)	2	5	2.5	2.5	1.5	2.5	2	1.5	3	3	4.5	3
	3	3	4	2.5	4.5	4	2	4	5	5	4.5	5
	4	1	2.5	2.5	4.5	2.5	2	3	2	3	1	2
	5	3	5	5	3	5	4.5	5	4	1	2.5	4
Ranking	1	3	1	2.5	1.5	1	4.5	1.5	1	3	2.5	1
(re-ordered)	4	1	2.5	2.5	4.5	2.5	2	3	2	3	1	2
	2	5	2.5	2.5	1.5	2.5	2	1.5	3	3	4.5	3
	5	3	5	5	3	5	4.5	5	4	1	2.5	4
	3	3	4	2.5	4.5	4	2	4	5	5	4.5	5
	P	4	8	3	6	8	2	7	10	4	6	–

order of the RD ranking values (the rows with label "ranking (re-ordered)" of Table 5.3). The P value is then calculated by counting for each scenario how many ranking values displayed below the current scenario are higher than the ranking for the current scenario. For example, in scenario 1, only 1 ranking value (i.e. for scenario 2) below scenario 1 is higher than the current ranking value, and hence, the contribution to P is 1. For scenario 4, three ranking values displayed below this scenario have a higher ranking value, and hence, its contribution to P equals 3. Consequently, the P value for activity 2 is equal to $1 + 0 + 3 + 0 + 0 = 4$ and CRI $(\tau) = |\frac{4*4}{5*(5-1)} - 1| = 0.20$. Alternatively, the value can be calculated using Eq. 5.10.

Schedule Sensitivity Index SSI: The schedule sensitivity index can be calculated as $\text{SSI} = \frac{0.98*0.80}{3.44} = 0.23$.

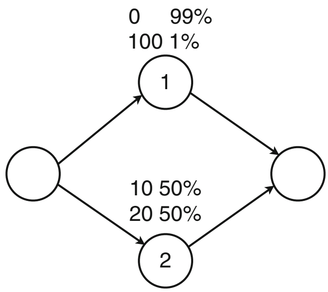
5.4.2 Counterintuitive Examples

In this section, a short critical review is given on the use of three of the four sensitivity measures as a summary from various sources in the literature. It will be shown that each of the following three sensitivity measures, CI, SI and CRI has their own weaknesses, which might lead to anomalies and counterintuitive results. Quite a number of extensions have been proposed to deal with these weaknesses, but only partial answers have been given in these studies. A detailed study of these sensitivity extensions is outside the scope of this book, and the interested reader is referred to the different sources in the literature (see e.g. Cho and Yum (1997), Elmaghraby et al. (1999), Elmaghraby (2000), Gutierrez and Paul (2000), Kuchta (2001), and Williams (1992)).

The use of the criticality index CI has been criticized throughout literature since it is based on probabilistic considerations, which are very far from management's view on the project. Moreover, the metric only considers probabilities, while it is generally known that the risk of an activity depends on a combination of probability and impact. The latter is completely ignored in the CI value, as illustrated in Fig. 5.5. The figure shows a parallel project network (the unnumbered nodes are used to denote the start and end dummy activities) with the possible durations and the corresponding probabilities denoted above each node. Obviously, activity 1 has the highest potential impact on the project duration since it might lead to a project with a total duration of 100 time units. However, the CI of activity 1 is equal to 1%, which is much lower than the CI = 99% of activity 2. Consequently, the values for the sensitivity measures are not always intuitively clear, and they might lead to strange and counterintuitive conclusions.

Although the SI and CRI measures have been proposed to reflect the relative importance of an activity in a better way than the CI, they can, however, both

Fig. 5.5 A parallel two nondummy activity example network (SP = 0) (Source: Williams 1992)



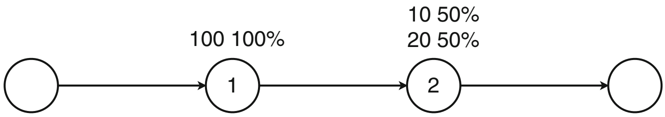


Fig. 5.6 A serial two nondummy activity example network (SP = 1) (Source: Williams 1992)

produce counterintuitive results as illustrated by means of the example network of Fig. 5.6. Clearly, activity 1 has the largest impact on the project duration and $E(\mathrm{RD}) = 115$. However, the SI values are equal for both activities and hence no distinction is made between the sensitivity of both activities. Indeed, the SI is equal to $100\% * \frac{100}{100} * \frac{115}{115} = 1$ for activity 1 and to $50\% * \frac{10}{10} * \frac{110}{115} + 50\% * \frac{20}{20} * \frac{120}{115} = 1$ for activity 2. Even worse, the CRI values show an opposite risk profile for both activities. The CRI measure shows only the effect on the risk of the total project and, consequently, if the duration of an activity is deterministic (or stochastic but with very low variance), then its CRI is zero (or close to zero) even if the activity is always on the critical path. The CRI value for activity 1 is equal to 0% (no variation) while it is equal to $\frac{(10-15)*(110-115)+(20-15)*(120-115)}{2*5*5} = 1$ for activity 2.

5.5 Schedule Risk Analysis in Action

Schedule risk analysis needs, like any risk assessment method, to be used to study and understand the risk inherent to the specific project. However, the different sensitivity measures discussed in this chapter might give different values for the same project and hence require interpretation before they can be blindly used to support decisions. Project managers can benefit from schedule risk analysis only if they understand the meaning of the various sensitivity measures for their specific project in order to provide better and more realistic time and cost forecasts and to support better decisions during a project's progress. In the next sections, the sensitivity measures are discussed as a tool to support the project tracking process to trigger corrective actions in case the project runs into trouble.

5.5.1 Project Tracking

It has been mentioned earlier that the critical path offers a black-and-white view on the project activities which leads to an extreme view on the importance of the various activities during project tracking: an activity deserves attention when it is critical or can be ignored when it is not. The extensions to sensitivity measures discussed in this chapter allow the project manager to refine his/her focus on the project in order to take appropriate corrective actions during project tracking. Rather than having a yes/no measure, it allows to set an action threshold to distinguish between important and less important activities. The use of schedule risk analysis and its activity sensitivity measures to guide the project tracking phase of the project life cycle is known as *bottom-up project tracking*.

Although project tracking or control is the subject of Part III of this book, Fig. 5.7 can be used to illustrate how sensitivity information of project activities (in this case, the CRI(r) of Table 5.2) can be used in a dynamic project tracking environment and how an action threshold can be set to trigger corrective actions in case of problems. This action threshold defines the degree of control, which can vary between no control and full control, and is shown by the vertical dotted line on the figure. All activities with a CRI(r) value higher than or equal to this line are said to be highly sensitive activities that require attention during the tracking process and corrective actions in case of delays. In the example case of the figure, the action threshold has been set at 60% such that only the most sensitive activities 2, 5, 7 and 8 with a CRI(r) value higher than 0.60 need to be considered during the tracking process. These highly sensitive activities (activities 2, 5, 7 and 8 at the bottom of the WBS tree) require full attention and action when necessary. All other activities are said to be insensitive and require less or no attention during project progress.

5.5.2 Network Topology

The bottom-up tracking approach is a project tracking system that classifies project activities in a sensitive/insensitive distinction based on sensitivity measures obtained by an SRA study. However, in order to guarantee timely and effective corrective actions in case of project problems, these sensitivity measures should be able to classify the right activity into the right class. The validity of the four sensitivity measures discussed in this chapter for a bottom-up tracking system has been investigated in a large simulation study of Vanhoucke (2010b) and Vanhoucke (2011) and the following conclusions could be made:

- Network topology: The bottom-up tracking approach is particularly relevant when projects contain more parallel activities, and less attractive for serial activity project networks. The serial/parallel structure of a project network can be measured by the SP (Serial or Parallel) or the OS (Order Strength) indicators discussed later in Sect. 8.3.1. The study has also shown that a top-down project

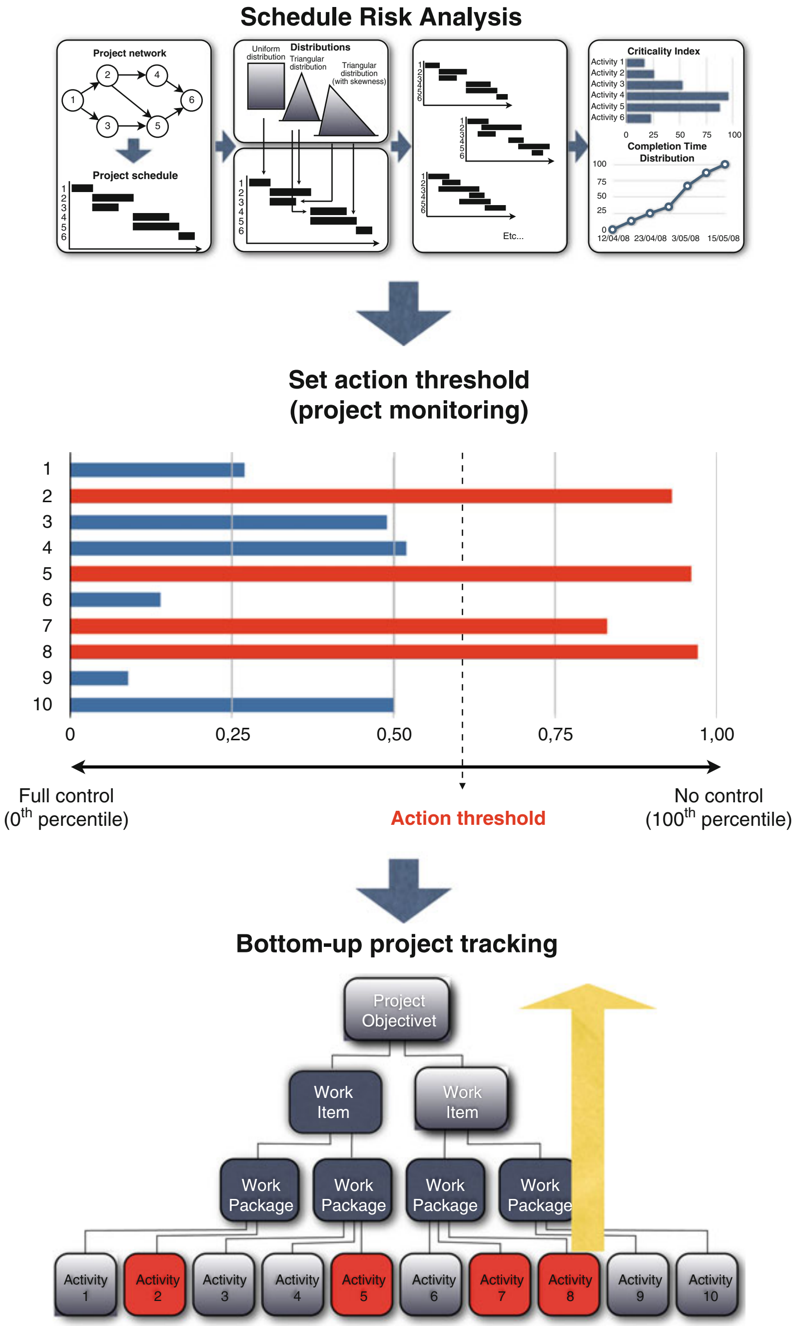


Fig. 5.7 Action thresholds during project tracking using SRA activity information

tracking (as the opposite of the previously mentioned bottom-up project tracking) approach using general project performance measures instead of relying on sensitivity information of individual activities brings a reliable project tracking alternative for more serial activity networks. The impact of network topology measures on the accuracy of top-down and bottom-up tracking approaches will be discussed in Chap. 13.

- The Schedule Sensitivity Index SSI performs best in a bottom-up tracking approach, followed by the CRI(r) and CRI(ρ) measures, when the project contains a lot of activities in parallel (i.e. when SP values are low). Even when action thresholds are set to high values to stimulate a less time consuming tracking approach, the total contribution of corrective actions to the highly sensitive activities remains relatively high. Since high action thresholds for the SSI measure lead to a relative small set of project activities that are said to be important, this means that a small subset of activities is responsible for a high project duration variance.
- When a project contains more and more serial activities (high SP values), the CI, SI and CRI(r) measures perform rather poor, as they are not able to select a small subset of activities to take significant corrective actions. Only the SSI performs reasonably well, leading to significant contributions when taking the appropriate corrective actions.

The influence of the network topology has been implicitly described in earlier SRA studies in the literature. It is recognized that a project with multiple parallel paths has almost always a higher probability to be overrun than a serial activity project network. This is known as "merge bias"(MacCrimmon and Ryavec 1967). This can be easily illustrated on two simplified projects as displayed in Fig. 5.8. Activities 1 and 2 have duration estimates that are, for the sake of simplicity, assumed to consist of three single point estimates with an equal probability, i.e. $d_i = 3, 4 \text{ or } 5, i = \{1, 2\}$ with a probability of 33%. Activity 3 has a fixed duration equal to 4. Since average activity durations are equal to 4 time units for all activities, both average critical paths are equal to 8 time units.

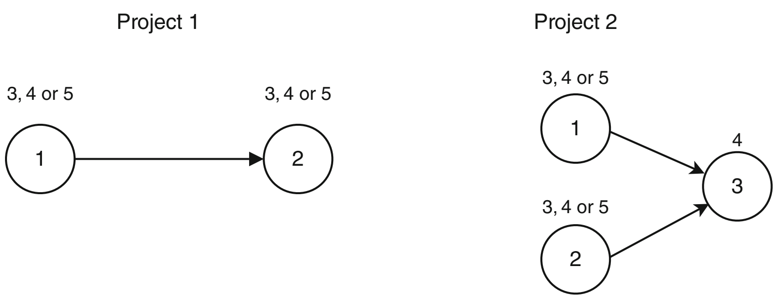


Fig. 5.8 Two projects with serial (*left*) and/or parallel (*right*) activities

Table 5.4 The effect of multiple parallel paths: the merge bias

Act 1	Act 2	Act 3	CP_1	CP_2
3	3	4	6	7
4	3	4	7	8
5	3	4	8	9
4	3	4	7	8
4	4	4	8	8
4	5	4	9	9
5	3	4	8	9
5	4	4	9	9
5	5	4	10	9
4	4	4	8	8.44

However, when risk is taken into account, the project duration might be different from the average deterministic critical path. Clearly, path merge points, i.e. project activities with multiple predecessor activities, will lead to an increase in project risk, as can be illustrated with the example projects in Table 5.4. The table shows all possible durations for each project activity and the corresponding project critical path for project 1 (CP_1) and project 2 (CP_2). The table shows that the second project duration is always longer than the first one, with an average project duration of 8.44 (bottom row), which is one time unit longer than the deterministic critical path of 8.

Consequently, it should be clear that for real projects, which contain multiple parallel paths and merge points, the deterministic critical path, which is based on average project duration estimates, is often not a realistic estimate of the total project duration. A schedule risk analysis identifies and quantifies this merge bias and highlights the real critical components of a project taking ranges of activity estimates into account.

5.6 Conclusion

This chapter discussed the features of a schedule risk analysis (SRA) in project scheduling and reviews the four basic steps: (1) create a baseline schedule, (2) define uncertainty as ranges in activity durations (and costs), (3) perform a Monte-Carlo run to simulate project progress and (4) report sensitivity measures and interpret the results. The chapter discussed the relevance of four activity based sensitivity measures: the criticality index CI, the sensitivity index SI, three variants of the cruciality index CRI and the schedule sensitivity index SSI, and illustrates their use on a fictitious project example. Finally, a simulation study has been briefly summarized to illustrate the usefulness of these sensitivity measures in practice. The study aimed at investigating whether the activity sensitivity measures are able to distinguish between highly sensitive and insensitive project activities in order to steer the focus of the project tracking and control phase to those activities that are likely to have the most beneficial effect on the project outcome.

The chapter should be relevant to practitioners since it provides general guidelines where the focus of a project manager should be during the project tracking phase. The results show that a bottom-up project tracking approach could lead to reliable results and that its use depends on the topological structure of the underlying project network. More precisely, the results show that it is particularly useful for parallel project networks where detailed activity sensitivity information is required at the lowest WBS levels during project tracking in order to support corrective actions when the project runs into trouble. Consequently, project managers need a certain feeling of the relative sensitivity of the individual activities on the project objective, in order to restrict the management focus to only a subpart of the project while still being able to provide an accurate response during project tracking to control the overall performance of the project. In Part III of this book, this bottom-up project tracking process is outlined and discussed into detail.