3

A Broader Look at Project Risk Management

3.1 Understanding the Fundamental Types of Uncertainty

We examined the power of the project risk management approach in Chapter 1, and we observed some limitations of PRM practices in Chapter 2. In order to understand the power of the PRM approach, and the roots of its failure, we need to understand and classify the *sources* of project risks, not only by the contextual source, as is done, for example, in risk lists, but also by the foreseeability of the underlying influence factors and by the complexity of the project. Figure 3.1 offers illustrations of the major concepts that we will be discussing in this chapter.

The top picture in Figure 3.1 illustrates the sources of risk that standard PRM methods are designed for: *foreseeable uncertainty* and *residual risk.* We saw in Chapter 1 how PRM embodies a mind-set of planned flexibility: Obstacles, alternative paths, and alternative targets are identified and outlined at the outset, and a switch to the preventive, mitigating, or contingent path (action) is triggered when monitoring indicates that an obstacle has indeed occurred. This may even include response to unforeseen, or "residual," risk via extra capacity (slack) or improvisational problem solving that allows the project to recover when small, unforeseen obstacles appear on the horizon.

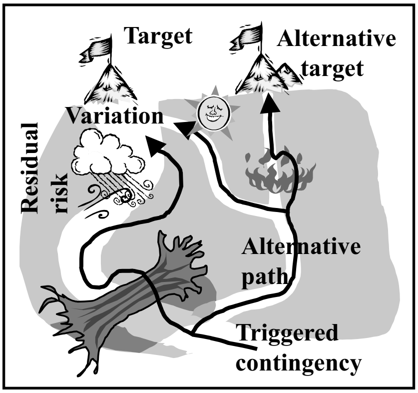
Another source of project uncertainty is project *complexity* (illustrated in the middle picture of Figure 3.1). Project complexity can arise from either complexity in project tasks or stakeholder relationships. As we saw in the PCNet example in Chapter 1, the complexity of potential interactions in the e-mail system made it virtually impossible for the project team to predict the consequences of local changes to the system, resulting in lost e-mails and other system malfunctions. Thus, the project team had to implement rigid control over, and fast response to, local tweaks to the system in order to keep it within a known "control state."

The final, and most difficult, sources of project uncertainty are what the engineering community refers to as *unknown unknowns* (unk unks) (illustrated in the bottom picture of Figure 3.1). As we saw in the Circored project in Chapter 2, projects that are novel in terms of the technology employed and/or the markets pursued, and projects of long duration, are commonly plagued by fundamentally unforeseeable events and/or unknown interactions among different parts of the project.[1] A "straight" application of PRM, without recognizing the additional novelty challenge, is insufficient and may have destructive effects.

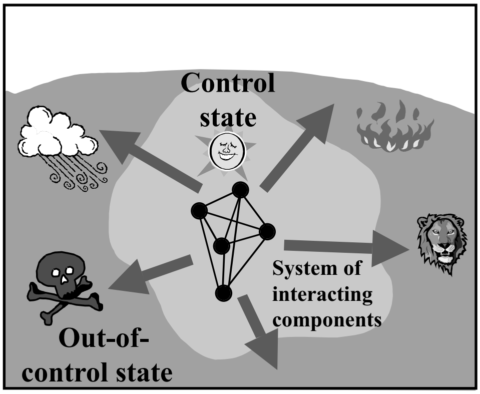
In this chapter, we classify sources of uncertainty and complexity in projects, discuss the current state of the art in PRM, and then preview what we propose should be done when a project must "manage the unknown."

3.2 Foreseeable Uncertainty and Residual Risk

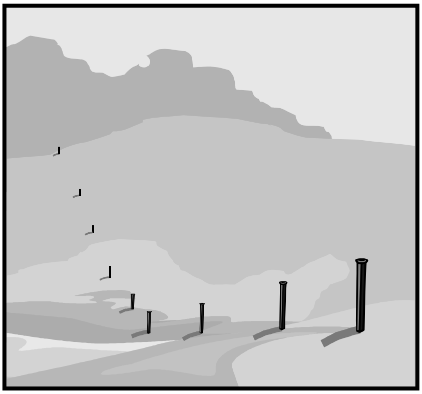
We begin by observing that the standard PRM approach rests on a fundamental assumption—namely, that we are operating essentially on known terrain, where it is known, in principle, what events and outcomes of actions to expect and, with moderate complexity where the nature of the "solution space" is roughly known, where an action does not cause entirely unexpected effects in different parts of the project and where a best course of action can be chosen. In other words, we can *foresee* the range of things that can happen, and their causes, even if we may not be able to predict with certainty which of the identified events will happen or to what degree of probability they are likely to occur.



Variation, risk, and residual risk



Maintaining a control state to avoid unk unks



Major unavoidable unk unks:
No known path but stakes in the
ground pretend we have one

Figure 3.1 The fundamental sources of project risk

We find it useful to consider two different types of foreseeable uncertainty, although theoretically, they are similar: variation and foreseeable events. We will then conclude this section with a discussion of residual risk, recognizing that there will always be some risk that escapes the initial risk planning process.

3.2.1 Variation

In many projects, it is not possible to identify and proactively influence all risk factors (partly because no historical data are available on which to base the estimates). The widening of the path in the top picture of Figure 3.1 depicts a situation that is virtually universal in projects: We can choose courses of action, but we do not know exactly what the values of the influence variables are and/or the nature of their impact on the final project status. Thus, the final project status can be planned only with "noise," represented in the picture by the widening of the path.

Variation in project performance makes the project outcome a nondeterministic event, a *range* of outcomes with probabilities. It is dangerous to pretend that this range of outcomes does not exist and to force teams to commit to deterministic targets. Forcing a deterministic answer to a stochastic problem often causes people to cover themselves and become overly conservative in their estimates. Project managers have long known this and have developed two methods for highlighting and managing variation: simulation techniques and project buffers.

Simulation and the Communication of Uncertainty

Consider the example of a traditional project plan, usually depicted in the form of a Gantt (or bar) chart, or equivalently, as a so-called network flow diagram or activity network. An example is shown in Figure 3.2, which depicts the plan of a 10-week project for preparing the bid for the development of an unmanned aerial vehicle (UAV), the type of small automated flying vehicle that was used for reconnaissance in the Iraq war in 2003.[2] The output of the project was not a UAV, but a bidding document for the development of a UAV, including a structural design and a cost analysis.

In the figure, nodes represent activities (with expected duration in days), and arrows the precedence relationships among the activities. The critical path is the traditional notion of the project's duration (marked by the bold arrows): It is determined by the longest path from the beginning node (A1) to the end node (A10), which restricts how quickly the project can be carried out. The length of the critical path in Figure 3.2 is 57 days. The critical path is used to give a feeling for the project's duration ("we can only do it in 10 weeks if we work 7 Saturdays out of the 10 weekends") and to focus on the critical activities.

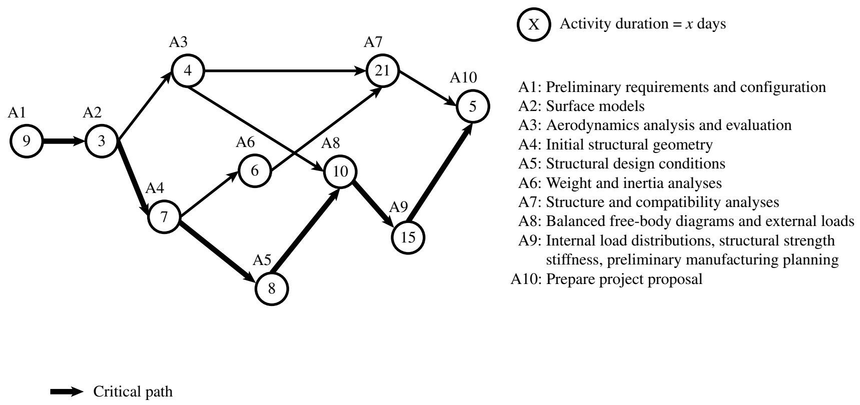


Figure 3.2 A network flow diagram of a project schedule

The problem with the critical path is that it implies that the duration is deterministic. For each activity, the "expected" durations are used. But that, of course, is fiction. In reality, activity durations are subject to variation—that is, to more or less important deviations from the expected duration. Variation is due to a myriad of little reasons that cannot be analyzed or predicted in detail, simply because there are too many of them. For instance, the engineers know that activity A1 may take between 9 and 12 days, and A7 between 18 and 27 days, and so on. The duration is not a number, but it has a (statistical) distribution.

Once we acknowledge that the activity durations have distributions, we can *simulate* the project duration.[3] Now, the project duration can be shown as a *histogram* (see the left-hand side of Figure 3.3); in other words, the project duration has a distribution, just as the activities do.

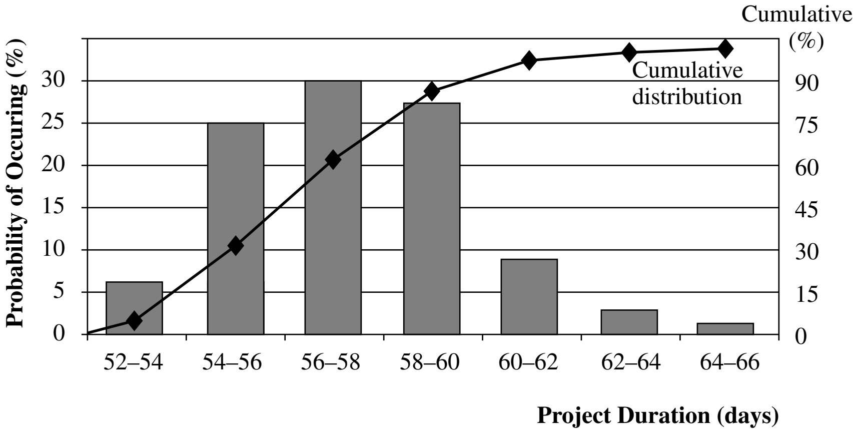


Figure 3.3 Histograms, or distributions, of the project duration

The histogram tells us several useful things: With variation, the project may be completed as quickly as in 53 days, but it may also take 65 days. Adding the bars to the right of 60 days, the histogram tells us that there is a 12 percent chance that the project may take longer than 60 days, which means that we can only get it done in 10 weeks if we work every Saturday plus several Sundays.

For the project manager, this raises the question: “Am I willing to bet that it will really take only 57 days, and schedule only 7 Saturdays, running a 12 percent risk that I will miss the bidding deadline?” In other words, making the variation explicit with simulation allows the project manager to think in terms of a service level, or a risk of missing the deadline, rather than working with a fixed estimate. If, for instance, the project manager wants to be 99 percent sure that the deadline will be made, she must schedule all the Saturdays plus four Sundays, so the deadline is missed with only a 1 percent chance that the project will take the maximum 65 days.

Project Buffers

An alternative way of explicitly acknowledging project variation, somewhat simplified in comparison to simulating the entire duration histogram, is to use project buffers. These take the form of schedule buffers, budget contingencies, or specification compromises. Buffer management has been a well-understood part of PRM for a long time.[4]

The idea is to schedule all activities at their latest start times according to classic critical path calculations (the critical path is the sequence of activities that have no “slack”—that is, for which a delay of one day immediately translates into a project delay of one day). A safety buffer is added at the *end* of the project rather than during each activity. This buffer protects the promised (deterministic) completion time from variation in the tasks on the critical path. “Feeding buffers” are placed whenever a noncritical activity feeds into the critical path, both to protect the critical path from disruptions caused by the feeding activities and to allow the critical chain activities to start early when things go well (see Figure 3.4).

A critical step is moving the “safeties” from the individual activities into the project buffer. Task completion time estimates should be at the median, implying that they are missed 50 percent of the time. As activities evolve, management keeps track of how much the buffers are consumed. As long as there is some predetermined fraction of the buffers remaining, all is assumed well; otherwise, problems are flagged or corrective action is taken. Goldratt (1997, p. 157) recommends that the project buffer be 50 percent of the sum of the safeties of the individual activities; Herroelen and Leus (2001) show that the project buffer may be even smaller, as little as 30 percent, in large projects with a “typical” structure of task distributions.

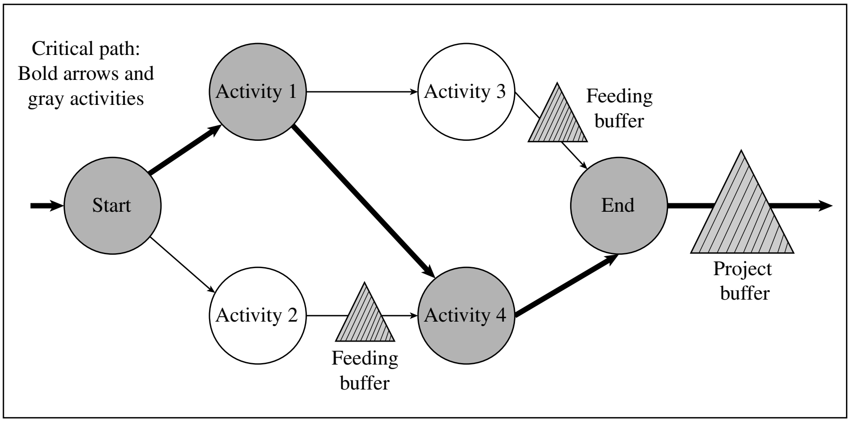


Figure 3.4 A project plan with project buffer (*Source:* Herroelen and Leus 2001).

The key to the effectiveness of the project buffer is realizing that it is not mainly a calculation device, but a tool to change attitudes: Project workers no longer need to protect their own schedule (so they no longer need to low-ball), nor can they procrastinate because they impact the overall buffer that everyone looks at and depends on. The entire team "sits in one boat." It is mostly this change in mutual commitment that has made buffer management popular over the last five years.

3.2.2 Foreseeable Events

Foreseeable events are represented by the alternative path and target in the left-hand picture of Figure 3.1. We know that certain events may take place (although we are not sure), and we can anticipate alternative courses of action that we trigger when the events occur. This is precisely the notion of risk identification and contingency planning that underlies established PRM, as described in Chapter 1, and represented by the Circored risk list in Figure 2.2.

Let us return to the UAV project described in Section 3.2.1. The project flow diagram, as depicted in Figure 3.2, is not correct. The engineers know from experience that in about 30 percent of bidding designs, the resulting load distributions and stiffness analyses indicate a problem that requires them to rerun the structural geometry, structural design, and free-body diagrams (tasks A4, A5, and A8 in Figure 3.5). Critical path analysis cannot handle loops (the path would be infinitely long, turning on itself). This inability really affects current project management tools: Try to specify a loop in Microsoft Project; it will give you an error beep!

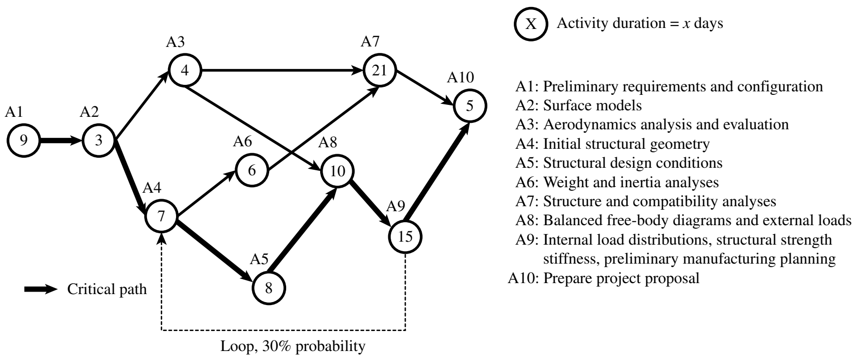


Figure 3.5 A network flow diagram of a project schedule with rework loop

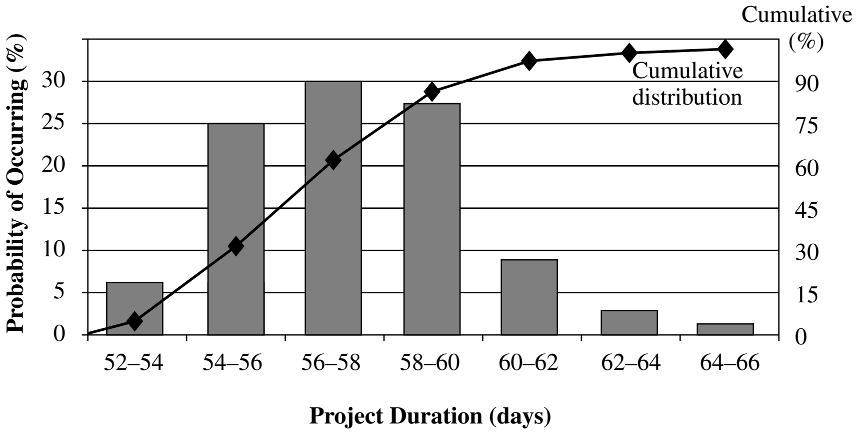
It is very easy to incorporate a rerunning of activities A4-A9 with a probability of 30 percent into the simulation. The resulting histogram is shown in the right-hand side of Figure 3.6. Bad news! The entire histogram of the left-hand side of the figure is now collapsed into the far left two bars (we need a larger scale of the *x*-axis in order to accommodate much longer durations). If the rework loop occurs, the project duration will be between 90 and 110 days! That means there is no way the team can make the deadline, even if it works 7 days a week, and on top of that, 2 hours' (25 percent) overtime every day.

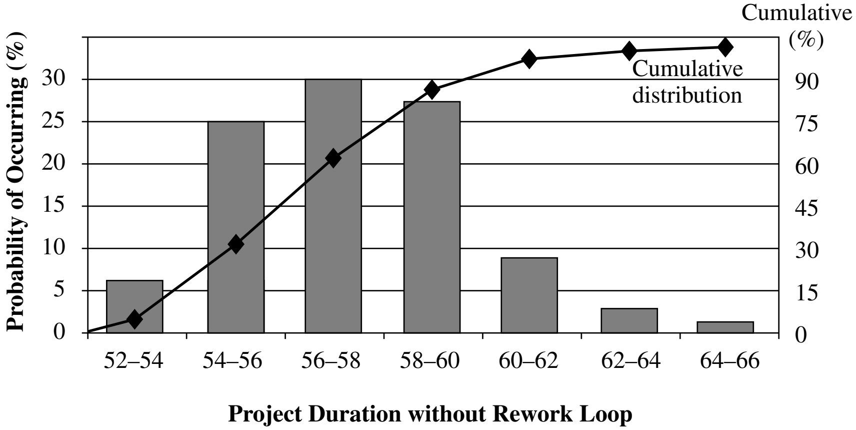
The rework loop, which is a foreseeable event, dominates the entire variation of the individual activities. If the rework loop occurs, the team might have to do something radically different. In other words, the loop goes beyond variation; it represents a major event whose occurrence is uncertain and that has an important impact on the project. The loop must be viewed and treated as a foreseeable event.

In this section, we discuss two classic approaches to foreseeable events: decision trees and risk lists.

Decision Trees

Two methods for incorporating the identified risks into the project plan are most widely used: decision trees and risk lists. We discuss both below. Figure 3.7 shows an example of a decision tree, corresponding to part of a drug research project for the development of a central nervous system drug (calcium channel receptor blocker for sleep disorder indication). Squares in the tree denote *decision nodes*, indicating decision points: Do/don't continue with the project at the stages of research, preclinical development, clinical development, and market introduction. Thus, each decision node has two branches, "yes" and "no." Under the "yes" branch, the time and cost of continuing are indicated.





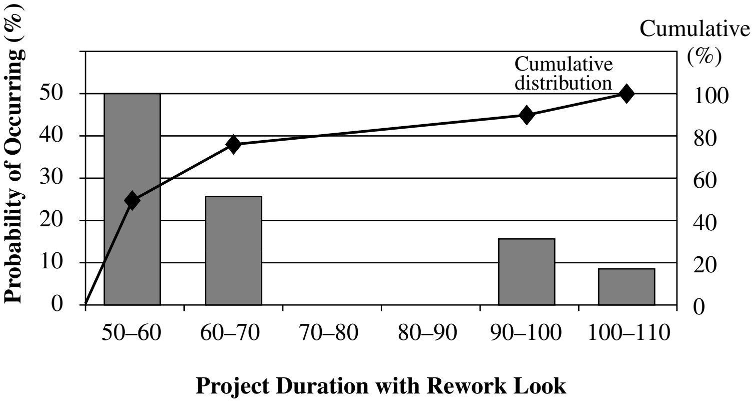


Figure 3.6 Project durations with and without rework loop

The circles in the tree denote *chance nodes*, indicating major risks: in this case, the discovery of side effects that would prevent successful market introduction of the drug. Each chance node captures one major risk, the side effects detected during one phase of the drug's development. Again, the chance nodes are simple because each one has only two branches, corresponding to "success" (the risk does not occur) and "failure" (the risk does occur). Late failure corresponds to side effects that are discovered after market introduction and force withdrawal of the drug from the market (this recently happened, for example, to Redux, a weight loss drug, and Baycol, an analgesic). The respective probabilities are indicated next to the branches (they are estimated based on historical statistics from similar drugs).

The estimated market potential of the drug is indicated on the far right, amounting to $1.8 billion in profits (not revenues!), cumulative over the life of the drug and discounted back to the time of market introduction (at an annual interest rate of 10 percent). This expected value has an estimation range of ±60%. The decision tree is analyzed backward: The value of "yes" at the decision node "market the drug?" is the expected value at the subsequent chance node, discounted by one year, minus the cost of continuing—that is, 1,466 = (.97)(1,787)/1.1 – 110. This is higher than zero, the value of stopping, so the optimal decision is to continue. Based on the value at this decision node, the decision tree can be analyzed further backward, in the same way, up to the value of the initial decision at the root of the tree.

Accounting for the low overall success rate of 3.6 percent and the discounting over 10 years (at 10 percent p.a.), the expected NPV at the time of the first decision, if the decision is "yes," is as little as $11 million (if this value negative, it would be preferable to not engage in the project in the first place). This is typical for pharmaceutical drugs—80 percent of chemical entities entering clinical development fail, and pharmaceutical development takes a long time.

Decision Tree and Abandonment Option

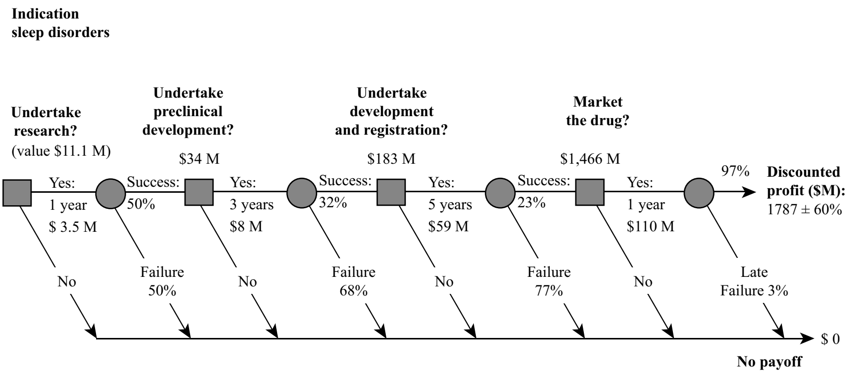


Figure 3.7 Decision tree of a central nervous system drug[5]

This example demonstrates several useful features of decision trees. First, the tree clearly identifies the *value of managerial flexibility*, or of contingent action in response to risk occurrence: If the company did not have the option of stopping after side effects occur in a given phase, all future investments would be wasted and the NPV of the project greatly reduced.[6] Second, the tree can also help to identify the *value of preventive and mitigating* action; if, for example, the failure probability after preclinical development (68 percent) could be eliminated or reduced, the value of the drug (at the initial decision) would be increased. This increase would correspond to the value of the preventive/mitigating action and could be compared to the cost of that action. Similarly, the value of additional contingent actions can be calculated; for example, in the case of a side effect, sell the drug patent for an industrial application. Third, the tree shows the *dependence among the risks*; for example, if the first one occurs, the future ones, as well as the contingent or preventive actions, become irrelevant. This dependence and ordering in time establishes a natural order of attention for the project manager.

Thus, a decision tree is a powerful tool for risk identification, a tool that not only identifies risks but also facilitates the subsequent PRM phases of risk prioritization and risk management. A decision tree offers a way of looking at project risks in a conceptually clear framework. However, decision trees have an important drawback: Their complexity explodes exponentially with the number of risks and decisions considered (for each decision and risk with *n* branches, the number of subsequent subtrees is multiplied by a factor of *n*). Even when it might still be possible to "crunch the numbers" of the tree on a powerful computer, the data-gathering effort quickly becomes unmanageable and the result of the tree analysis intransparent, and therefore much less useful, for the decision making team or manager.

The exponential explosion renders decision trees unusable for projects with large numbers of risks. Therefore, decision trees are commonly used only to *focus* on a handful of the most important risks. Sophisticated project management companies—engineering service providers, for example—perform this focused analysis, ignoring other "smaller" risks at the first cut and then incorporating them through risk lists. The pharmaceutical industry uses decision trees extensively in this way, which is facilitated by the fact that the *effect of major risks is simple*, that is, decision and chance nodes have only two branches (*go/kill*), and thus a relatively large number of risks can be incorporated without losing transparency.

Risk Lists

A risk list is a simpler tool than a decision tree. It simply describes each risk separately, with its nature, its effect, its probability, and preventive, mitigating, or contingent actions. Unlike decision trees, risk lists do not explode in complexity when the number of risks is large. If the risks do interact (that is, if a downstream risk looks different, as a result of what happened upstream), the simplification loses information compared to the decision tree. However, many project risks have a "local" effect; they do not influence the actions downstream. In this case, a risk list is fully adequate, and a decision tree is not necessary at all.

Another advantage of risk lists is that they can be summarized in "generic" templates that group all the risks that have occurred in the past, but without the actual numbers (impact, probability). Such templates are a powerful way of summarizing experience (as we have seen in the PCNet project). Figure 3.8 shows a summary of a generic risk template from the pharmaceutical industry, analogous to the risk list that was used in the PCNet project. The full template is 20 pages long; it embodies experience about risks in pharmaceutical development.

3.2.3 Residual Risk

Residual risk is depicted in the top picture of Figure 3.1 as the response to the hostile wind that threatens to blow the project off course, but does not require a fundamentally different approach. Residual risk is what is left over after planning for foreseeable uncertainty. In many projects, there are simply too many foreseeable events, and planning for each event becomes impossible. While many of these events, if small enough, may be captured in the project variation, some may have quite large impacts on the project.

For example, when HP merged with COMPAQ, it ran into major trouble when it migrated its industry-standard servers (ISS) division to an SAP enterprise resource planning (ERP) system. While HP had invested significantly in contingency planning, not only on the IT side but also by putting aside inventory and capacity in order to mitigate against any IT disruptions in the customer order process, it did not anticipate the extent to which the migration could disrupt its business. As Gilles Bouchard, CIO and EVP of global operations for HP, was quoted as saying, "We had a series of small problems, none of which would have been too much to handle, but together they created the perfect storm."[7] When this "perfect storm" hit, as many as 20 percent of HP's customer orders were kicked out of the ERP system because of its inability to deal with certain customized orders. The contingent inventory and capacity put aside by HP to mitigate against any disruption proved insufficient to cope with this level of disruption. HP estimates that it lost $40 million in revenue: $10 million more than the cost of the entire IT project.[8]

This is the dark side of contingency planning. Weick and Sutcliffe call this danger of contingency planning "double-blind": "Contingent actions are doubly blind. They are blind because they restrict attention to what we expect, and they are blind because they limit our present view of our capabilities to those we now have. When we plan contingent actions, we tend not to imagine how we might recombine the actions in our current repertoire to deal with the unexpected. In other words, contingency plans reduce improvisation."[9] Of course, the managers of the PCNet project in Chapter 1 may retort that they planned thoroughly *and* improvised with the help of the PRM office. The question is not one of either/or, but how to do both.

Risk Category	**Detailed Subcategories**
Substance and Production	
Ingredients	Risk from suppliers (dependency, stability, transfer, contracts), cost of production, availability of drug substance, process (reproducibility, scale-up, impurities), stability (shelf life)
Final product	As above, plus dosage changes, formulation changes
Analytical methods	Specificity, transfer of license or to a different site
Regulatory issues	Ingredient status, toxicity documentation, mixtures, impurity limits
Preclinical	
Safety pharmacology	Findings in core battery studies, supplemental studies, toxicity in cell cultures
Primary pharmacology	Choice of endpoints and species, target selectivity, and specificity
Bioanalytics	Detection of parent compound and metabolites, toxicity or metabolism in test species different from humans, drug accumulation, oral bioactivity, in vivo tests, body penetration
Toxicology	Availability of test substance, pharmacodynamic side effects, high mortality rate in long-term studies, drug-specific side effects
Clinical	
Phase I	Pharmacokinetics (e.g., different in subpopulations, interactions with other compounds or foods), pharmacodynamics (e.g., subject tolerance different from patient tolerance)
Phase II	Appropriate dosage, exposure duration, relevance of placebo control
Phase III	Study delay (e.g., because of season), patient recruitment (e.g., tough criteria, special patient groups, dropout rates), negative outcome (not significant), new regulatory requirements
General Regulatory Risks	Status of comparator, toxants in environment, availability of guidelines, interaction with agencies (e.g., process time, contradictions among different agencies), requirement differences across countries
General Risks	
Licenses	Dependence on licensing partners
Patents	Disclosure of new patents
Trademarks	Viability/acceptance of trademark at submission
Costs	Currencies, inflation, additional patients or studies needed
Market risks	New competitors, new therapies, patient acceptance, target profile, political risks (e.g., pricing, prevention versus therapy)

Figure 3-8 Generic risk list (template) of a pharmaceutical development project

Organizations must recognize that no amount of contingency planning will identify all the risks or all the combinations of foreseeable events that might happen. Thus, organizations must be prepared to deal with them as they arise. As there is no contingency plan for dealing with such events, the project team must be prepared to improvise and respond quickly to events as they arise. We saw in the PCNet project in Chapter 1 how a separate team and dedicated resources were assembled to deal with the residual risks.

3.3 Complexity

The contingency planning approach is based on the obvious and fundamental assumption that the project and its contingencies can be planned. In other words, a near-best set of actions can be specified for any course of foreseeable events. Many project management tools, such as the critical path method, PERT (Program Evaluation and Review Technique), GERT

(Graphical Evaluation and Review Technique), and Q-GERT have been developed to assist project teams in finding these near-best courses of action. However, many projects are simply too complex to yield a near-best solution—that is, they are simply unpredictable.

Complexity stems from "a large number of parts that interact in non-simple ways [such that] given the properties of the parts and the laws of their interactions, it is not a trivial matter to infer the properties of the whole."[10] Complexity has two "ingredients": system size (the number of parts) and the number of interactions among the parts. A large system is not complex if the parts do not interact—we can treat them in isolation and simply add them up to understand system performance. The essence is that the interactions of the elements make the system more than the sum of the parts and the system's behavior hard to predict from the behavior of the parts.[11] Complexity makes it difficult to find the "best" configuration of a system. Project complexity is a typical challenge in many large-scale projects: Too many combinations of actions and influence variables exist, all with different performance implications that cannot be extrapolated from similar combinations. In this case, it is impossible to "optimize" the project plan, and the team has to find an acceptable plan that works satisfactorily.

This was certainly the case in the Circored project—there were over 300 dynamic flow control parameters alone, and decisions on temperature and flow rate interacted with material characteristics (such as viscosity and abrasiveness) and equipment specifications (such as stiffness, toughness, and brittleness).

We can take another example from the car industry, which is currently experiencing an intensive discussion of future hydrogen cars. A hydrogen engine car "system" can be viewed as being made up of the "chunks" engine (including hydrogen storing tank and injection under high pressure), drive train, chassis (axles, wheels, brakes, frame), exterior body, passenger compartment, driver interface and controls, market positioning, and infrastructure (permission and hydrogen refueling infrastructure). Each chunk consists of many components.

Note how market and infrastructure are viewed as chunks of the "system," as they influence success, pose uncertainty, and interact with the design of the physical product. Engine, chassis, drive train, and body also interact among one another because of physical dimensions, exchange of forces, and mutual impact through control systems. Note also that the number of interactions may include not only technical interactions (task complexity), but also interactions among interests of multiple stakeholders (relationship complexity). This system contains so many interactions with so many performance "peaks" that it cannot be completely understood. The design goal is something that works; "optimization" is elusive.[12]

The network planning approach (critical path), shown in Section 3.2, can deal with some degree of complexity: the number of interactions among many activities that are caused by precedence relationships. This level of complexity is (most often) rather low because any activity has precedence relationships (at least ones that influence the plan) with only a few other activities, so the number of interdependencies is small. We discuss the diagnosis of complexity in a project further in Chapter 4.

To deal with high complexity, we discuss two existing methods: control-and-fast-response, or "high-reliability organizations" to deal with task complexity, and project contracts for relationship complexity.

3.3.1 Task Complexity: Control-and-Fast-Response

Control-and-fast-response is a useful and interesting approach to risks that follows a different mind-set than established PRM. In their book, *Managing the Unexpected*, Karl Weick and Kathleen Sutcliffe discuss what high-reliability organizations, such as a nuclear power plant or an aircraft carrier, must do to guarantee a reliable functioning of a very complex system. Reliable operation must be guaranteed (almost at all cost) because much is at stake.

A striking example is the operation of an aircraft carrier: " . . . you have six thousand people crammed into tight spaces away from the shore on a 1,100-foot, 95,000-ton floating city run by an overburdened 'major.' Within those tight spaces on a carrier, you also have people working with jet aircraft, jet fuel, nuclear reactors, nuclear weapons, an onboard air traffic control system, refueling and re-supply from adjacent ships that are moving, a surrounding battle group of seven to nine ships that are supposed to protect the carrier but that can themselves also be dangerous obstacles in fog or high seas and unpredictable weather. The list of 'gee whiz' stuff on a carrier seems endless."[13]

People on a carrier cannot afford to be wrong, or lives will be lost. This is a huge challenge because the system is so complex—the different parts of the carrier are tightly coupled, and impact one another, and the individual components constantly change, because, for example, of human error, equipment failure, or changing weather conditions. "Safety is elusive because it is a dynamic non-event—what produces the stable outcome is constant change rather than continuous repetition. To achieve this stability, a change in one system parameter must be compensated for by a change in other parameters."[14] And yet, accidents rarely happen.

Weick and Sutcliffe recommend that the organization develop what they call "mindfulness." This refers to "the combination of ongoing scrutiny of existing expectations, continuous refinement and differentiation of expectations based on newer experiences, willingness and capability to invent new expectations that make sense of unprecedented events, [and] a more nuanced appreciation of context and ways to deal with it."[15]

Mindfulness includes a number of "soft skills," such as preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience, and deference to expertise. In our language of "systems," mindfulness means the ability to know precisely what the "in control" target state of each component of the system is, to detect even small deviations from the target state, and to quickly react to them and contain them so that they do not spread to other components of the system, causing a major problem there. In other words, mindfulness represents *control-and fast-response*: We prevent deviations if possible, and if one occurs, we contain it immediately. We will come back to mindfulness in Chapter 8, when we discuss the project mind-set that prepares a team for unk unks.

Control takes the form of preoccupation with failure, or ever-paranoid and pervasive monitoring. For example, aircraft carriers conduct foreign-object-damage walk-downs on deck several times a day to prevent small objects (such as bolts or trash) from being sucked into airplane engines. In the constant chatter of simultaneous loops of conversation and verification, "seasoned personnel do not 'listen' so much as they monitor for deviations, reacting instantly to anything that does not fit their expectations of the correct routine."[16] Similarly, high-performing nuclear power plants conduct almost daily departmental incident reviews of seemingly minor slips that have no obvious link to any consequential damage.[17] Reluctance to simplify means that deviations are not conveniently explained away but investigated until their root cause is found. Deference to expertise refers to the principle that the judgment of the people who know the daily operations is respected, even if it is disruptive or painful, no matter where they are in the hierarchy.

When a slight deviation is discovered, even if it seems inconsequential, corrective and, if necessary, drastic action is taken. For example, a seaman on the nuclear carrier *Carl Vinson* reported the loss of a tool on the deck. All aircraft aloft were redirected to land bases until the tool was found, and the seaman was commended for his action—recognizing a potential danger—the next day at a formal ceremony.[18] Commitment to resilience means the ability to substantially deviate from established routines, and to modify those routines, in order to mitigate the deviations before they escalate out of control.

In Section 1.7, we contrasted the critical path mentality with the PRM mentality: the assumption that there is a well-defined target, a path to get there, and the project must reach it versus the prevision of the need for alternative targets and paths, and a willingness to switch to contingencies. Control-and-fast-response embodies yet a different mentality: It admits that there is a wide "state space" of influence factor configurations out there, which contains many nasty surprises, and therefore we insulate the system from this state space and keep it iron-fisted at the state that we know works. Figure 3.9 repeats the center pane of Figure 3.1.

Compared to PRM, the emphasis is not on planning contingencies but on mutual adjustment of the system elements (such as ground crew, pilots, and ship operations) to bad news that emanates from different system elements, in order to keep the system in the control state, or to minimize deviations from it before they escalate. This relies not only on planned routines but also, critically, on a willingness to improvise (resilience) if that particular combination of circumstances has not been foreseen. And because of system complexity, it is not possible to anticipate all system constellations.

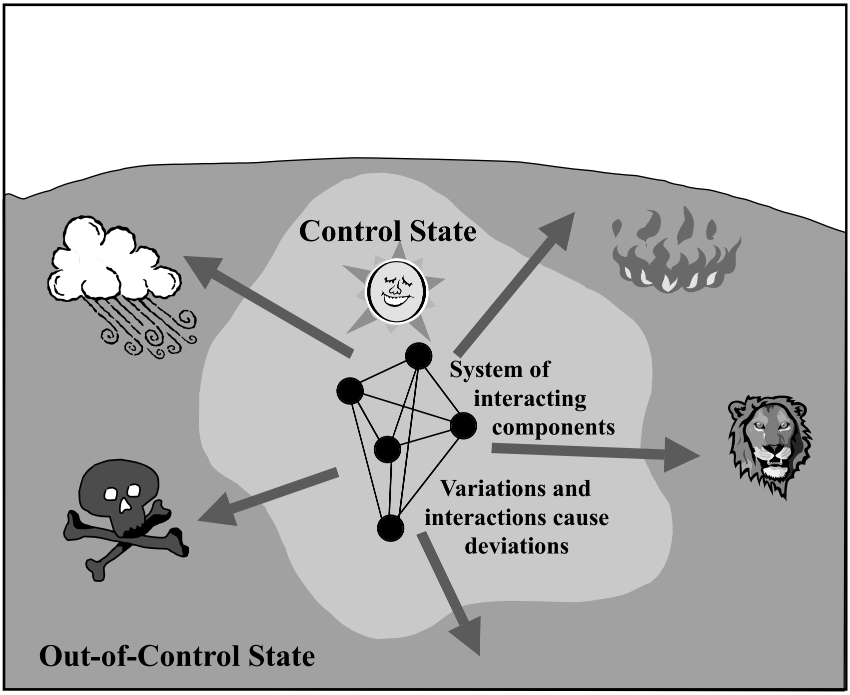


Figure 3.9 The control-and-fast-response mind-set

Control-and-fast-response and mindfulness are highly relevant to project management for two reasons. First, they provide a good discipline of knowing as much as possible and reacting to deviations that are not required for learning about the path toward the goal. Second, mindfulness helps to alert us to the problems of complexity, the interactions among multiple system parts, as a major source of risks. Mutual adjustment and resilience are highly applicable in project management.

3.3.2 Relationship Complexity: Contracts as Risk-Sharing Tools

Complex interactions arise not only from the interdependence of the tasks, but also from conflicts of interest, stemming from relationships among the parties that are involved in a project. We refer to this as relationship complexity. This is becoming more and more relevant as project participants increasingly come from different organizations. A widely used tool for defining the interests of the players and for sharing risks is a *project contract*.

Large projects are rarely performed with one organization's internal resources alone: The resource commitment is too great, the risk becomes too high, and the range of specialized expertise areas goes beyond what exists in one company. Therefore, managing major projects typically involves working with partners. Collaboration with external parties poses a trade-off—the above advantages have to be weighed against multiple interests, which are never perfectly aligned and which cause possible interactions among multiple influences, or, in other words, complexity.

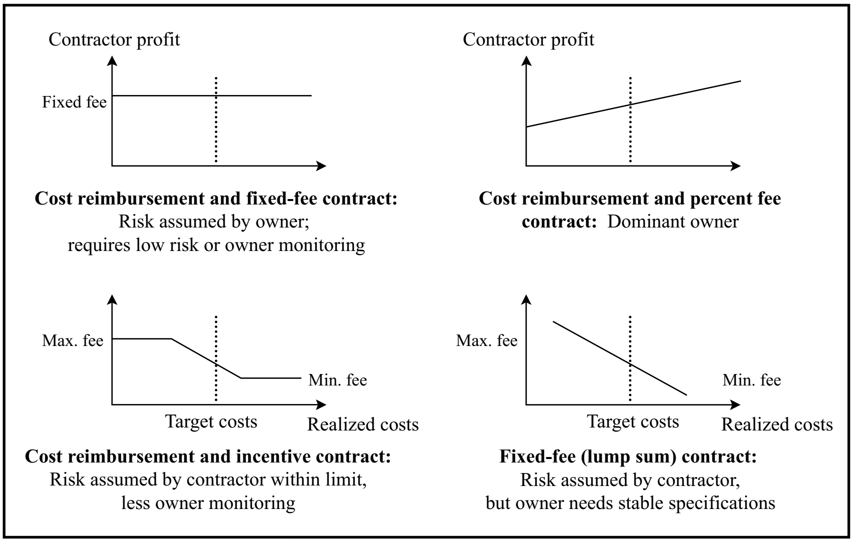
Contracts are the most widely used way of handling external partners. Contract management has developed its own jargon, but in this section, we argue that the logic behind contract design is very closely related to PRM. Project management literature distinguishes three major contract forms: fixed price, cost reimbursable, and mixed incentive contracts, summarized in Figure 3.10.[19] They differ in their appropriateness in allocating risks. Lump-sum turn-key (LSTK) fixed-price contracts allocate total risk to the contractor; they seem to have increased in importance over the years, as they clearly allocate responsibility to one major contractor who assumes most risk and can control the project's execution, minimizing interfaces and working with more overlap.

In cost-reimbursable contracts, including engineering, procurement, and construction management (EPCM) contracts, the contractor is entitled to charge all justified costs. The client must drive the project, investing more resources and assuming all risks. The contractor has little incentive to be efficient. There are also "intermediate" contract types, involving incentive fees, bonuses/penalties, and target prices to compel the contractor to trim costs without sacrificing quality. These contracts are not used as widely as one might expect, because negotiating targets is complex, and because the required implementation involvement by the client is (almost) as high as in a cost-reimbursable contract.[20]

Although contracts are agreements among partners, they must include elements of a "hierarchy" (as if the parties were coordinated internally within one organization), in order to be operable during the myriad of small decisions to be taken during execution. These elements of hierarchy include command structures and authority systems, dispute resolution procedures, standard operating procedures (SOPs), and incentive systems. In other words, these hierarchical elements are necessary in order to respond to the residual risks that we have seen in the PCNet example.

A useful view of a contract is that of a *business deal*.[21] The contract must, therefore, above all address the major contents of the business proposed. Specifications define the business function of the project outcome, and price and schedule the investment, with payment terms determining the timing. Then there are multiple tools for mutual insurance, warranties, damages and limitations to them, and securities. They are depicted in Figure 3.10 and further explained in Table 3.1.

The contract shapes the culture: first, because a project is not a permanent relationship in which the prospect of future interaction would discipline behavior, and second, because personnel turnover during the project is common. Thus, the contract is the key framework for setting standards of behavior and trust shown by others and, ultimately, the project's performance. The perceived fairness, realism, completeness, and transparency of the business deal are key elements in building up needed trust.



Cost reimbursement and fixed-fee contract: Risk assumed by owner; requires low risk or owner monitoring

Cost reimbursement and percent fee contract: Dominant owner

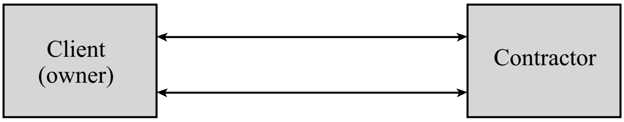
Cost reimbursement and incentive contract: Risk assumed by contractor within limit, less owner monitoring

Fixed-fee (lump sum) contract: Risk assumed by contractor, but owner needs stable specifications

Figure 3.10 Contract types and risk allocation among the parties

Content of the Project

- Fulfilling the specifications
- Within budget price/cost estimates
- According to schedule
- Payment of the contract price, with payment terms



Assurance for both sides:

- *Warranties* (faults after delivery)
- *Liquidated damages* (penalties for nonperformance)
- *Limitation of liability* to protect contractor
- Mutual assurance of fulfilment with *securities*

Figure 3.11 The eight key business levers in the contract

As the contract sets the tone of the collaboration, it is critical that the price in Figure 3.11 is based on reasonable cost estimates for the project. While the price is a zero-sum game in the short term (the client wants to get the best deal while the contractor wants to make a living), deviating from the true cost in either direction is very dangerous: If the price is too low, the contractor will feel an irresistible temptation to shirk (there is no complex project in which the contractor cannot save costs by compromising on quality). If the price is too high, the client may not react this time but may find out and retaliate next time. Either side should avoid dictating contract terms and conditions, no matter how powerful he is; virtually always, *both* sides have the opportunity of shirking. This implies that contracts, especially fixed-price LSTK contracts, should not be awarded on the basis of the lowest bid but based on identified risks, capabilities, and track records.[22]

In other words, the eight business levers represent the basis for risk identification—they are areas of high risk impact, and each area should be underpinned by careful estimates, which represent nothing other than PRM risk identification and assessment. While the eight key business drivers determine the fundamental logic of the business deal, the additional hierarchical contract components govern the micro-interactions during the project. The hierarchical contract components manage inevitable residual risks. For example, the parties must agree upon a process via intermediate deliverable deadlines such as document sign-off, equipment inspection and triggering of payments, change-order procedures, and conflict resolution.

Table 3.1: Definition of the Key Drivers of a Contract Business Deal

Key Driver	***Definition/Key Issue to Be Clarified***
Technical specifications	Adequacy, completeness, and consistency of the description of the scope of work. Consistency between technical and commercial parts.
Price (quality of cost estimates)	Consistency of price and cost estimates with technical specifications. Adequacy of contingency and profit margin.
Payment terms	Schedule of partial payments. This determines to what extent cash receipts by the contractor cover his cash expenses over the course of the project, defining the contractor's exposure from cash flow during the project.
Schedule	Achievability of key (intermediate and final) completion dates and consistency of their definitions. Impact of possible project delay/acceleration costs relative to contractual liquidated damages.
Performance guarantees	Acceptable tolerances of key performance measures; definition of preconditions for achievement of these performances; and liquidated damages that compensate for deviations from the performance tolerances.
Warranties	Payments for the repair or replacement of unsuitable or defective equipment. Possible compensation for consequences of defective services (such as engineering).
Limitation of liability	What is the maximum extent of the contractor's liability toward the client under the contract (excluding tort or negligence)? Is it contractually clearly limited, and are indirect and consequential damages excluded?
Securities	How does the contractor ensure his performance toward the client? How does the client ensure his payment obligations toward the contractor? For example, deposits, bonds, or guarantees by third parties.

In summary, project contracts are a widely used way of governing projects with multiple parties, by implementing PRM across different organizations. While the language used in contract design is different from the language used in PRM, the principles of PRM (risk identification through key business levers, monitoring, and hierarchical structures to respond to residual risk) are consistent with contract design principles.

3.4 Unknown Unknowns

We have already discussed in this chapter, and elsewhere, that in major projects, not all project influence factors can be foreseen and planned for—some of them are not known by the project team at all. The same effect results if the project team is not aware of major interactions among influence variables and actions. They are not within the team's horizon; they are outside its knowledge. Therefore, the team cannot plan for them. In addition, there are actions (relating to these unknown variables) of which the team is not aware. The decision theory and economics disciplines call this "unawareness" or "incomplete state space," and technology management scholars call it "ambiguity." As mentioned, in project management, unforeseeable uncertainty has been referred to as unknown unknowns, or unk unks.[23] Weick and Sutcliffe call unk unks "bolts from the blue," referring to events for which the team had no expectation at all, no hint, and no prior model.[24]

Unk unks are fundamental for novel projects. This has been acknowledged by experts before. For example, Miller and Lessard conclude that the challenge is "ignorance of the true state of nature and the causal structures of decision issues."[25] Similarly, researchers of new venture startup projects have observed, "What has made or broken the companies . . . is the ability or inability to recognize and react to the completely unpredictable."[26]

We have already discussed one response to unk unks in residual risk management in Section 3.2.3. Managing residual risk implies first a recognition that there are things you do not know that you do not know (unk unks), and second the ability to improvise to either take an alternative path or to bring the project back to the known path. Residual risk management works when the basic control state is known—that is, we have a pretty good idea what we want to do. For example, none of the residual risks in the PCNet project fundamentally changed the nature of the project: It was known what they wanted to achieve and how they would achieve it, more or less, and residual risk management mostly dealt with events that threatened to blow the project off course.

The second approach to unk unks that we have discussed is control-and-fast-response (Section 3.3.1). The idea is to avoid the unk unks altogether by an instantaneous and iron-fisted reaction to any deviations from the control state of the project before they can spiral out of control.

Control-and-fast-response works if a well-defined target state of the project can be identified and if actions are available to maintain it.

However, unk unks may be so fundamental that the project goal and path are, themselves, fundamentally unknown. There is no path from which residual risk management can deviate; there is no control state to be maintained. This is the situation that is represented in the right-hand picture of Figure 3.1, and that was faced by the Circored project: It was unknown what part of the scale-up would not work and what type of actions might be required to make the chemical process work.

If a project is faced with important unk unks of this type, there is really no project plan. Or, any plan is a fiction. It corresponds to a set of stakes in the desert (Figure 3.1), of which we do not know whether they lead to an oasis or not. Any project plan will run into major surprises (many of them negative), and the plan will miss major actions that arise as attractive ex post but were not identified ex ante. A serious danger is that the stakes in the ground are easily interpreted as a real plan, as if they "claimed" to be a plan. Planning is always necessary in order to have a base line; however, a plan in the presence of unk unks may constitute "false precision," misleading a project team to be less alert to changes than is required.

We must plan; it is the basic building block on which everything else rests. However, in novel projects, where we face fundamental knowledge gaps and must be ready for unk unks, adherence to a plan (even with contingencies) must not become an end in itself. Unk unks (whether they come from unknown influence factors or from complexity and ill-understood interactions) require the readiness to abandon assumptions and look for solutions in nonanticipated places.

In the presence of fundamental unk unks (see the right-hand picture of Figure 3.1), flexibility in dealing with residual uncertainty will not be sufficient to respond to major unk unks that were not visible at the outset and emerge only mid-course during the project. Nor can a control-and-fast-response attempt to maintain a control state that cannot be defined. This is what the Circored project experienced, and what damaged the careers of several of the people involved.

At this point, it is worth coming back to complexity (Section 3.3). Not only does complexity prevent a project team from designing the "optimal" project plan, but it is also a major source of unk unks if the nature of the interactions among the project influences and actions are not fully known or understood: If there is a slight deviation from the plan in one variable (let's say, process temperature in the Circored facility), it may cause major problems in another part of the project (for example, difficult forming and sticking in the briquetting machine). Moreover, these problems cannot be foreseen by the people responsible for that part of the project because the interaction was not understood. Nonanticipated interactions often cause major crises in large engineering projects and require an addition to the classic project management toolbox.[27]

Unstructured problems that are not amenable to a planned solution approach have long been identified in the design community as "wicked problems."[28] Coming from a background of urban planning and policy making, the design community characterized wicked problems as those that do not have a definite formulation, have no stopping rule that allows one to determine when the problem is solved, where solutions cannot be fully tested and the problems cannot be generalized, and where there is ambiguity about problem causes. In other words, these are ill-understood problems with major unk unks. Wicked problems are the opposite of "tame" problems that we know how to solve in science and with formal project management methods.

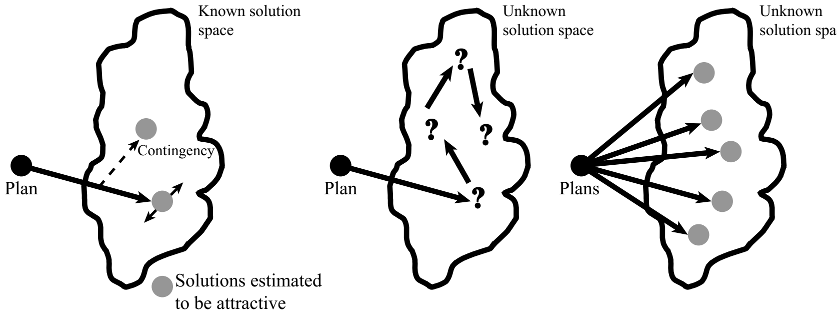
3.4.1 Two Fundamental Approaches: Learning and Selectionism

Figure 3.12 outlines the logic of three fundamental approaches to project management in the face of the different sources of risk. The first (Figure 3.12a) is, again as a reminder, a summary of PRM, as described in Chapter 1: If we have an adequate picture of the influence variables, the causal effects of our actions, and the resulting performance, we can choose a desired outcome and a course of action that is manifested in a project plan. We may plan for contingencies if new information about a (initially identified) major risk emerges, and we may have to "improvise" around the target outcome in order to respond to residual risk. But fundamentally, the approach is a *planned approach*; the important problem solving occurs at the beginning and then the emphasis shifts to executing the plan.

We have seen in the Circored example that this approach leads to negative surprises and crises if the unk unks are so significant that residual management around the target outcome does not adequately address them. Figures 3.12b and 3.12c show two fundamental approaches that project teams can use to respond to major unforeseen influences.[29]

If we admit that we know too little about the universe of possible project outcomes (and how to get there), we may not insist on choosing a target outcome at the outset. Nor may we try to maintain a control state, because the target state is unknown; this is the limit of the applicability of control-and-fast-response to project management. Rather, we start moving toward one outcome (the best we can identify), but we are prepared to repeatedly and fundamentally change both the outcome and the course of action as we proceed, and as new information becomes available. In other words, we *iterate and learn* (Figure 3.12b). The most important problem solving is distributed at the outset and throughout the duration of the project.

This approach has been given different names by previous project management workers. For example, Chew et al. (1991) examined unk unks in the context of introducing new manufacturing technologies in plants and concluded that iteration, learning, original new problem solving, and adjustment are required. In the context of new product development,



a. The Planning Approach (with contingency and residual risk) **b. The Iterate and Learn Approach** **c. The Selectionist Approach**

Figure 3.12 Three fundamental PRM approaches in face of uncertainty

Leonard-Barton (1995) called the iterate-and-learn approach "product morphing" (meaning repeated changes of a product concept over time), and Lynn et al. (1996) called it "probe-and-learn," referring to repeatedly pushing a project all the way into the market and then iterating *after* market introduction. In general, iteration and experimentation are a fundamental feature of problem solving in innovation and engineering projects[30] as well as venture startup projects.[31] It cannot be overstated that this is difficult to do—it feels uncomfortable (especially to senior managers) not to have the feeling of control that stems from defined targets, and repeated iterations are time-consuming and expensive.

The other fundamental approach is to try out several plans and see ex post what works best (Figure 3.12c). Again, this approach has been identified before—in operations research and engineering (addressing the solution methods for very complex problems), it is called "parallel trials," and in management, Leonard-Barton (1995) has called it "Darwinian selection," and McGrath (2001) has called it "creating requisite variety" for the complex problems to be solved by the organization. We emphasize the "selectionist" logic because the fundamental feature is that one out of many trials is selected ex post (whether the trials are executed in parallel or one after the other is secondary). Again, this is difficult to do—executing multiple parallel attempts is expensive, and the parallel teams may compete rather than collaborate if everyone knows that only one team will be chosen in the end.

3.5 Expanding the Toolbox: Fundamental Approaches to Project Uncertainty

The sources of project uncertainty are placed in relation to one another in a framework in Figure 3.13. The vertical axis represents low and high complexity. The horizontal axis does not represent a cardinal measure of "more" or "less" uncertainty; it simply shows the different sources, namely variation, foreseeable influences, and unknown unknowns. It is important to remember that several of these can be present in a project at the same time.

We discussed in Chapter 1 how PRM methods can deal with variation and foreseeable influences. The project management community also possesses powerful methods for dealing with complexity: The traditional network planning methods (such as PERT and CPM) are designed to schedule and control many (up to thousands of) activities with many predecessor interactions. In addition, we know that high complexity requires tight coordination and frequent communication among the parties that are responsible for the many interacting project tasks: Changes in any one task may propagate to other tasks and cycle around, and therefore, the fast exchange of preliminary information is of paramount importance. Some of these coordination principles were popularized under the topic of "concurrent engineering" during the 1990s.[32]

Our methods are less well developed in the face of unforeseeable influences, or of foreseeable influences that heavily interact, so a foreseen change in one influence factor may ricochet around and cause unforeseeable changes in other task teams or system components.

The Circored team at CAL also faced such interaction problems: Many of the component problems might have been foreseeable, in principle, through a dedicated analysis, but there were simply "too many trees in the forest," as the manager expressed it. In a novel project such as Circored, control-and-fast-response is not feasible because the "allowable operating regime" is not yet established. Yet, it is important to understand this approach because it establishes an ideal and because it alerts us to the danger of the combination of complexity and (foreseeable or unforeseeable) uncertainty. Unk unks may reflect true unknown influences, or they may arise from ill-understood interactions among, in principle, known influences.

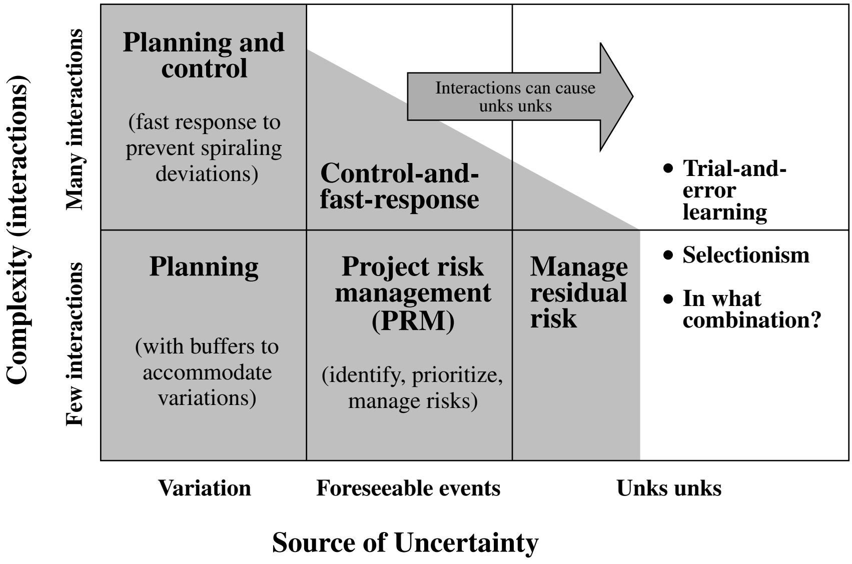


Figure 3.13 A framework of the sources of uncertainty in project management

The obvious question that we want to answer is this: What can project managers do in order to respond to complexity and unk unks in a way that avoids the negative experience of a Circored project? In this chapter, we outline two fundamental approaches. The rest of the book examines how these two approaches can be put into practice.

As we mentioned above, these fundamental approaches have been identified before, and both are used in practice. Even the field of business strategy has undergone an evolution over the last decade that is parallel to what we are proposing here: Strategy has moved from emphasizing planned and contingency approaches to "emergent strategy" that changes over time in unforeseeable ways.[33]

However, selectionism and learning are often used ad hoc and piecemeal, not as parts of an overarching strategy and toolbox for dealing with unk unks. No conceptual map and toolbox exist that compare the relative strengths and weaknesses of iteration and learning versus selectionist trials, nor do we understand well how they can fruitfully be combined. It is these managerial challenges for which this book proposes solutions.

Are There More Project Management Approaches than These Three?

We have discussed three fundamental approaches to cope with uncertainty: planning and triggering contingencies, selectionism, and learning. The reader may ask whether this representation is complete or whether other approaches exist. We have conducted a large number of case studies, and we have not found any other strategy to cope with uncertainty and complexity. Nor has any approach that is conceptually different been reported in academic and managerial publications on project management and product development (obviously, detailed implementations always differ). That is, of course, not proof that there would not be more approaches. We have, however, been able to demonstrate by a comparison with work in biology that the set of the three approaches is complete and robust.[34]

The project management challenges of dealing with uncertainty is very similar to the one that is known in biology as the "uncertain futures problem," or how to accomplish the successful propagation of a species into the next generation.[35] Plotkin has indeed shown that nature has three and only three responses. One strategy for a species is to avoid uncertainty by restricting itself to ecological niches that are simple and change slowly. However, such a strategy can be devastating if there are sudden changes in the environment. A more flexible approach of a "planned approach," with the ability to cope with foreseeable uncertainty, takes the form of contingent policies. For example, many species tolerate variations in their physical state (e.g., body temperature, caloric intake) up to a certain degree and "genetically trigger" adjustments when this variation exceeds a certain threshold (e.g., growing fur in the winter). This is a very similar approach to planned projects with contingency plans.

Some species have an ability to learn to adjust to their environment. They have the ability to extend their behavior beyond prespecified triggers by perceiving critical new features of their environment and replanning, or modifying their behavior accordingly. One example of this is the reaction of immune systems with pathogens. Biologists have shown that these learning devices are metabolically costly and that only a limited number of species have developed a learning capability.

Certain species have no ability to learn yet have a tremendous ability to adapt in a new generation to new environments that lie outside their historical experience. As each individual offspring dips into the gene pool, coming up with variants of genetic instructions, the resulting genetic variation increases the chance that some will survive. For example, bacteria with fast propagation and high mutation rates have conquered niches that were, until recently, believed to be hostile to life forms (e.g., hot sulfur vents in deep seas).

These three strategies used by nature to cope with uncertainty are conceptually similar to the project management approaches we have described in this chapter. Evolution provides an unparalleled database of strategies to deal with uncertainty and complexity. If nature, with its over 3 billion years of creative solutions, has produced the same three fundamental strategies that we find, this is corroborative evidence that there are no other fundamental strategies.

Endnotes

1. See, for example, Morris and Hugh 1987, Schrader et al. 1993, Hamel and Prahalad 1994, Miller and Lessard 2000, or Pich et al. 2002.
2. This example is based on Loch, Kavadias and De Meyer 2000.
3. That means that we draw each activity duration randomly, using its distribution, and calculate the critical path for those durations (the project duration). Then we draw a different set of random durations and calculate the critical path again, and so on, thousands of times. The thousands of project durations give a probability distribution, shown as a histogram. This can be easily done on the computer, even using simple tools such as Excel, but professional project planning packages have the simulation capability built in, for example, the Graphical Evaluation and Review Technique (GERT), for which commercial packages exist. A positive feature of simulations is that they are usually very robust with respect to the precise distributions of the activity durations. In other words, as long as we get the expected values, and the minima and the maxima of the activity durations roughly right, the histogram will be in the right ballpark.
4. See, for example, Goldratt 1997, or Herroelen and Leus 2001. Buffer scheduling exists as an add-on to commercial scheduling software packages. See an overview in Herroelen 2005.
5. Source: Loch and Bode-Greuel 2001.
6. This seems obvious in this simple tree, where each decision has only two branches, but the existence of managerial flexibility is much less obvious and, in fact, is often overlooked in projects with more complicated multibranch decisions.
7. See "When Bad Things Happen to Good Projects," *CIO Magazine*, December 1, 2004.
8. Ibid.
9. Weick and Sutcliffe 2001, p. 80.
10. Simon 1969, p. 195.
11. See also Sommer and Loch 2004, and Williams 2002, p. 50.
12. Our definition of complexity is consistent with that of other authors, although the terminology differs. For example, Shenhar (2001) calls a large project that combines task complexity and relational complexity an "array." Williams (2002) emphasizes the different interdependencies among system components (sequential, reciprocal, pooled), and he views *uncertainty as an aspect of complexity*. We believe that it is important to distinguish the two concepts, as their fundamental effects are different—complexity causes many local performance peaks in decision space, making the search for the best system solution difficult. Uncertainty, in contrast, makes the performance landscape "shift under your feet." We emphasize several times in the remainder of the book that complexity can cause uncertainty (even unforeseen uncertainty) for subprojects, or parties in the project, if the different parts of the project do not coordinate. However, this does not make uncertainty an aspect of complexity; it is an additional concept (lack of coordination) that connects complexity and uncertainty.

13. Weick and Sutcliffe 2001, p. 28.

14. Weick and Sutcliffe 2001, p. 30.

15. Weick and Sutcliffe 2001, p. 42.

16. Weick and Sutcliffe 2001, p. 32.

17. Weick and Sutcliffe 2001, p. 57.

18. Weick and Sutcliffe 2001, p. 59.

19. For example, Stinchcombe and Heimer 1985, Kerzner 2003, Ferreira and Rogerson 1999.

20. See Ward and Chapman 1994.

21. This is proposed by Von Branconi and Loch 2004.

22. See Hackney 1965, Chapman and Ward 1997, and Von Branconi and Loch 2004.

23. An example of technology management work that introduced the term "ambiguity" is Schrader et al. 1993. For the term "unk unks," see, for example, Wideman 1992, although the term has been used in aerospace and electrical and nuclear engineering for decades. Floricel and Miller 1998 call the unk unks "strategic surprises."

24. Weick and Sutcliffe 2001, p. 36.

25. Miller and Lessard 2000, p. 76.

26. See Brokaw 1991, p. 54.

27. Miller and Lessard, 2000, have demonstrated the effect of unanticipated interactions. Williams, 1999, calls for new project management approaches for complex projects.

28. This term was coined by Rittel and Webber 1973.

29. Why are we proposing just these two approaches? Examinations of what has been proposed by previous analyses, as well as theoretical considerations, suggest that all responses to unforeseeable uncertainty represent combinations of the ones we discuss here (see Pich et al. 2002). See also Box on p. 77.

30. See, for example, Van de Ven et al. 1999 (Chapter 2), or Thomke 2003.

31. See, for example, Drucker 1985, Pitt and Kannemeyer 2000, or Chesbrough and Rosenbloom 2003.

32. For overviews, see Mihm and Loch 2004, Terwiesch et al. 2002, Smith 1997.

33. From a project management perspective, see the discussion in Boddy 2002, pp. 49–52. In the strategy field, see, for example, Mintzberg 1994, who was one of the first to call for a new paradigm in strategy, Bettis and Hitt 1995, or Adner and Levinthal 2004. The latter authors argue that real options evaluation (which is equivalent to decision trees when projects cannot be hedged in financial markets) is not enough in strategy when target markets are highly uncertain.

34. Pich et al. 2002.

35. Plotkin 1993, pp.145–48.