国外大学优秀教材——工业工程系列（影印版）

项目管理
过程、方法与效益（第3版）

Project Management: Processes, Methodologies, and Economics
(Third Edition)

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Foreword

This textbook series is published at a very opportunity time when the discipline of industrial engineering is experiencing a phenomenal growth in China academia and with its increased interests in the utilization of the concepts, methods and tools of industrial engineering in the workplace. Effective utilization of these industrial engineering approaches in the workplace should result in increased productivity, quality of work, satisfaction and profitability to the cooperation.

The books in this series should be most suitable to junior and senior undergraduate students and first year graduate students, and to those in industry who need to solve problems on the design, operation and management of industrial systems.

Gavriel Salvendy

Department of Industrial Engineering, Tsinghua University

School of Industrial Engineering, Purdue University

April, 2002

序　言

本教材系列的出版正值中国学术界工业工程学科经历巨大发展，实际工作中对工业工程的概念、方法和工具的使用兴趣日渐浓厚之时。在实际工作中有效地应用工业工程的手段无疑将会提高生产率、工作质量、合作的满意度和效果。

该系列中的书籍对工业工程专业的本科生、研究生和工业界中需要解决工程系统设计、运作和管理诸方面问题的人士最为适用。

加弗瑞尔・沙尔文迪
清华大学工业工程系
普渡大学工业工程学院（美国）
2002 年 4 月

This book is dedicated to my grandchildren Zoey, Danielle, Adam, and Noam Shtub.

This book is dedicated to my wife, Debbie; my three children, David, Hannah, and Benjamin; my late parents, Zvi and Blanche Rosenwein; and my in-laws, Dr. Herman and Irma Kaplan.

Nomenclature

AC	annual cost
ACWP	actual cost of work performed
AHP	analytic hierarchy process
AOA	activity on arrow
AON	activity on node
AW	annual worth
BAC	budget at completion
B/C	benefit/cost
BCWP	budgeted cost of work performed
BCWS	budgeted cost of work scheduled
CBS	cost breakdown structure
CCB	change control board
CCBM	critical chain buffer management
CDR	critical design review
CE	certainty equivalent, concurrent engineering
C-E	cost-effectiveness
CER	cost estimating relationship
CI	cost index; consistency index; criticality index
CM	configuration management
COO	chief operating officer
CPIF	cost plus incentive fee
CPM	critical path method
CR	capital recovery, consistency ratio
C/SCSC	cost/schedule control systems criteria
CV	cost variance
DOD	Department of Defense
DOE	Department of Energy
DOH	direct overhead costs
DSS	decision support system
EAC	estimate at completion
ECO	engineering change order
ECR	engineering change request
EMV	expected monetary value
EOM	end of month
EOY	end of year
ERP	enterprise resource planning
ETC	estimate to complete
ETMS	early termination monitoring system
EUAC	equivalent uniform annual cost
EV	earned value
EVPI	expected value of perfect information
EVSI	expected value of sample information
FFP	firm fixed price
FMS	flexible manufacturing system
FPIF	fixed price incentive fee
FW	future worth
GAO	General Accounting Office
GDSS	group decision support system
GERT	graphical evaluation and review technique
HR	human resources

IPT	integraded product team
IRR	internal rate of return
IRS	Internal Revenue Service
ISO	International Standards Organization
IT	information technology
LCC	life-cycle cost
LOB	line of balance
LOE	level of effort
LP	linear program
LRC	linear responsibility chart
MACRS	modified accelerated cost recovery system
MARR	minimum acceptable (attractive) rate of return
MAUT	multiattribute utility theory
MBO	management by objectives
MIS	management information system
MIT	Massachusetts Institute of Technology
MPS	master production schedule
MTBF	mean time between failures
MTTR	mean time to repair
NAC	net annual cost
NASA	National Aeronautics and Space Administration
NBC	nuclear, biological, chemical
NPV	net present value
OBS	organizational breakdown structure
O&M	operations and maintenance
PDMS	product data management system
PDR	preliminary design review
PERT	program evaluation and review technique
PMBOK	project management body of knowledge
PMI	Project Management Institute
PMP	project management professional
PO	project office
PT	project team
PV	planned value
PW	present worth
QA	quality assurance
QFD	quality function deployment
RAM	reliability, availability, and maintainability; random access memory
R&D	research and development
RDT&E	research, development, testing, and evaluation
RFP	request for proposal
ROR	rate of return
SI	schedule index
SOW	statement of work
SOYD	sum-of-the-years digits
SV	schedule variance
TQM	total quality management
WBS	work breakdown structure
WP	work package
WR	work remaining

Preface

We all deal with projects in our daily lives. In most cases, organization and management simply amount to constructing a list of tasks and executing them in sequence, but when the information is limited or imprecise and when cause-and-effect relationships are uncertain, a more considered approach is called for. This is especially true when the stakes are high and time is pressing. Getting the job done right the first time is essential. This means doing the upfront work thoroughly, even at the cost of lengthening the initial phases of the project. Shaving expenses in the early stages with the intent of leaving time and money for revisions later might seem like a good idea but could have consequences of painful proportions. Seasoned managers will tell you that it is more cost-effective in the long run to add five extra engineers at the beginning of a project than to have to add 50 toward the end.

The quality revolution in manufacturing has brought this point home. Companies in all areas of technology have come to learn that quality cannot be inspected into a product; it must be built in. Recalling the 1980s, the global competitive battles of that time were won by companies that could achieve cost and quality advantages in existing, well-defined markets. In the 1990s, these battles were won by companies that could build and dominate new markets. Today, the emphasis is partnering and better coordination of the supply chain. Planning is a critical component of this process and is the foundation of project management.

Projects may involve dozens of firms and hundreds of people who need to be managed and coordinated. They need to know what has to be done, who is to do it, when it should be done, how it will be done, and what resources will be used. Proper planning is the first step in communicating these intentions. The problem is made difficult by what can be characterized as an atmosphere of uncertainty, chaos, and conflicting goals. To ensure teamwork, all major participants and stakeholders should be involved at each stage of the process.

How is this achieved efficiently, within budget, and on schedule? The primary objective in writing our first book was to answer this question from the perspective of the project manager. We did this by identifying the components of modern project management and showing how they relate to the basic phases of a project, starting with conceptual design and advanced development, and continuing through detailed design, production, and termination. Taking a practical approach, we drew on our collective experience in the electronics, information services, and aerospace industries. The purpose of the second edition was to update the developments in the field over the last 10 years and to expand on some of the concerns that are foremost in the minds of practitioners. In doing so, we have incorporated new material in many of the chapters specifically related to the *Project Management Body of Knowledge* (PMBOK) published by the Project Management Institute. This material reflects the tools, techniques, and processes that have gained widespread acceptance by the profession because of their proven value and usefulness.

Over the years, numerous books have been written with similar objectives in mind. We acknowledge their contribution and have endeavored to build on their strengths. As such in the third edition of the book, we have focused on integrative concepts rather than isolated methodologies. We have relied on simple models to convey ideas and have intentionally avoided detailed mathematical formulations and solution algorithms—aspects of the field better left to other parts of the curriculum. Nevertheless, we do present some models of a more technical nature and provide references for readers who wish to gain a deeper understanding of their use. The availability of powerful, commercial codes brings model solutions within reach of the project team.

To ensure that project participants work toward the same end and hold the same expectations, short- and long-term goals must be identified and communicated continually. The project plan is the vehicle by which this is accomplished and, once approved, becomes the basis for monitoring, controlling, and evaluating progress at each phase of the project's life cycle. To help the project manager in this effort, various software packages have been developed; the most common run interactively on microcomputers and have full functional and report-generating capabilities. In our experience, even the most timid users are able to take advantage of their main features after only a few hours of hands-on instruction.

A second objective in writing this book has been to fill a void between texts aimed at low- to mid-level managers and those aimed at technical personnel with strong analytic skills but little training in or exposure to organizational issues. Those who teach engineering or business students at both the late undergraduate and early graduate levels should find it suitable. In addition, the book is intended to serve as a reference for the practitioner who is new to the field or who would like to gain a surer footing in project management concepts and techniques.

The core material, including most of the underlying theory, can be covered in a one-semester course. At the end of Chapter 1, we outline the book's contents. Chapter 3 deals with economic issues, such as cash flow, time value of money, and depreciation, as they relate to projects. With this material and some supplementary notes, coupled with the evaluation methods and multiple criteria decision-making techniques discussed in Chapters 5 and 6, respectively, it should be possible to teach a combined course in project management and engineering economy. This is the direction in which many undergraduate engineering programs are now headed after many years of industry prodding. Young engineers are often thrust into leadership roles without adequate preparation or training in project management skills.

Among the enhancements in the Third Edition is a section on Lean project management, discussed in Chapter 8, and a new Chapter 16 on simulation-based training for project management.

Lean project management is a Quality Management initiative that focuses on maximizing the value that a project generates for its stakeholders while minimizing waste.

Lean project management is based on the Toyota production system philosophy originally developed for a repetitive environment and modified to a nonrepetitive environment to support project managers and project teams in launching, planning, executing, and terminating projects. Lean project management is all about people—selecting the right project team members, teaching them the art and science of project management, and developing a highly motivated team that works together to achieve project goals.

Simulation-based training is a great tool for training project team members and for team development. Chapter 16 discusses the principles of simulation-based training and its application to project management. The chapter reports on the authors' experience in using simulation-based training in leading business schools, such as members of the Global Network for Advanced Management (GNAM), and in leading engineering schools, such as the Columbia University School of Engineering and the Technion. The authors also incorporated feedback received from European universities such as Technische Universität München (TUM) School of Management and Katholieke Universiteit Leuven that used the Project Team Builder (PTB) simulation-based training environment. Adopters of this book are encouraged to try the PTB—it is available from http://www.sandboxmodel.com/—and to integrate it into their courses.

Writing a textbook is a collaborative effort involving many people whose names do not always appear on the cover. In particular, we thank all faculty who adopted the first and second editions of the book and provided us with their constructive and informative comments over the years. With regard to production, much appreciation goes to Lillian Bluestein for her thorough job in proofreading and editing the manuscript. We would also like to thank Chen Gretz-Shmueli for her contribution to the discussion in the human resources section. Finally, we are forever grateful to the phalanx of students who have studied project management at our universities and who have made the painstaking efforts of gathering and writing new material all worthwhile.

Avraham Shtub
Moshe Rosenwein

What's New in this Edition

The purpose of the new, third edition of this book is to update developments in the project management field over the last 10 years and to more broadly address some of the concerns that have increased in prominence in the minds of practitioners. We incorporated new material in many of the chapters specifically related to the *Project Management Body of Knowledge* (PMBOK) published by the Project Management Institute. This material reflects the tools, techniques, and processes that have gained widespread acceptance by the profession because of their proven value and usefulness.

Noteworthy enhancements in the third edition include:

- An expanded section regarding Lean project management in Chapter 8;
- A new chapter, Chapter 16, discussing the use of simulation and the Project Team Builder software;
- A detailed discussion on activity splitting and its advantages and disadvantages in project management;
- Descriptions, with examples, of resource-scheduling heuristics such as the longest-duration first heuristic and the Activity Time (ACTIM) algorithm;
- Examples that demonstrate the use of Excel Solver to model project management problems such as the time–cost tradeoff;
- A description of project management courses at Columbia University and the Global Network of Advanced Management.

About the Authors

Professor Avraham Shtub holds the Stephen and Sharon Seiden Chair in Project Management. He has a B.Sc. in Electrical Engineering from the Technion–Israel Institute of Technology (1974), an MBA from Tel Aviv University (1978), and a Ph.D. in Management Science and Industrial Engineering from the University of Washington (1982).

He is a certified Project Management Professional (PMP) and a member of the Project Management Institute (PMI-USA). He is the recipient of the Institute of Industrial Engineering 1995 Book of the Year Award for his book *Project Management: Engineering, Technology, and Implementation* (coauthored with Jonathan Bard and Shlomo Globerson), Prentice Hall, 1994. He is the recipient of the Production Operations Management Society Wick Skinner Teaching Innovation Achievements Award for his book *Enterprise Resource Planning (ERP): The Dynamics of Operations Management*. His books on Project Management were published in English, Hebrew, Greek, and Chinese.

He is the recipient of the 2008 Project Management Institute Professional Development Product of the Year Award for the training simulator "Project Team Builder – PTB."

Professor Shtub was a Department Editor for IIE Transactions, he was on the Editorial Boards of the Project Management Journal, The International Journal of Project Management, IIE Transactions, and the International Journal of Production Research. He was a faculty member of the department of Industrial Engineering at Tel Aviv University from 1984 to 1998, where he also served as a chairman of the department (1993–1996). He joined the Technion in 1998 and was the Associate Dean and head of the MBA program.

He has been a consultant to industry in the areas of project management, training by simulators, and the design of production—operation systems. He was invited to speak at special seminars on Project Management and Operations in Europe, the Far East, North America, South America, and Australia.

Professor Shtub visited and taught at Vanderbilt University, The University of Pennsylvania, Korean Institute of Technology, Bilkent University in Turkey, Otego University in New Zealand, Yale University, Universitat Politécnica de Valencia, and the University of Bergamo in Italy.

Dr. Moshe Rosenwein has a B.S.E. from Princeton University and a Ph.D. in Decision Sciences from the University of Pennsylvania. He has worked in the industry throughout his professional career, applying management science modeling and methodologies to business problems in supply chain optimization, network design, customer relationship management, and scheduling. He has served as an adjunct professor at Columbia University on multiple occasions over the past 20 years and developed a project management course for the School of Engineering that has been taught since 2009. He has also taught at Seton Hall University and Rutgers University. Dr. Rosenwein has published over 20 refereed papers and has delivered numerous talks at universities and conferences. In 2001, he led an industry team that was awarded a semi-finalist in the Franz Edelman competition for the practice of management science.

Contents

Chapter 1

Introduction

1.1 NATURE OF PROJECT MANAGEMENT

Many of the most difficult engineering and business challenges of recent decades have been to design, develop, and implement new systems of a type and complexity never before attempted. Examples include the construction of oil drilling platforms in the North Sea off the coast of Great Britain, the development of the manned space program in both the United States and the former Soviet Union, and the worldwide installation of fiber optic lines for broadband telecommunications. The creation of these systems with performance capabilities not previously available and within acceptable schedules and budgets has required the development of new methods of planning, organizing, and controlling events. This is the essence of project management.

A project is an organized endeavor aimed at accomplishing a specific nonroutine or low-volume task. Although projects are not repetitive, they may take significant amounts of time and, for our purposes, are sufficiently large or complex to be recognized and managed as separate undertakings. Teams have emerged as the way of supplying the needed talents. The use of teams complicates the flow of information and places additional burdens on management to communicate with and coordinate the activities of the participants.

The amount of time in which an individual or an organizational unit is involved in a project may vary considerably. Someone in operations may work only with other operations personnel on a project or may work with a team composed of specialists from various functional areas to study and solve a specific problem or to perform a secondary task.

Management of a project differs in several ways from management of a typical organization. The objective of a project team is to accomplish its prescribed mission and disband. Few firms are in business to perform just one job and then disappear. Because a project is intended to have a finite life, employees are seldom hired with the intent of building a career with the project. Instead, a team is pulled together on an ad-hoc basis from among people who normally have assignments in other parts of the organization. They may be asked to work full time on the project until its completion; or they may be asked to work only part time, such as two days a week, on the project and spend the rest of the time at their usual assignments. A project may involve a short-term task that lasts only a matter of days, or it may run for years. After completion, the team normally disperses and its members return to their original jobs.

The need to manage large, complex projects, constrained by tight schedules and budgets, motivated the development of methodologies different from those used to manage a typical enterprise. The increasingly complex task of managing large-scale, enterprise-wide projects has led to the rise in importance of the project management function and the role of the project manager or project management office. Project management is increasingly viewed in both industry and government as a critical role on a project team and has led to the development of project management as a profession (much like finance, marketing, or information technology, for example). The Project Management Institute (PMI), a nonprofit organization, is in the forefront of developing project management methodologies and of providing educational services in the form of workshops, training, and professional literature.

1.2 RELATIONSHIP BETWEEN PROJECTS AND OTHER PRODUCTION SYSTEMS

Operations and production management contains three major classes of systems: (1) those designed for mass production, (2) those designed for batch (or lot) production, and (3) those designed for undertaking nonrepetitive projects common to construction and new product development. Each of these classes may be found in both the manufacturing and service sectors.

Mass production systems are typically designed around the specific processes used to assemble a product or perform a service. Their orientation is fixed and their applications are limited. Resources and facilities are composed of special-purpose equipment designed to perform the operations required by the product or the service in an efficient way. By laying out the equipment to parallel the natural routings, material handling and information processing are greatly simplified. Frequently, material handling is automated and the use of conveyors and monorails is extensive. The resulting system is capital intensive and very efficient in the processing of large quantities of specific products or services for which relatively little management and control are necessary. However, these systems are very difficult to alter should a need arise to produce new or modified products or to provide new services. As a result, they are most appropriate for operations that experience a high rate of demand (e.g., several hundred thousand units annually) as well as high aggregate demand (e.g., several million units throughout the life cycle of the system).

Batch-oriented systems are used when several products or services are processed in the same facility. When the demand rate is not high enough or when long-run expectations do not justify the investment in special-purpose equipment, an effort is made to design a more flexible system on which a variety of products or services can be processed. Because the resources used in such systems have to be adjusted (set up) when production switches from one product to another, jobs are typically scheduled in batches to save setup time. Flexibility is achieved by using general-purpose resources that can be adjusted to handle different processes. The complexity of operations planning, scheduling, and control is greater than in mass production systems as each product has its own routing (sequence of operations). To simplify planning, resources are frequently grouped together based on the type of processes that they perform. Thus, batch-oriented systems contain organizational units that specialize in a function or a process, as opposed to product lines that are found in mass production systems. Departments such as metal cutting, painting, testing, and packaging/shipping are typical examples from the batch-oriented manufacturing sector, whereas word processing centers and diagnostic laboratories are examples from the service sector.

In the batch-oriented system, it is particularly important to pay attention to material handling needs because each product has its specific set of operations and routings. Material handling equipment, such as forklifts, is used to move in-process inventory between departments and work centers. The flexibility of batch-oriented systems makes them attractive for many organizations.

In recent years, flexible manufacturing systems have been quick to gain acceptance in some industrial settings. With the help of microelectronics and computer technology, these systems are designed to achieve mass production efficiencies in low-demand environments. They work by reducing setup times and automating material handling operations but are extremely capital intensive. Hence they cannot always be justified when product demand is low or when labor costs are minimal. Another approach is to take advantage of local economies of scale. Group technology cells, which are based on clustering similar products or components into families processed by dedicated resources of the facility, are one way to implement this approach. Higher utilization rates and greater throughput can be achieved by processing similar components on dedicated machines.

By way of contrast, systems that are subject to very low demand (no more than a few units) are substantially different from the first two mentioned. Because of the nonrepetitive nature of these systems, past experience may be of limited value so little learning takes place. In this environment, extensive management effort is required to plan, monitor, and control the activities of the organization. Project management is a direct outgrowth of these efforts.

It is possible to classify organizations based on their production orientation as a function of volume and batch size. This is illustrated in Figure 1.1.

The borderlines between mass production, batch-oriented, and project-oriented systems are hard to define. In some organizations where the project approach has been adopted, several units of the same product (a batch) are produced, whereas other organizations use a batch-oriented system that produces small lots (the just-in-time approach) of very large volumes of products. To better understand the transition between the three types of systems, consider an electronics firm that assembles printed circuit boards in small batches in a job shop. As demand for the boards picks up, a decision is made to develop a flow line for assembly. The design and implementation of this new line is a project.

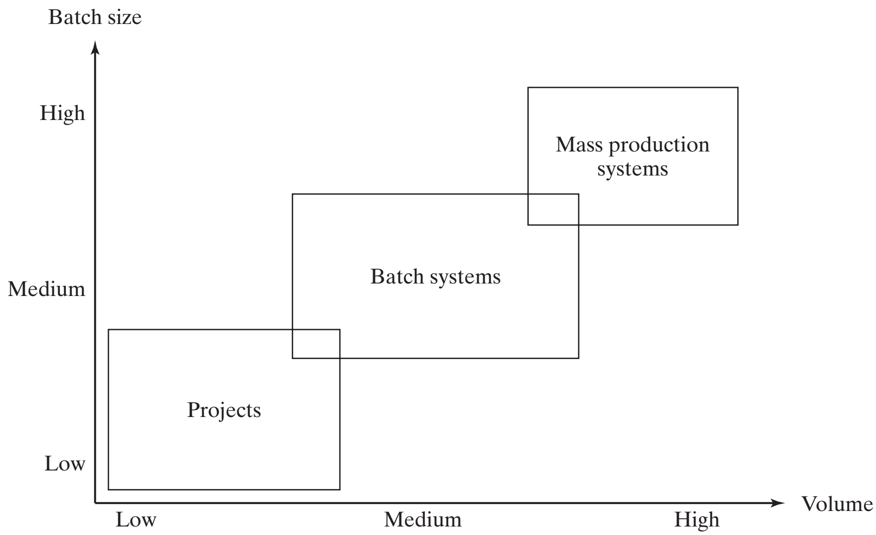

Figure 1.1 Classification of production systems.

1.3 CHARACTERISTICS OF PROJECTS

Although the Manhattan project—the development of the first atomic bomb—is considered by many to be the first instance when modern project management techniques were used, ancient history is replete with examples. Some of the better known ones include the construction of the Egyptian pyramids, the conquest of the Persian Empire by Alexander the Great, and the building of the Temple in Jerusalem. In the 1960s, formal project management methods received their greatest impetus with the Apollo program and a cluster of large, formidable construction projects.

Today, activities such as the transport of American forces in Operations in Iraq and Afghanistan, the pursuit of new treatments for AIDS and Ebola, and the development of the joint U.S.–Russian space station and the manned space mission to Mars are examples of three projects with which most of us are familiar. Additional examples of a more routine nature include:

- Selecting a software package
- Developing a new office plan or layout
- Implementing a new decision support system
- Introducing a new product to the market
- Designing an airplane, supercomputer, or work center
- Opening a new store
- Constructing a bridge, dam, highway, or building
- Relocating an office or a factory

- Performing major maintenance or repair
- Starting up a new manufacturing or service facility
- Producing and directing a movie

1.3.1 Definitions and Issues

As the list above suggests, a project may be viewed or defined in several different ways: for example, as "the entire process required to produce a new product, new plant, new system, or other specified results" (Archibald 2003) or as "a narrowly defined activity which is planned for a finite duration with a specific goal to be achieved" (General Electric Corporation 1983). Generally speaking, project management occurs when emphasis and special attention are given to the performance of nonrepetitive activities for the purpose of meeting a single set of goals, typically under a set of constraints such as time and budget constraints.

By implication, project management deals with a one-time effort to achieve a focused objective. How progress and outcomes are measured, though, depends on a number of critical factors. Typical among these are technology (specifications, performance, quality), time (due dates, milestones), and cost (total investment, required cash flow), as well as profits, resource utilization, market share, and market acceptance.

These factors and their relative importance are major issues in project management. These factors are based on the needs and expectations of the stakeholders. Stakeholders are individuals and parties interested in the problem the project is designed to solve or in the solution selected. With a well-defined set of goals, it is possible to develop appropriate performance measures and to select the right technology, the organizational structure, required resources, and people who will team up to achieve these goals. Figure 1.2 summarizes the underlying processes. As illustrated, most projects are initiated by a need. A new need may be identified by stakeholders such as a customer, the marketing department, or any member of an organization. When management is convinced that the need is genuine, goals may be defined, and the first steps may be taken toward putting together a project team. Most projects have several goals covering such aspects as technical and operational requirements, delivery dates, and cost. A set of potential projects to undertake should be ranked by stakeholders based on the relative importance of the goals and the perceived probability of each potential project to achieve each of the individual goals.

On the basis of these rankings and a derived set of performance measures for each goal, the technological alternatives are evaluated and a concept (or initial design) is developed along with a schedule and a budget for the project. This early phase of the project life cycle is known as the initiation phase, the front end of the project, or the conceptual phase. The next step is to integrate the design, the schedule, and the budget into a project plan specifying what should be done, by whom, at what cost, and when. As the plan is implemented, the actual accomplishments are monitored and recorded. Adjustments, aimed at keeping the project on track, are made when deviations or overruns appear. When the project terminates, its success is evaluated based on the predetermined goals and performance measures. Figure 1.3 compares two projects with these points in mind. In project 1, a "design to cost" approach is taken. Here, the budget is fixed and the technological goals are clearly specified. Cost, performance, and schedule are all given equal weight. In project 2, the technological goals are paramount and must be achieved, even if it means compromising the schedule and the budget in the process.

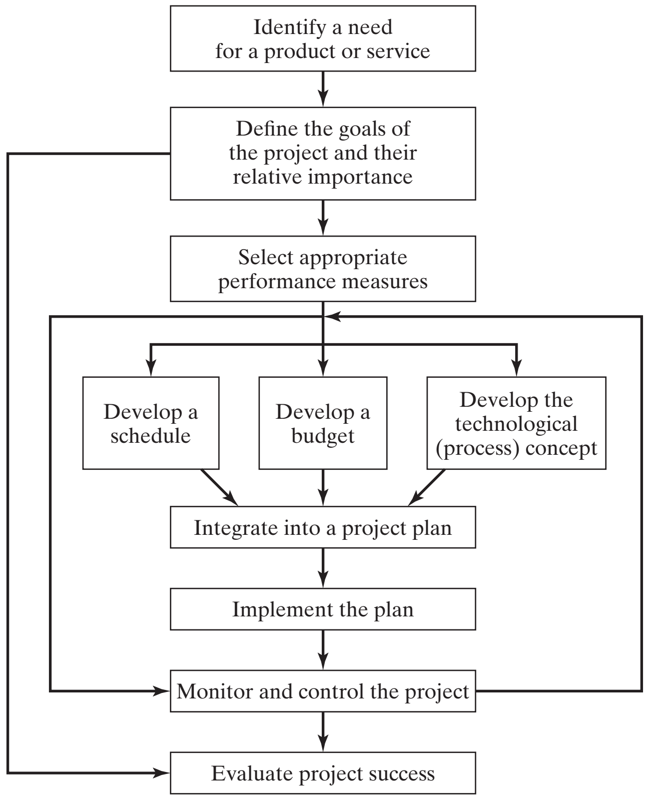

Figure 1.2 Major processes in project management.

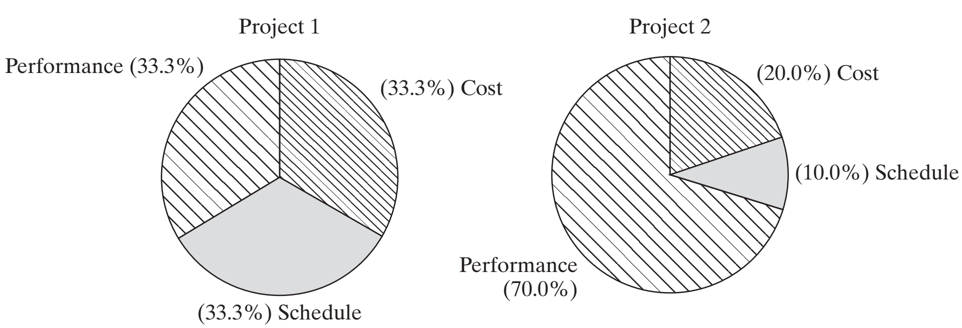

Figure 1.3 Relative importance of goals.

The first situation is typical of standard construction and manufacturing projects, whereby a contractor agrees to supply a system or a product in accordance with a given schedule and budget. The second situation is typical of "cost plus fixed fee" projects where the technological uncertainties argue against a contractor's committing to a fixed cost and schedule. This arrangement is most common in a research and development (R&D) environment.

A well-designed organizational structure is required to handle projects as a result of their uniqueness, variety, and limited life span. In addition, special skills are required to manage them successfully. Taken together, these skills and organizational structures have been the catalyst for the development of the project management discipline. Some of the accompanying tools and techniques, though, are equally applicable in the manufacturing and service sectors.

Because projects are characterized by a "one-time only" effort, learning is limited and most operations never become routine. This results in a need for extensive management involvement throughout the life cycle of the project. In addition, the lack of continuity leads to a high degree of uncertainty.

1.3.2 Risk and Uncertainty

In project management, it is common to refer to very high levels of uncertainty as sources of risk. Risk is present in most projects, especially in the R&D environment. Without trying to sound too pessimistic, it is prudent to assume that what can go wrong will go wrong. Principal sources of uncertainty include random variations in component and subsystem performance, inaccurate or inadequate data, and the inability to forecast satisfactorily as a result of lack of experience. Specifically, there may be

1. *Uncertainty in scheduling.* Changes in the environment that are impossible to forecast accurately at the outset of a project are likely to have a critical impact on the length of certain activities. For example, subcontractor performance or the time it takes to obtain a long-term loan is bound to influence the length of various subtasks. The availability of scarce resources may also add to uncertainty in scheduling. Methods are needed to deal with problematic or unstable time estimates. Probability theory and simulation both have been used successfully for this purpose, as discussed in Chapter 9.
2. *Uncertainty in cost.* Limited information on the duration of activities makes it difficult to predict the amount of resources needed to complete them on schedule. This translates directly into an uncertainty in cost. In addition, the expected hourly rate of resources and the cost of materials used to carry out project tasks may possess a high degree of variability.
3. *Technological uncertainty.* This form of uncertainty is typically present in R&D projects in which new (not thoroughly tested and approved) technologies, methods, equipment, and systems are developed or used. Technological uncertainty may affect the schedule, the cost, and the ultimate success of the project. The integration of familiar technologies into one system or product may cause technological uncertainty as well. The same applies to the development of software and its integration with hardware.

There are other sources of uncertainty, including those of an organizational and political nature. New regulations might affect the market for a project, whereas the turnover of personnel and changes in the policies of one or more of the participating organizations may disrupt the flow of work.

To gain a better understanding of the effects of uncertainty, consider the three projects mentioned earlier. The transport of American armed forces in Operation Iraqi Freedom faced extreme political and logistical uncertainties. In the initial stages, none of the planners had a clear idea of how many troops would be needed or how much time was available to put the troops in place. Also, it was unknown whether permission would be granted to use NATO air bases or even to fly over European and Middle Eastern countries, or how much tactical support would be forthcoming from U.S. allies.

The development of a treatment for AIDS is an ongoing project fraught with technological uncertainty. Hundreds of millions of dollars have already been spent with little progress toward a cure. As expected, researchers have taken many false steps, and many promising paths have turned out to be dead ends. Lengthy trial procedures and duplicative efforts have produced additional frustration. If success finally comes, it is unlikely that the original plans or schemes will have predicted its form.

The design of the U.S.–Russian space station is an example in which virtually every form of uncertainty is present. Politicians continue to play havoc with the budget, while other stakeholders like special interest groups (both friendly and hostile) push their individual agendas; schedules get altered and rearranged; software fails to perform correctly; and the needed resources never seem to be available in adequate supply. Inflation, high turnover rates, and scaled-down expectations take their toll on the internal workforce, as well as on the legion of subcontractors.

The American Production and Inventory Control Society has, tongue-in-cheek, fashioned the following laws in an attempt to explain the consequences of uncertainty on project management.

Laws of Project Management

1. No major project is ever installed on time, within budget or with the same staff that started it. Yours will not be the first.
2. Projects progress quickly until they become 90% complete, then they remain at 90% complete forever.
3. One advantage of fuzzy project objectives is that they let you avoid the embarrassment of estimating the corresponding costs.
4. When things are going well, something will go wrong.
   - When things just cannot get any worse, they will.
   - When things seem to be going better, you have overlooked something.
5. If project content is allowed to change freely, then the rate of change will exceed the rate of progress.
6. No system is ever completely debugged. Attempts to debug a system inevitably introduce new bugs that are even harder to find.

7. A carelessly planned project will take three times longer to complete than expected; a carefully planned project will take only twice as long.
8. Project teams detest progress reporting because it vividly manifests their lack of progress.

1.3.3 Phases of a Project

A project passes through a life cycle that may vary with size and complexity and with the style established by the organization. The names of the various phases may differ but typically include those shown in Figure 1.4. To begin, there is an *initiation* or a *conceptual design* phase during which the organization realizes that a project may be needed or receives a request from a customer to propose a plan to perform a project; at this phase alternative technologies and operational solutions are evaluated and the

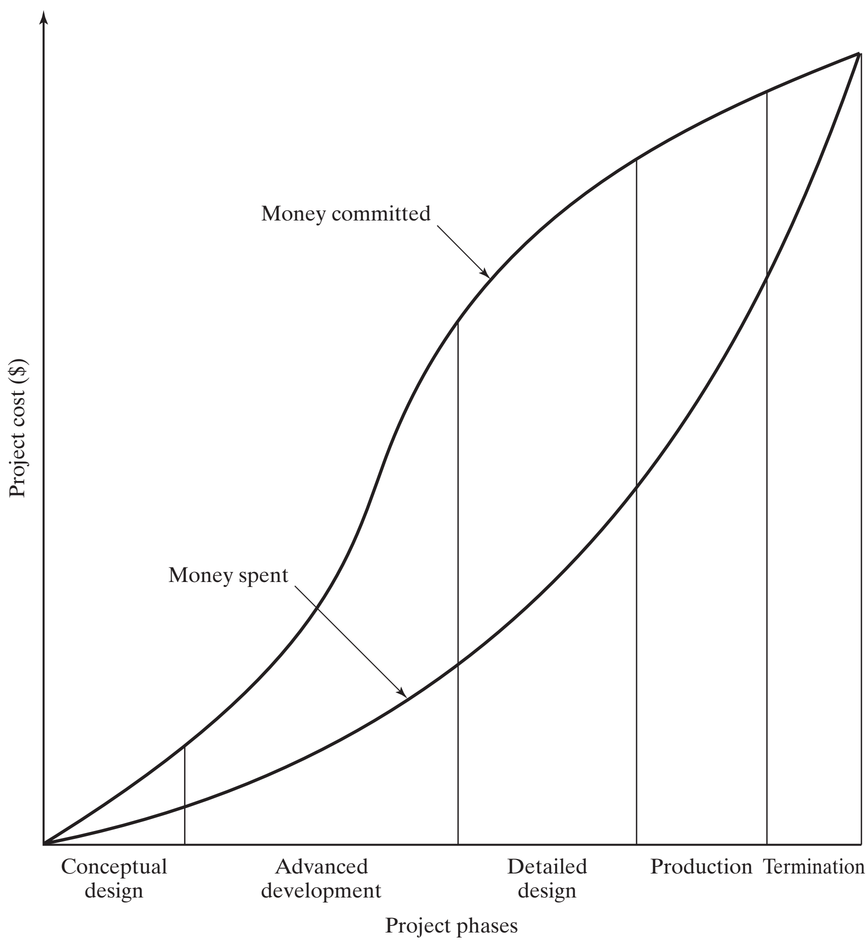

Figure 1.4 Relationship between project life cycle and cost.

most promising are selected based on performances, cost, risk, and schedule considerations. Next there is an *advanced development or preliminary system design* phase in which the project manager (and perhaps a staff if the project is complex) plans the project to a level of detail sufficient for initial scheduling and budgeting. If the project is approved, it then will enter a more *detailed design* phase, a *production* phase, and a *termination* phase.

In Figure 1.4, the five phases in the life cycle of a project are presented as a function of time. The cost during each phase depends on the specifics, but usually the majority of the budget is spent during the production phase. However, most of this budget is committed during the advanced development phase and the detailed design phase before the actual work takes place. Management plays a vital role during the conceptual design phase, the advanced development phase, and the detailed design phase. The importance of this involvement in defining goals, selecting performance measures, evaluating alternatives (including the no-go or not to do the project), selecting the most promising alternative and planning the project cannot be overemphasized. Pressures to start the "real work" on the project, that is, to begin the production (or execution) phase as early as possible, may lead to the selection of the wrong technological or operational alternatives and consequently to high cost and schedule risks as a result of the commitment of resources without adequate planning.

In most cases, a work breakdown structure (WBS) is developed during the conceptual design phase. The WBS is a document that divides the project work into major hardware, software, data, and service elements. These elements are further divided and a list is produced identifying all tasks that must be accomplished to complete the project. The WBS helps to define the work to be performed and provides a framework for planning, budgeting, monitoring, and control. Therefore, as the project advances, schedule and cost performance can be compared with plans and budgets. Table 1.1 shows an abbreviated WBS for an orbital space laboratory vehicle.

The detailed project definition, as reflected in the WBS, is examined during the advanced development phase to determine the skills necessary to achieve the project's goals. Depending on the planning horizon, personnel from other parts of the organization may be used temporarily to accomplish the project. However, previous commitments may limit the availability of these resources. Other strategies might include

TABLE 1.1 Partial WBS for Space Laboratory

Index	Work element
1.0	Command module
2.0	Laboratory module
3.0	Main propulsion system
3.1	Fuel supply system
3.1.1	Fuel tank assembly
3.1.1.1	Fuel tank casing
3.1.1.2	Fuel tank insulation
4.0	Guidance system
5.0	Habitat module
6.0	Training system
7.0	Logistic support system

hiring new personnel or subcontracting various work elements, as well as leasing equipment and facilities.

1.3.4 Organizing for a Project

A variety of structures are used by organizations to perform project work. The actual arrangement may depend on the proportion of the company's business that is project oriented, the scope and duration of the underlying tasks, the capabilities of the available personnel, preferences of the decision makers, and so on. The following five possibilities range from no special structure to a totally separate project organization.

1. *Functional organization.* Many companies are organized as a hierarchy with functional departments that specialize in a particular type of work, such as engineering or sales (see Figure 1.5). These departments are often broken down into smaller units that focus on special areas within the function. Upper management may

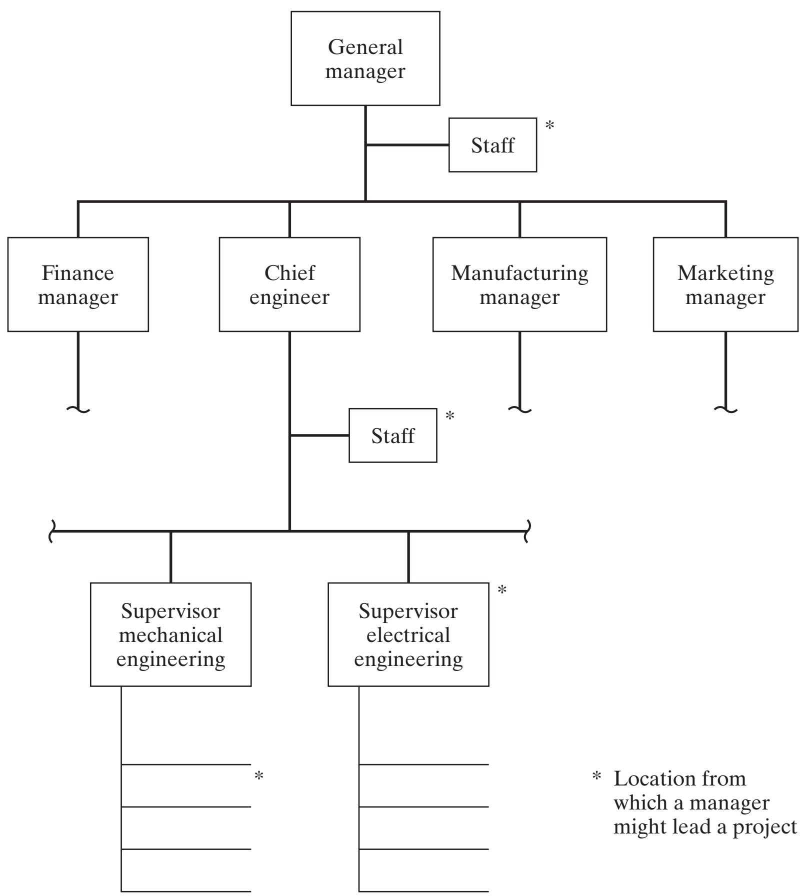

Figure 1.5 Portion of a typical functional organization.

divide a project into work tasks and assign them to the appropriate functional units. The project is then budgeted and managed through the normal management hierarchy.

2. *Project coordinator.* A project may be handled through the organization as described above, but with a special appointee to coordinate it. The project is still funded through the normal channels and the functional managers retain responsibility and authority for their portion of the work. The coordinator meets with the functional managers and provides direction and impetus for the project and may report its status to higher management.
3. *Matrix organization.* In a matrix organization, a project manager is responsible for completion of the project and is often assigned a budget. The project manager essentially contracts with the functional managers for completion of specific tasks and coordinates project efforts across the functional units. The functional managers assign work to employees and coordinate work within their areas. These arrangements are depicted schematically in Figure 1.6.
4. *Project team.* A particularly significant project (development of a new product or business venture) that will have a long duration and requires the full-time efforts of a group may be supervised by a project team. Full-time personnel are assigned to the project and are physically located with other team members. The project has its own management structure and budget as though it were a separate division of the company.
5. *Projectized organization.* When the project is of strategic importance, extremely complex and of long duration, and involves a number of disparate organizations, it is advisable to give one person complete control of all the elements necessary to accomplish the stated goals. For example, when Rockwell International was awarded two multimillion-dollar contracts (the Apollo command and service modules, and the second stage of the Saturn launch vehicle) by NASA, two separate programs were set up in different locations of the organization. Each program was under a division vice president and had its own manufacturing plant and staff of specialists. Such an arrangement takes the idea of a self-sufficient project team to an extreme and is known as a *projectized* organization.

Table 1.2 enumerates some advantages and disadvantages of the two extremes—the functional and projectized organizations. Companies that are frequently involved in a series of projects and occasionally shift around personnel often elect to use a matrix organization. This type of organization provides the flexibility to assign employees to one or more projects. In this arrangement, project personnel maintain a permanent reporting relationship that connects vertically to a supervisor in a functional area, who directs the scope of their work. At the same time, each person is assigned to one or more projects and has a horizontal reporting relationship to the manager of a particular project, who coordinates his or her participation in that project. Pay and career advancement are developed within a particular discipline even though a person may be assigned to different projects. At times, this dual reporting relationship can give rise to a host of personnel problems and creates conflicts.

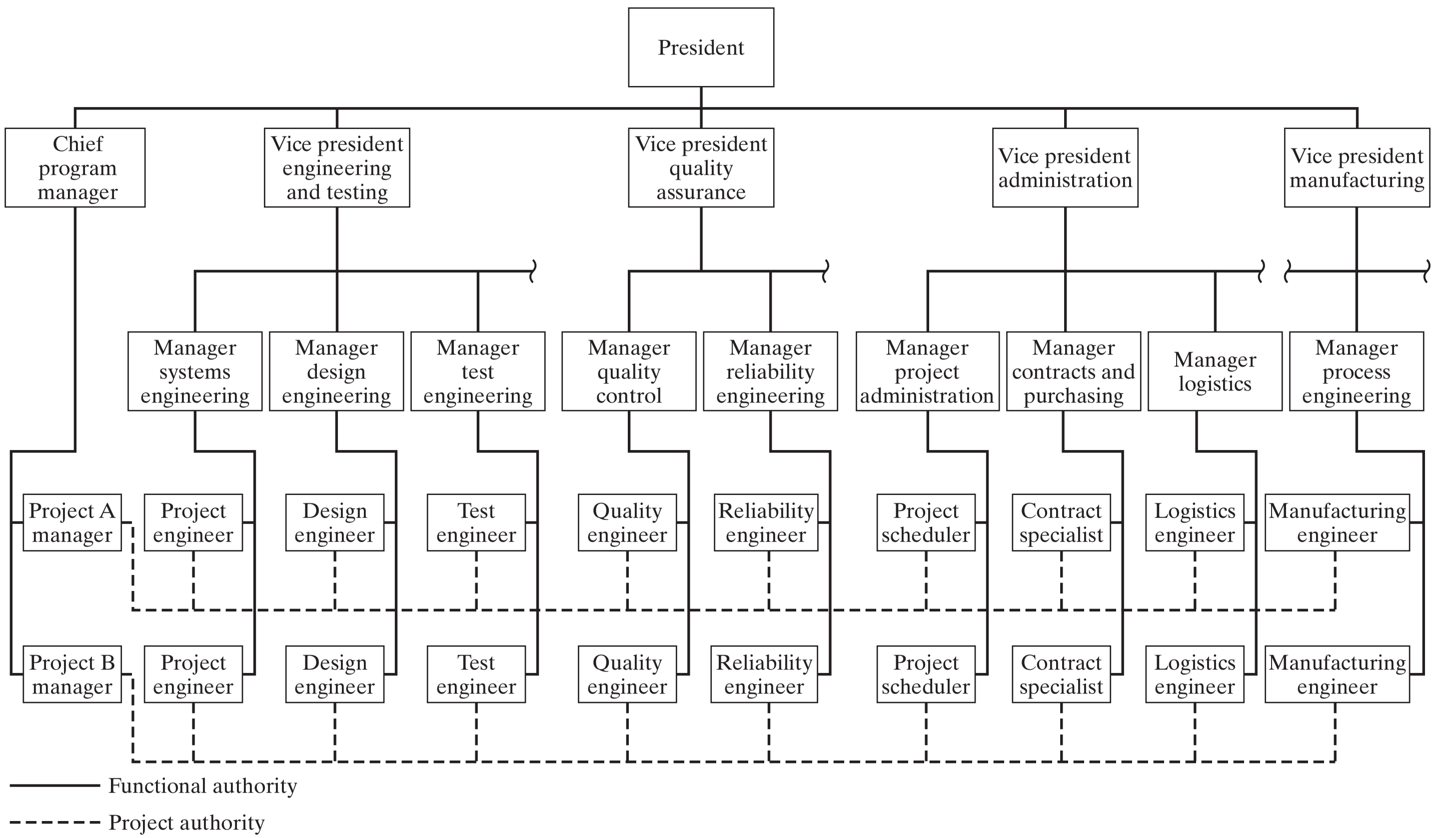

Figure 1.6 Typical matrix organization.

TABLE 1.2 Advantages and Disadvantages of Two Organizational Structures

Functional organization	Projectized organization
	Advantages
Efficient use of technical personnel	Good project schedule and cost control
Career continuity and growth for technical personnel	Single point for customer contact
Good technology transfer between projects	Rapid reaction time possible
Good stability, security, and morale	Simpler project communication
	Training ground for general management
	Disadvantages
Weak customer interface	Uncertain technical direction
Weak project authority	Inefficient use of specialists
Poor horizontal communications	Insecurity regarding future job assignments
Discipline (technology) oriented rather than program oriented	Poor crossfeed of technical information between projects
Slower work flow	

1.4 PROJECT MANAGER

The presence of uncertainty coupled with limited experience and hard-to-find data makes project management a combination of art, science, and, most of all, logical thinking. A good project manager must be familiar with a large number of disciplines and techniques. Breadth of knowledge is particularly important because most projects have technical, financial, marketing, and organizational aspects that inevitably conspire to derail the best of plans.

The role of the project manager may start at different points in the life cycle of a project. Some managers are involved from the beginning, helping to select the best technological and operational alternatives for the project, form the team, and negotiate the contracts. Others may begin at a later stage and be asked to execute plans that they did not have a hand in developing. At some point, though, most project managers deal with the basic issues: scheduling, budgeting, resource allocation, resource management, stakeholder management (e.g., human relations and negotiations).

It is an essential and perhaps the most difficult part of the project manager's job to pay close attention to the big picture without losing sight of critical details, no matter how slight. In order to efficiently and effectively achieve high-level project goals, project managers must prioritize concerns key stakeholders while managing change that inevitably arises during a project's life cycle. A project manager is an integrator and needs to trade off different aspects of the project each time a decision is called for. Questions such as, "How important is the budget relative to the schedule?" and "Should more resources be acquired to avoid delays at the expense of a budget overrun, or should a slight deviation in performance standards be tolerated as long as the project is kept on schedule and on budget?" are common.

Some skills can be taught, other skills are acquired only with time and experience, and yet other skills are very hard to learn or to acquire, such as the ability to lead a team without formal authority and the ability to deal with high levels of uncertainty without panic. We will not dwell on these but simply point them out, as we define fundamental principles and procedures. Nevertheless, one of our basic aims is to highlight the practical aspects of project management and to show how modern organizations can function more effectively by adopting them. In so doing, we hope to provide all members of the project team with a comprehensive view of the field.

1.4.1 Basic Functions

The PMI (2012) identifies ten knowledge areas that the discipline must address:

1. Integration management
2. Scope management
3. Time management
4. Cost management
5. Quality management
6. Human resource management
7. Communication management
8. Risk management
9. Procurement management
10. Stakeholders management

Managing a project is a complex and challenging assignment. Because projects are one-of-a-kind endeavors, there is little in the way of experience, normal working relationships, or established procedures to guide participants. A project manager may have to coordinate many diverse efforts and activities to achieve project goals. People from various disciplines and from various parts of the organization who have never worked together may be assigned to a project for different spans of time. Subcontractors who are unfamiliar with the organization may be brought in to carry out major tasks. A project may involve thousands of interrelated activities performed by people who are employed by any one of several different subcontractors or by the sponsoring organization.

Project leaders must have an effective means of identifying and communicating the planned activities and their interrelationships. A computer-based scheduling and monitoring system is usually essential. Network techniques such as CPM (*critical path method*) and PERT (*program evaluation and review technique*) are likely to figure prominently in such systems. CPM was developed in 1957 by J.E. Kelly of Remington-Rand and M.R. Walker of Dupont to aid in scheduling maintenance shutdowns of chemical plants. PERT was developed in 1958 under the sponsorship of the U.S. Navy

Special Projects Office, as a management tool for scheduling and controlling the Polaris missile program. Collectively, their value has been demonstrated time and again during both the planning and the execution phases of projects.

1.4.2 Characteristics of Effective Project Managers

The project manager is responsible for ensuring that tasks are completed on time and within budget, but often has no formal authority over those who actually perform the work. He or she, therefore, must have a firm understanding of the overall job and rely on negotiation and persuasion skills to influence the array of contractors, functionaries, and specialists assigned to the project. The skills that a typical project manager needs are summarized in Figure 1.7; the complexity of the situation is depicted in Figure 1.8, which shows the interactions between some of the stakeholders: client, subcontractor, and top management.

The project manager is a lightning rod, frequently under a storm of pressure and stress. He or she must deal effectively with the changing priorities of the client, the anxieties of his or her own management ever fearful of cost and schedule overruns or technological failures, and the divided loyalties of the personnel assigned to the team. The ability to trade off conflicting goals and to find the optimal balance between conflicting positions is probably the most important skill of the job.

In general, project managers require enthusiasm, stamina, and an appetite for hard work to withstand the onslaught of technical and political concerns. Where possible, they should have seniority and position in the organization commensurate with that of the functional managers with whom they must deal. Regardless of whether they are coordinators within a functional structure or managers in a matrix structure, they will frequently find their formal authority incomplete. Therefore, they must have the blend of technical, administrative, and interpersonal skills as illustrated in Figure 1.7 to furnish effective leadership.

1.5 COMPONENTS, CONCEPTS, AND TERMINOLOGY

Although each project has a unique set of goals, there is enough commonality at a generic level to permit the development of a unified framework for planning and control. Project management techniques are designed to handle the common processes and problems that arise during a project's life cycle. This does not mean, however, that one versed in such techniques will be a successful manager. Experts are needed to collect and interpret data, negotiate contracts, arrange for resources, manage stakeholders, and deal with a wide range of technical and organizational issues that impinge on both the cost and the schedule.

The following list contains the major components of a "typical" project.

- Project initiation, selection, and definition

    Identification of needs

    Mapping of stakeholders (who are they, what are their needs and expectations, how much influence and power they have, will they be engaged and by how much and will they be involved in the project and by how much)

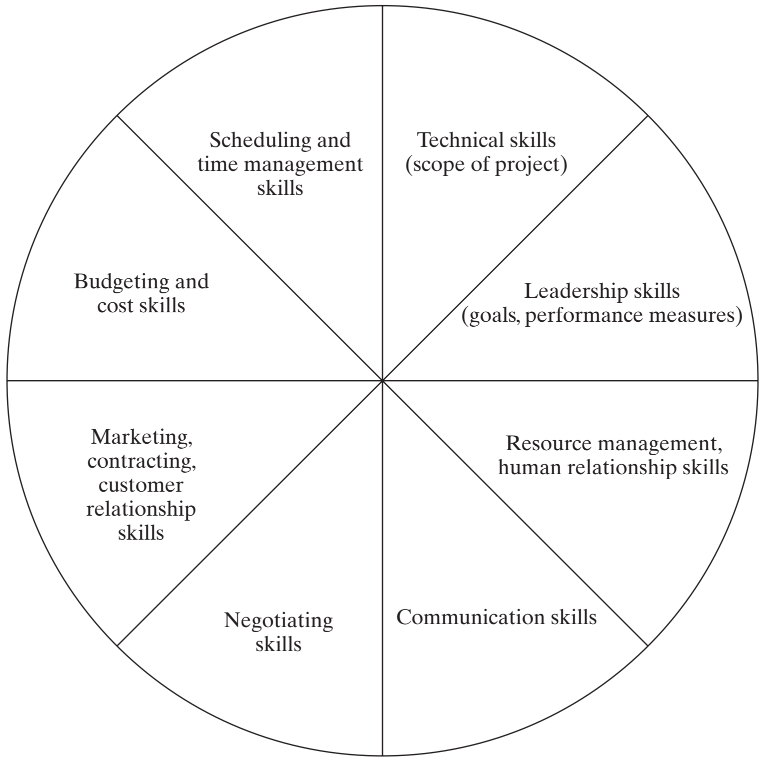

Figure 1.7 Important skills for the project manager.

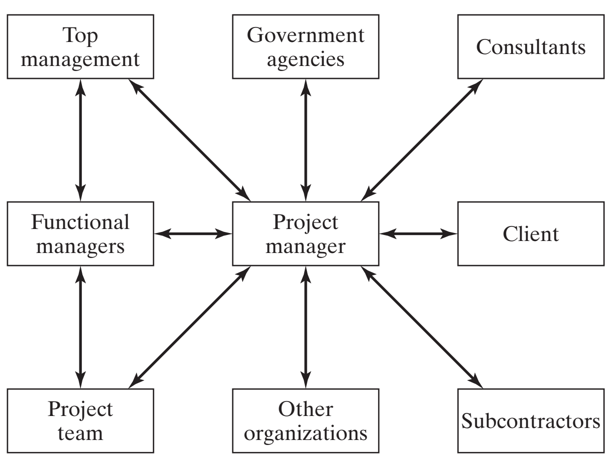

Figure 1.8 Major interactions of project stakeholders.

Development of (technological and operational) alternatives
Evaluation of alternatives based on performances, cost, duration, and risk
Selection of the "most promising" alternatives
Estimation of the *life cycle cost* (LCC) of the promising alternatives
Assessment of risk of the promising alternatives
Development of a *configuration baseline*
"Selling" the configuration and getting approval

- Project organization
  - Selection of participating organizations
  - Structuring the work content of the project into smaller work packages using a WBS
  - Allocation of WBS elements to participating organizations and assigning managers to the work packages
  - Development of the project organizational structure and associated communication and reporting facilities
- Analysis of activities
  - Definition of the project's major tasks
  - Development of a list of activities required to complete the project's tasks
  - Development of precedence relations among activities
  - Development of a network model
  - Development of higher level network elements (hammock activities, subnetworks)
  - Selection of milestones
  - Updating the network and its elements
- Project scheduling
  - Development of a calendar
  - Assigning resources to activities and estimation of activity durations
  - Estimation of activity performance dates
  - Monitoring actual progress and milestones
  - Updating the schedule
- Resource management
  - Definition of resource requirements
  - Acquisition of resources
  - Allocation of resources among projects/activities
  - Monitoring resource use and cost
- Technological management
  - Development of a configuration management plan
  - Identification of technological risks

Configuration control
Risk management and control
Total quality management (TQM)

- Project budgeting
  Estimation of direct and indirect costs
  Development of a cash flow forecast
  Development of a budget
  Monitoring actual cost

- Project execution and control
  Development of data collection systems
  Development of data analysis systems
  Execution of activities
  Data collection and analysis
  Detection of deviations in cost, configuration, schedule, and quality
  Development of corrective plans
  Implementation of corrective plans
  Forecasting of project cost at completion

- Project termination
  Evaluation of project success
  Recommendation for improvements in project management practices
  Analysis and storage of information on actual cost, actual duration, actual performance, and configuration

Each of these activities is discussed in detail in subsequent chapters. Here, we give an overview with the intention of introducing important concepts and the relationships among them. We also mention some of the tools developed to support the management of each activity.

1. *Project initiation, selection, and definition.* This process starts with identifying a need for a new service, product, or system. The trigger can come from any number of sources, including a current client, line personnel, or a proposed request from an outside organization. The trigger can come from one or more stakeholders who may have similar or conflicting needs and expectations. If the need is considered important and feasible solutions exist, then the need is translated into technical specifications. Next, a study of alternative solution approaches is initiated. Each alternative is evaluated based on a predetermined set of performance measures, and the most promising compose the "efficient frontier" of possible solutions. An effort is made to estimate the performances, duration, costs, and risks associated with the efficient alternatives. Cost estimates for development, production (or purchasing), maintenance, and operations form the basis of a Life Cycle Cost (LCC) model used for selecting the "optimal" alternative.

Because of uncertainty, most of the estimates are likely to be problematic. A risk assessment may be required if high levels of uncertainty are present. The risk associated with an unfavorable outcome is defined as the probability of that outcome multiplied by the cost associated with it. A proactive risk management approach means that major risk drivers should be identified early in the process, and contingency plans should be prepared to handle unfavorable events if and when they occur.

Once an alternative is chosen, design details are fleshed out during the concept formulation and definition phase of the project. Preliminary design efforts end with a configuration baseline. This configuration (the principal alternative) has to satisfy the needs and expectations of the most important stakeholders and be accepted and approved by management. A well-structured selection and evaluation process, in which all relevant parties are involved, increases the probability of management approval. A generic flow diagram for the processes of project initiation selection and definition is presented in Figure 1.9.

2. *Project organization.* Many stakeholders, ranging from private firms and research laboratories to public utilities and government agencies, may participate in a particular project. In the advanced development phase, it is common to define the work content [statement of work (SOW)] as a set of tasks, and to array them hierarchically in a treelike form known as the WBS. The relationship between participating organizations, known as the *organizational breakdown structure* (OBS) is similarly represented.

In the OBS, the lines of communication between and within organizations are defined, and procedures for work authorization and report preparation and distribution are established. Finally, lower-level WBS elements are assigned to lower-level OBS elements to form work packages and a responsibility matrix is constructed, indicating which organizational unit is responsible for which WBS element.

At the end of the advanced development phase, a more detailed cost estimate and a long-range budget proposal are prepared and submitted for management approval. A positive response signals the go-ahead for detailed planning and organizational design. This includes the next five functions.

3. *Analysis of activities.* To assess the need for resources and to prepare a detailed schedule, it is necessary to develop a detailed list of activities that are to be performed. These activities should be aimed at accomplishing the WBS tasks in a logical, economically sound, and technically feasible manner. Each task defined in the initial planning phase may consist of one or more activities. Feasibility is ensured by introducing precedence relations among activities. These relations can be represented graphically in the form of a network model.

Completion of an important activity may define a milestone and is represented in the network model. Milestones provide feedback in support of project control and form the basis for budgeting, scheduling, and resource management. As progress is made, the model has to be updated to account for the inclusion of new activities in the WBS, the successful completion of tasks, and any changes in design, organization, and schedule as a result of uncertainty, new needs, or new technological and political developments.

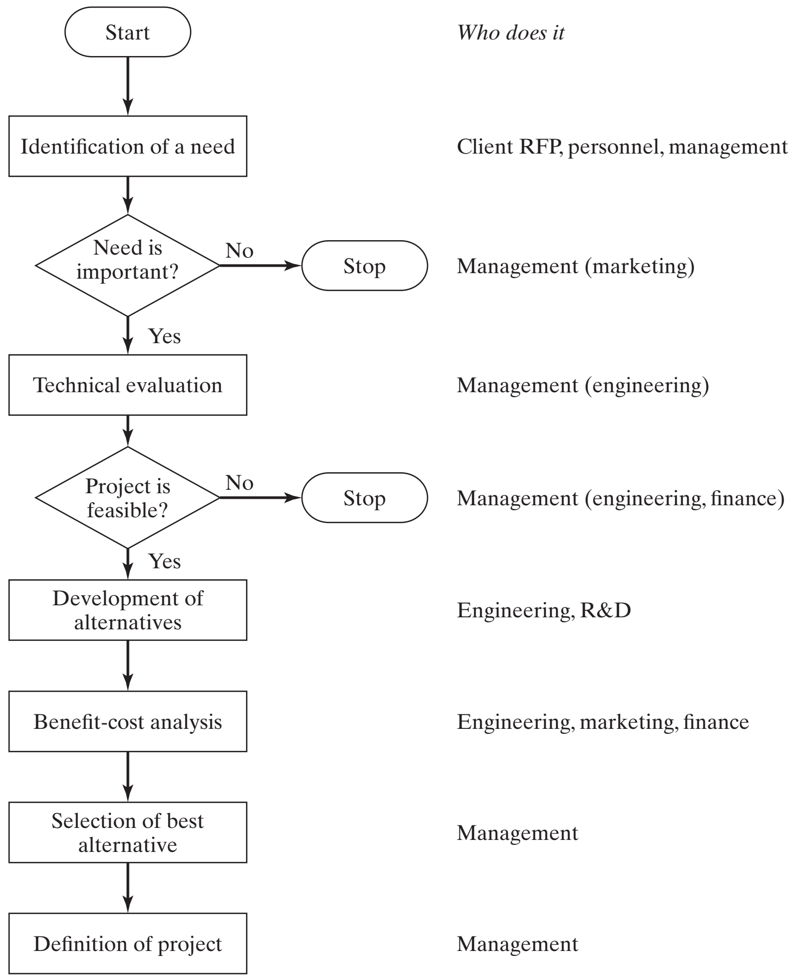

Figure 1.9 Major activities in the conceptual design phase.

4. *Project scheduling.* The expected execution dates of activities are important from both a financial (acquisition of the required funds) and an operational (acquisition of the required resources) point of view. Scheduling of project activities starts with the definition of a calendar specifying the working hours per day, working days per week, holidays, and so on. The expected duration of each activity is estimated, and a project schedule is developed based on the calendar, precedence relations among activities, and the expected duration of each activity. The schedule specifies the starting and ending dates of each activity and the accompanying slack or leeway. This information is used in budgeting and resource management. The schedule is used as a basis for work authorization and as a baseline against which actual progress is measured. It is updated throughout the life cycle of the project to reflect actual progress.

5. *Resource management.* Activities are performed by resources so that before any concrete steps can be taken, requirements have to be identified. This means defining one or more alternatives for meeting the estimated needs of each activity (the duration of an activity may be a function of the resources assigned to perform it). Based on the results, and in light of the project schedule, total resource requirements are estimated. These requirements are the basis of resource management and resource acquisition planning.

When requirements exceed expected availability, schedule delays may occur unless the difference is made up by acquiring additional resources or by subcontracting. Alternatively, it may be possible to reschedule activities (especially those with slack) so as not to exceed expected resource availability. Other considerations, such as minimizing fluctuations in resource usage and maximizing resource utilization, may be applicable as well.

During the execution phase, resources are allocated periodically to projects and activities in accordance with a predetermined timetable. However, because actual and planned use may differ, it is important to monitor and compare progress to plans. Low utilization as well as higher-than-planned costs or consumption rates indicate problems and should be brought to the immediate attention of management. Large discrepancies may call for significant alterations in the schedule.

6. *Technological management.* Once the technological alternatives are evaluated and a consensus forms, the approved configuration is adopted as a baseline. From the baseline, plans for project execution are developed, tests to validate operational and technical requirements are designed, and contingency plans for risky areas are formulated. Changes in needs or in the environment may trigger modifications to the configuration. Technological management deals with execution of the project to achieve the approved baseline. Principal functions include the evaluation of proposed changes, the introduction of approved changes into the configuration baseline, and development of a total quality management (TQM) program. TQM involves the continuous effort to prevent defects, to improve processes, and to guarantee a final result that fits the specifications of the project and the expectations of the client.

7. *Project budgeting.* Money is the most common resource used in a project. Equipment and labor have to be acquired, and suppliers have to be paid. Overhead costs have to be assigned, and subcontractors have to be put on the payroll. Preparation of a budget is an important management activity that results in a time-phased plan summarizing expected expenditures, income, and milestones.

The budget is derived by estimating the cost of activities and resources. Because the schedule of the project relates activities and resource use to the calendar, the budget is also related to the same calendar. With this information, a cash flow analysis can be performed, and the feasibility of the predicted outlays can be tested. If the resulting cash flow or the resulting budget is not acceptable, then the schedule should be modified. This is frequently done by delaying activities that have slack.

Once an acceptable budget is developed, it serves as the basic financial tool for the project. Credit lines and loans can be arranged, and the cost of financing the project can be assessed. As work progresses, information on actual cost is accumulated and

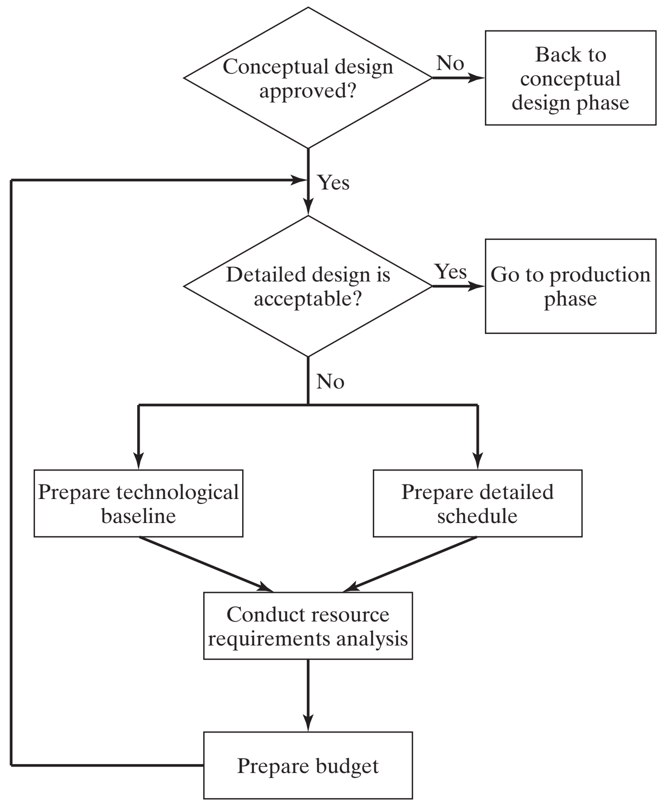

Figure 1.10 Major activities in the detailed design phase.

compared with the budget. This comparison forms the basis for controlling costs. The sequence of activities performed during the detailed design phase is summarized in Figure 1.10.

8. *Project execution and control.* The activities described so far compose the necessary steps in initializing and preparing a project for execution. A feasible schedule that integrates task deadlines, budget considerations, resource availability, and technological requirements, while satisfying the precedence relations among activities, provides a good starting point for a project.

It is important, however, to remember that successful implementation of the initial schedule is subject to unexpected or random effects that are difficult (or impossible) to predict. In situations in which all resources are under the direct control of management and activated according to plan, unexpected circumstances or events may sharply divert progress from the original plan. For resources that are not under complete management control, much higher levels of uncertainty may exist, for example, a downturn in the economy, labor unrest, technology breakthroughs or failures, and new environmental regulations.

Project control systems are designed with three purposes in mind: (1) to detect current deviations and to forecast future deviations between actual progress and the project plans; (2) to trace the source of these deviations; and (3) to support management decisions aimed at putting the project back on the desired course.

Project control is based on the collection and analysis of the most recent performance data. Actual progress, actual cost, resource use, and technological achievements should be monitored continually. The information gleaned from this process is compared with updated plans across all aspects of the project. Deviations in one area (e.g., schedule overrun) may affect the performance and deviations in other areas (e.g., cost overrun).

In general, all operational data collected by the control system are analyzed, and, if deviations are detected, a scheme is devised to put the project back on course. The existing plan is modified accordingly, and steps are taken to monitor its implementation.

During the life cycle of the project, a continuous effort is made to update original estimates of completion dates and costs. These updates are used by management to evaluate the progress of the project and the efficiency of the participating organizations. These evaluations form the basis of management forecasts regarding the expected success of the project at each stage of its life cycle.

Schedule deviations might have implications on a project's finances or Profit and Loss (P and L), if payments are based on actual progress. If a schedule overrun occurs and payments are delayed, then cash flow difficulties might result. Schedule overruns might also cause excess load on resources as a result of the accumulation of work content. A well-designed control system in the hands of a well-trained project manager is the best way to counteract the negative effects of uncertainty.

9. *Project termination.* A project does not necessarily terminate as soon as its technical objectives are met. Management should strive to learn from past experience to improve the handling of future projects. A detailed analysis of the original plan, the modifications made over time, the actual progress, and the relative success of the project should be conducted. The underlying goal is to identify procedures and techniques that were not effective and to recommend ways to improve operations. An effort aimed at identifying missing or redundant managerial tools should also be initiated; new techniques for project management should be adopted when necessary, and obsolete procedures and tools should be discarded.

Information on the actual cost and duration of activities and the cost and utilization of resources should be stored in well-organized databases to support the planning effort in future projects. Only by striving for continuous improvement and organizational learning through programs based on past experience is competitiveness likely to persist in an organization. Policies, procedures, and tools must be updated on a regular basis.

1.6 MOVEMENT TO PROJECT-BASED WORK

Increased reliance on the use of project management techniques, especially for research and development, stems from the changing circumstances in which modern businesses must compete. Pinto (2002) pointed out that among the most important influences promoting a project orientation in recent years have been the following:

1. *Shortened product life cycles.* Products become obsolete at an increasingly rapid rate, requiring companies to invest ever-higher amounts in R&D and new product development.
2. *Narrow product launch windows.* When a delay of months or even weeks can cost a firm its competitive advantage, new products are often scheduled for launch within a narrow time band.
3. *Huge influx of global markets.* New global opportunities raise new global challenges, such as the increasing difficulty of being first to market with superior products.
4. *Increasingly complex and technical problems.* As technical advances are diffused into organizations and technical complexity grows, the challenge of R&D becomes increasingly difficult.
5. *Low inflation.* Corporate profits must now come less from raising prices year after year and more from streamlining internal operations to become ever more efficient.

Durney and Donnelly investigated the effects of rapid technological change on complex information technology projects (2013). The impact of these and other economic factors has created conditions under which companies that use project management are flourishing. Their success has encouraged increasingly more organizations to give the discipline a serious look as they contemplate how to become "project savvy." At the same time, they recognize that, for all the interest in developing a project-based outlook, there is a severe shortage of trained project managers needed to convert market opportunities into profits. Historically, lack of training, poor career ladders, strong political resistance from line managers, unclear reward structures, and almost nonexistent documentation and operating protocols made the decision to become a project manager a risky move at best and downright career suicide at worst. Increasingly, however, management writers such as Tom Peters and insightful corporate executives such as Jack Welch have become strong advocates of the project management role. Between their sponsorship and the business pressures for enhancing the project management function, there is no doubt that we are witnessing a groundswell of support that is likely to continue into the foreseeable future.

Recent Trends in Project Management. Like any robust field, project management is continuously growing and reorienting itself. Some of the more pronounced shifts and advances can be classified as follows:

1. *Risk management.* Developing more sophisticated up-front methodologies to better assess risk before significant commitment to the project.
2. *Scheduling.* New approaches to project scheduling, such as critical chain project management, that offer some visible improvements over traditional techniques.

3. *Structure.* Two important movements in organizational structure are the rise of the heavyweight project organization and the increasing use of project management offices.
4. *Project team coordination.* Two powerful advances in the area of project team development are the emphasis on cross-functional cooperation and the model of punctuated equilibrium as it pertains to intra-team dynamics. Punctuated equilibrium proposes that rather than evolution occurring gradually in small steps, real natural change comes about through long periods of status quo interrupted by some seismic event.
5. *Control.* Important new methods for tracking project costs relative to performance are best exemplified by earned value analysis. Although the technique has been around for some time, its wider diffusion and use are growing.
6. *Impact of new technologies.* Internet and web technologies have given rise to greater use of distributed and virtual project teams, groups that may never physically interact but must work in close collaboration for project success.
7. *Lean project management.* The work of teams of experts from academia and industry led to the development of the guide to lean enablers for managing engineering programs (2012). The list of these enablers and the way they should be implemented is an important step in the development and application of lean project management methodologies.
8. *Process-based project management.* The PMBOK (PMI Standards Committee 2012) views project management as a combination of the ten knowledge areas listed in Section 1.14.1. Each area is composed of a set of processes whose proper execution defines the essence of the field.

1.7 LIFE CYCLE OF A PROJECT: STRATEGIC AND TACTICAL ISSUES

Because of the degree to which projects differ in their principal attributes, such as duration, cost, type of technology used, and sources of uncertainty, it is difficult to generalize the operational and technical issues they each face. It is possible, however, to discuss some strategic and tactical issues that are relevant to many types of projects. The framework for the discussion is the project life cycle or the major phases through which a "typical" project progresses. An outline of these phases is depicted in Figure 1.11 and elaborated on by Cleland and Ireland (2006), who identify the long-range (strategic) and medium-range (tactical) issues that management must consider. A synopsis follows.

1. *Conceptual design phase.* In this phase, a stakeholder (client, contractor, or subcontractor) initiates the project and evaluates potential alternatives. A client organization may start by identifying a need or a deficiency in existing operations and issuing a request for proposal (RFP).

The selection of projects at the conceptual design phase is a strategic decision based on the established goals of the organization, needs, ongoing projects, and

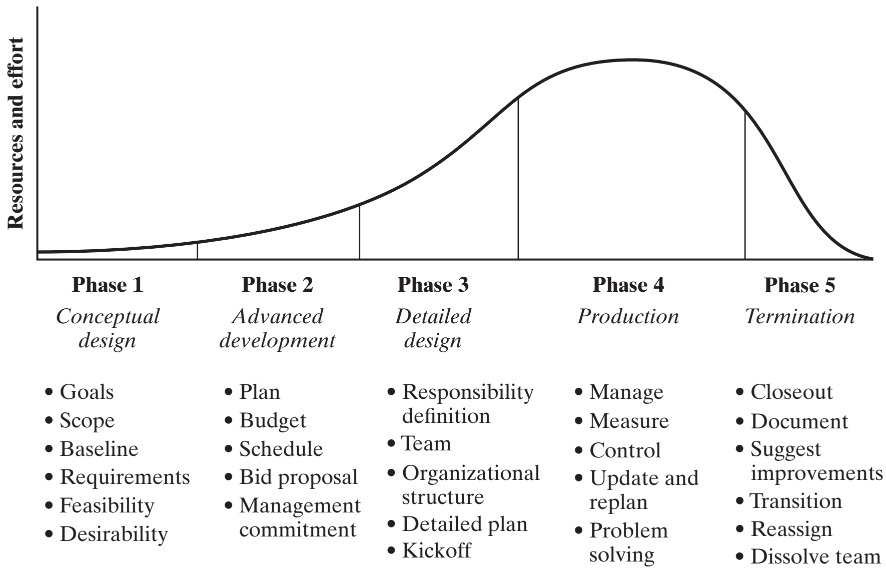

Figure 1.11 Project life cycle.

long-term commitments and objectives. In this phase, expected benefits from alternative projects, assessment of cost and risks, and estimates of required resources are some of the factors weighed. Important action items include the initial "go/no go" decision for the entire project and "make or buy" decisions for components and equipment, development of contingency plans for high-risk areas, and the preliminary selection of subcontractors and other team members who will participate in the project.

In addition, upper management must consider the technological aspects, such as availability and maturity of the required technology, its performance, and expected usage in subsequent projects. Environmental factors related to government regulations, potential markets, and competition also must be analyzed.

The selection of projects is based on a variety of goals and performance measures, including expected cost, profitability, risk, and potential for follow-on assignments. Once a project is selected and its conceptual design is approved, work begins on the second phase where many of the details are ironed out.

2. *Advanced development phase.* In this phase, the organizational structure of the project is formed by weighing the tactical advantages and disadvantages of each possible arrangement mentioned in Section 1.3.4. Once a decision is made, lines of communication and procedures for work authorization and performance reporting are established. This leads to the framework in which the project is executed.

3. *Detailed design phase.* This is the phase in a project's life cycle in which comprehensive plans are prepared. These plans consist of:

- Product and process design
- Final performance requirements

- Detailed breakdown of the work structure
- Scheduling information
- Blueprints for cost and resource management
- Detailed contingency plans for high-risk activities
- Budgets
- Expected cash flows

In addition—and most importantly—procedures and tools for executing, controlling, and correcting the project are developed. When this phase is completed, implementation can begin since the various plans should cover all aspects of the project in sufficient detail to support work authorization and execution.

The success of a project is highly correlated with the quality and the depth of the plans prepared during this phase. A detailed design review of each plan and each aspect of the project is, therefore, conducted before approval. A sensitivity analysis of environmental factors that contribute to uncertainty also may be needed. This analysis is typically performed as part of "what-if" studies using expert opinions and simulation as supporting mechanisms.

In most situations, the resources committed to the project are defined during the initial phases of its life cycle. Although these resources are used later, the strategic issues of how much to spend and at what rate are addressed here.

4. *Production or execution phase.* The fourth life-cycle phase involves the execution of plans and in most projects dominates the others in effort and duration. The critical strategic issue here relates to maintaining top management support, while the critical tactical issues center on the flow of communications within and among the participating organizations. At this level, the focus is on actual performance and changes in the original plans. Modifications can take different forms—in the extreme case, a project may be canceled. More likely, though, the scope of work, schedule, and budget will be adjusted as the situation dictates. Throughout this phase, management's task is to assign work to the participating parties, to monitor actual progress and compare it with the baseline plans. The establishment and operation of a well-designed communications and control system therefore are necessary.

Support of the product or system throughout its entire life (logistic support) requires management attention in most engineering projects for which an operational phase is scheduled to follow implementation. The preparation for logistic support includes documentation, personnel training, maintenance, and initial acquisition of spare parts. Neglecting this activity or giving it only cursory attention can doom an otherwise successful venture.

5. *Termination phase.* In this phase, management's goal is to consolidate what it has learned and translate this knowledge into ongoing improvements in the process. Current lessons and experience serve as the basis for improved practice. Although successful projects can provide valuable insights, failures can teach us even more. Databases that store and support the retrieval of project management information related to project cost, schedules, resource utilization, and so on are assets of an organization. Readily available, accurate information is a key factor in the success of future projects.

6. *Operational phase.* The operational phase is frequently outside the scope of a project and may be carried out by organizations other than those involved in the earlier life-cycle stages. If, for example, the project is to design and build an assembly line for a new model of automobile, then the operation of the line (i.e., the production of the new cars) will not be part of the project because running a mass production system requires a different type of management approach. Alternatively, consider the design and testing of a prototype electric vehicle. Here, the operational phase, which involves operating and testing the prototype, will be part of the project because it is a one-time effort aimed at a very specific goal. In any case, from the project manager's point of view, the operational phase is the most crucial because it is here that a judgment is made as to whether the project has achieved its technical and operational goals.

Strategic issues such as long-term relationships with customers, as well as customer service and satisfaction, have a strong influence on upper management's attitudes and decisions. Therefore, the project manager should be particularly aware of the need to open and maintain lines of communication between all parties, especially during this phase.

Other life cycle models are used including the Spiral model (Boehm, 1986), which emphasizes prototyping and Agile Project Management (2001), which emphasizes collaboration and communication, with particular application to software development.

1.8 FACTORS THAT AFFECT THE SUCCESS OF A PROJECT

A study by Pinto and Slevin (1987) sought to find those factors that contribute most to a project's success and to measure their significance over the life cycle. They found the following ten factors to be of primary importance. Additional insights are provided by Balachandra and Friar (1997) regarding new product development and by the Standish Group that focused on Information Technology (IT) projects since 1994 (The CHAOS reports 1995–2013).

1. *Project mission and goals.* Well-defined and intelligible understanding of the project goals are the basis of planning and executing the project. Understanding the goals and performance measures used in the evaluation is important for good coordination of efforts and building organizational support. Therefore, starting at the project initiation or the conceptual design phase of the project life cycle, the overall mission should be defined and explained to team members, contractors, and other participants.

2. *Top management support.* The competition for resources, coupled with the high levels of uncertainty typically found in the project environment, often leads to conflict and crisis. The continuous involvement of top management throughout the life cycle of the project increases their understanding of its mission and importance. This awareness, if translated into support, may prove invaluable in resolving problems when crises and conflicts arise or when uncertainty strikes. Therefore, continued, solid communication between the project manager and top management is a catalyst for the project to be a success.

3. *Project planning.* The translation of the project mission, goals, and performance measures into a workable (feasible) plan is the link between the initiation phase and the execution or production phase. A detailed plan that covers all aspects of the project—technical, financial, organizational, scheduling, communication, and control—is the basis of implementation. Planning does not end when execution starts because deviations from the original plans during implementation may call for replanning and updating from one period to the next. Thus, planning is a dynamic and continuous process that links changing goals and performance to the final results.

4. *Client consultation.* The ultimate user of the project is the final judge of its success. A project that was completed on time according to the technical specifications and within budget but was never (or rarely) used can certainly be classified as a failure. In the conceptual design phase of the project life cycle, client input is the basis for setting the mission and establishing goals. In subsequent phases, continual consultation with the client can help in correcting errors previously made in translating goals into performance measures. In many projects, the client is a group of project stakeholders, each having needs and expectations from the project. However, as a result of changing needs and conditions, a mission statement that represented accurately the client's needs in the conceptual design phase may no longer be valid in the planning or implementation phases. As discussed in Chapter 6, the configuration management system provides the link between existing plans and change requests issued by the client, as well as the project team.

5. *Personnel issues.* Satisfactory achievement of technical goals without violating schedule and budgetary constraints does not necessarily constitute a complete success, even if the stakeholders are satisfied. If relations among team members, between team members and the client, or between team members and other personnel in the organization are poor and morale problems are frequent, then project success is doubtful. Well-motivated teams with a sufficient level of commitment to the project and a good relationship with the other stakeholders are the key determinants of project success.

6. *Technical issues.* Understanding the technical aspects of the project and ensuring that members of the project team possess the necessary skills are important responsibilities of the project manager. Inappropriate technologies or technical incompatibility may affect all aspects of the project, including cost, schedule, system performance, and morale.

7. *Client acceptance.* Ongoing client consultation (as well as consultation with other important stakeholders) during the project life cycle increases the probability of success regarding user acceptance. In the final stages of implementation, the stakeholders evaluate the resulting project and decide whether it is acceptable. A project that is rejected at this point must be viewed as a failure.

8. *Project control.* The continuous flow of information regarding actual progress is a feedback mechanism that allows the project manager to cope with uncertainty. By comparing actual progress with current plans, the project manager can identify deviations, anticipate problems, and initiate corrective actions. Lower-than-planned achievements in technical areas as well as schedule and cost deviations detected early in the life cycle can help the project manager focus on the important issues. Plans can be updated or partially adjusted to keep the project on schedule, on budget, and on target with respect to its mission.

9. *Communication.* The successful transition between the phases of a project's life cycle and good coordination between participants during each phase requires a continuous exchange of information. In general, communication within the project team, with other parts of the organization, and between the project manager and the client is made easier when lines of authority are well defined. The organizational structure of the project should specify the communication channels and the information that should flow through each one. In addition, it should specify the frequency at which this information should be generated and transmitted. The formal communication lines and a positive working environment that enhances informal communication within the project team contribute to the success of a project.

10. *Troubleshooting.* The control system is designed to identify problem areas and, if possible, to trace their source through the organization. Because uncertainty is always a likely culprit, the development of contingency plans is a valuable preventive step. The availability of prepared plans and procedures for handling problems can reduce the effort required for dealing with them should they actually occur.

1.9 ABOUT THE BOOK: PURPOSE AND STRUCTURE

This book is designed to bridge the gap between theory and practice by presenting the tools and techniques most suited for modern project management. A principal goal is to give managers, engineers, and technology experts a larger appreciation of their roles by defining a common terminology and by explaining the interfaces between the underlying disciplines.

Theoretical aspects are covered at a level appropriate for a senior undergraduate course or a first-year graduate course in either an Engineering or an MBA program. Special attention is paid to the use and evaluation of specific tools with respect to their real-world applicability. Whether the book is adopted for a course or is read by practitioners who want to learn the "tools of the trade," we tried to present the subject matter in a concise and fully integrated manner.

A simulation tool, called the Project Team Builder (PTB), can be used to integrate the different aspects of project management and to provide hands-on experience of using these tools in a dynamic, uncertain environment. The PTB software is available from Sandboxmodel http://www.sandboxmodel.com/.

The book is structured along functional lines and offers an in-depth treatment of basic processes, the economic aspects of project selection and evaluation, the technological aspects of configuration management, and the various issues related to budgeting, scheduling, and control. By examining these functions and their organizational links, a comprehensive picture emerges of the relationship that exists between project planning and implementation.

The end of each chapter contains a series of discussion questions and exercises designed to stimulate thought and to test the readers' grasp of the material. In some cases, the intent is to explore supplementary issues in a more open-ended manner. Also included at the end of each chapter is a team project centering on the design and construction of a solid waste disposal facility known as a *thermal transfer plant*. As the readers go from one chapter to the next, they are asked to address a particular aspect of project management as it relates to the planning of this facility.

Each of the remaining chapters deals with a specific component of project management or a specific phase in the project life cycle. A short description of Chapters 2 through 16 follows.

Chapter 2 focuses on process-based project management; it begins with a discussion of life-cycle models and their importance in planning, coordination, and control. We then introduce the concept of a *process*, which is a group of activities designed to transform a set of inputs consisting of data, technology, and resources into the desired outputs. The remainder of the chapter is devoted to the processes underlying the ten project management knowledge areas contained in the PMBOK. As we explain, these processes, along with an appropriate information system, constitute the cornerstones of process-based project management.

In Chapter 3, we address the economic aspects of projects and the quantitative techniques developed for analyzing a specific alternative. The long-term perspective is presented first by focusing on the time value of money. Investment evaluation criteria based on net present value, internal rate of return, and the payback period are discussed. Next, the short-term perspective is given by considering the role that cash flow analysis plays in evaluating projects and comparing alternatives. Ideas surrounding risk and uncertainty are introduced, followed by some concepts common to decision making, such as expected monetary value, utility theory, breakeven analysis, and diminishing returns. Specific decisions such as buy, make, rent, or lease are also elaborated.

The integration of LCC analysis into the project management system is covered in Chapter 4. LCC concepts and the treatment of uncertainty in the analysis are discussed, as well as classification schemes for cost components. The steps required in building LCC models are outlined and explained to facilitate their implementation. The idea that the cost of new product development is only a fraction of the total cost of ownership is a central theme of the chapter. The total LCC is determined largely in the early phases of a project when decisions regarding product design and process selection are being made. Some of the issues discussed in this context include cost estimation and risk evaluation. The concept of the cost breakdown structure and how it is used in planning is also presented.

The selection of a project from a list of available candidates and the selection of a particular configuration for a specific project are two key management decisions. The purpose of Chapter 5 is to present several basic techniques that can be used to support this process. Checklists and scoring models are the simplest and first to be introduced. This is followed by a presentation of the formal aspects of benefit-cost and cost-effectiveness analysis. Issues related to risk, and how to deal with them, tie all the material together. The chapter closes with a comprehensive treatment of decision trees. The strengths and weakness of each methodology are highlighted and examples are given to demonstrate the computations.

It is rare that any decision is made on the basis of one criterion alone. To deal more thoroughly with situations in which many objectives, often in conflict with one another, must be juggled simultaneously, a value model that goes beyond simple checklists is needed. In Chapter 6, we introduce two of the most popular such models for combining multiple, possibly conflicting objectives into a single measure of performance. Multiattribute utility theory (MAUT) is the first presented. Basic theory is discussed along with the guiding axioms. Next, the concepts and assumptions behind the analytical hierarchy process (AHP) are detailed. A case study contained in the appendix documents the results of a project aimed at comparing the two approaches and points out the relative advantages of each.

The OBS and the WBS are introduced in Chapter 7. The former combines several organizational units that reside in one or more organizations by defining communication channels for work authorization, performance reports, and assigning general responsibility for tasks. Questions related to the selection of the most appropriate organizational structure are addressed, and the advantages and disadvantages of each are presented. Next, the WBS of projects is discussed. This structure combines hardware, software, data, and services performed in a project into a hierarchical framework. It further facilitates identification of the critical relationships that exist among various project components. Subsequently, the combined OBS-WBS matrix is introduced, whereby each element in the lowest WBS level is assigned to an organizational unit at the lowest level of the OBS. This type of integration is the basis for detailed planning and control, as explained in subsequent chapters. We close with a discussion of human resources, focusing on a project manager's responsibilities in this area.

In Chapter 8, the process by which the technological configuration of projects is developed and maintained is discussed. The first topic relates to the importance of time-based competition, the use of teams, and the role of QFD in engineering. We then show how tools such as benefit-cost analysis and MAUT can be used to select the best technological alternative from a set of potential candidates. Procedures used to handle engineering change requests via configuration management and configuration control are presented. Finally, the integration of quality management into the project and its relationship to configuration test and audit are highlighted.

Network analysis has played an important role in project scheduling over the past 50 years. In Chapter 9, we introduce the notions of activities, precedence relations, and task times, and show how they can be combined in an analytic framework to provide a mechanism for planning and control. The idea of a calendar and the relationship between activities and time are presented, first by Gantt charts and then by network models of the activity-on-arrow/activity-on-node type. This is followed by a discussion of precedence relations, feasibility issues, and the concepts of milestones, hammock activities, and subnetworks. Finally, uncertainty is introduced along with the PERT approach to estimating the critical path and the use of Monte Carlo simulation to gain a deeper understanding of a project's dynamics.

Chapter 10 opens with a discussion of the type of resources used in projects. A classification scheme is developed according to resource availability, and performance measures are suggested for assessing efficiency and effectiveness. Some general guidelines are presented as to how resources should be used to achieve better performance levels. The relationship between resources and their cost and the project schedule is analyzed, and mathematical models for resources allocation and leveling are described.

In Chapter 11, we deal with the budget as a tool by which organizational strategies, goals, policies, and constraints are transformed into an executable plan that relates task completions and capital expenditures to time. Techniques commonly used for budget development, presentation, and execution are discussed. Issues also examined are the relationship between the duration and timing of activities and the budget of a project, cash flow constraints and liabilities, and the interrelationship among several projects performed by a single organizational unit.

The execution of a project is frequently subject to unforeseen difficulties that cause deviation from the original plans. The focus of Chapter 12 is on project monitoring and control—a function that depends heavily on early detection of such deviations. The integration of OBS and WBS elements serves as a basis for the control system. Complementary components include a mechanism for tracing the source of each deviation and a forecasting procedure for assessing their implications if no corrective action is taken. Cost and schedule control techniques such as the earned value approach are presented and discussed.

Engineering projects where new technologies are developed and implemented are subject to high levels of uncertainty. In Chapter 13, we define R&D projects and highlight their unique characteristics. The typical goals of such projects are discussed, and measures of success are suggested. Techniques for handling risk, including the idea of parallel funding, are presented. The need for rework or repetition of some activities is discussed, and techniques for scheduling R&D projects are outlined. The idea of a portfolio is introduced, and tools used for portfolio management are discussed. A case study that involves screening criteria, project selection and termination criteria, and the allocation of limited resources is contained in the appendix.

A wide variety of software has been developed to assist the project manager. In Chapter 14, we discuss the basic functions and range of capabilities associated with these packages. A classification system is devised, and a process by which the most appropriate package can be selected for a project or an organization is outlined.

In Chapter 15, the need to terminate a project in a planned, orderly manner is discussed. The process by which information gathered in past projects can be stored, retrieved, and analyzed is presented. Post-mortem analysis is suggested as a vehicle by which continuous improvement can be achieved in an organization. The goal is to show how projects can be terminated so that the collective experience and knowledge can be transferred to future endeavors.

In Chapter 16, we present new developments in teaching Project Management in MBA and Engineering programs. First we discuss the need to improve the way we teach project management. Next the idea of Simulation Based Training (SBT) as a way to gain "hands-on" experience in a controlled, safe environment where the cost of errors is minimized and learning by doing is implemented. The "Project Team Builder (PTB)" simulator is described next with a focus on the main features of this SBT tool. This is followed by two specific examples based on our experience using Simulation Based Training and PTB in the Global Network for Advanced Management (GNAM) New Product Development (NPD) Course and in a Project Management course at Columbia University, School of Engineering.

It goes without saying that the huge body of knowledge in the area of project management cannot be condensed into a single book. Over the past 25 years alone, much has been written on the subject in technical journals, textbooks, company reports, and trade magazines. In an effort to cover some of this material, a bibliography of important works is provided at the end of each chapter. The interested reader can further his or her understanding of a particular topic by consulting these references.

TEAM PROJECT*

Thermal Transfer Plant

Introduction

To exercise the techniques used for project planning and control, the reader is encouraged to work out each aspect of the *thermal transfer plant* case study. At the end of each chapter, a short description of the relevant components of the thermal transfer plant is provided along with an assignment. If possible, the assignment should be done in groups of three or four to develop the interpersonal and organizational skills necessary for teamwork.

Not all of the information required for each assignment is given. Before proceeding, it may be necessary for the group to research a particular topic and to make some logical assumptions. Accordingly, there is no "correct solution" to compare recommendations and conclusions. Each assignment should be judged with respect to the availability of information and the force of the underlying assumptions.

Total Manufacturing Solutions, Inc.

Total Manufacturing Solutions, Inc. (TMS) designs and integrates manufacturing and assembly plants. Their line of products and services includes the selection of manufacturing and assembly processes for new or existing products, the design and selection of manufacturing equipment, facilities design and layout, the integration of manufacturing and assembly systems, and the training of personnel and startup management teams. The broad range of services that TMS provides to its customers makes it a unique and successful organization. Its headquarters are in Nashville, Tennessee, with branches in New York and Los Angeles.

* The authors thank Warren Sharp and Ian St. Maurice for their help in writing this case study.

TMS began operations in 1980 as a consulting firm in the areas of industrial engineering and operations management. In the late 1990s, the company started its design and integration business. Recently it began promoting just-in-time systems and group technology-based manufacturing facilities. The organization structure of TMS is depicted in Figure 1.12; financial data are presented in Tables 1.3 and 1.4.

TMS employs approximately 500 people, 300 of whom are in the Nashville area, 100 in New York, and 100 in Los Angeles. Approximately 50% of these are industrial, mechanical, and electrical engineers, and approximately 10% also have MBA degrees, mostly with operations management concentrations. The other employees are technicians, support personnel, and managers. Some information on labor costs follows.

Engineers	\$50,000/year
Technicians	\$25/hour
Administrators	\$35,000/year
Other	\$10/hour

These rates do not include fringe benefits or overhead. Moreover, bear in mind that individual salaries are a function of experience, position, and seniority within the company.

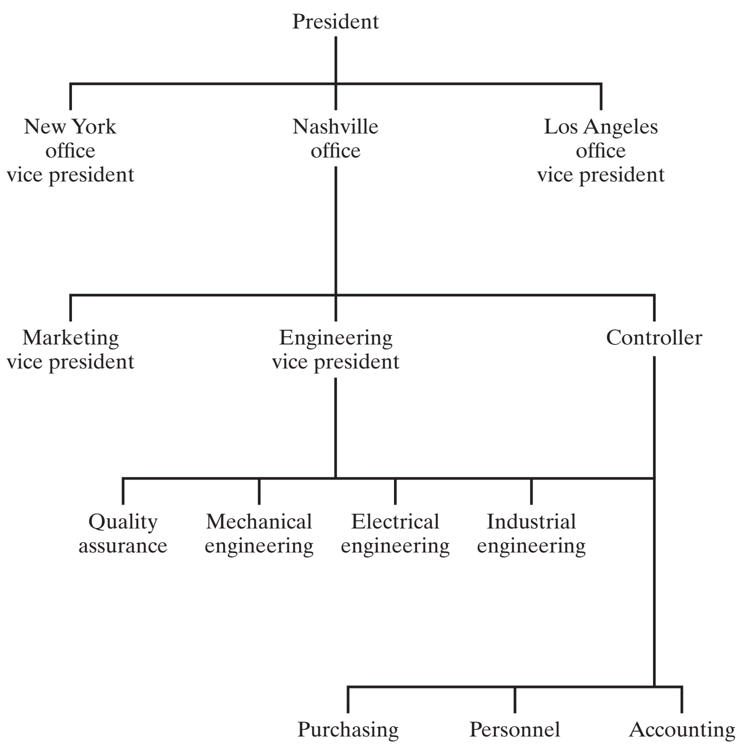

Figure 1.12 Simplified organization chart.

TABLE 1.3 TMS Financial Data: Income Statement

Income Statement ($1,000) Year ending December 31, 2004	
Net sales	$47,350
Cost of goods sold	
Direct labor	26,600
Overhead	6,000
	32,600
Gross profit	14,750
General and administrative	5,350
Marketing	4,900
	10,250
Profit before taxes	4,500
Income tax (32%)	1,440
Net profit	$3,060

TABLE 1.4 TMS Financial Data: Balance Sheet

Balance Sheet ($1,000) Year ending December 31, 2004	
Assets	
Current assets	
Cash	$1,100
Accounts receivables	1,500
Inventory	12
Other	3
Total current assets	2,615
Net fixed assets	325
Total assets	2,940
Liabilities	
Current Liabilities	
Notes payable	35
Accounts payable	137
Accruals	90
Total current liabilities	262
Long-term debt	50
Capital stock and surplus	1,300
Earned surplus	1,328
Net worth	2,628
Total liabilities	$2,940

In the past 10 years, TMS averaged 20 major projects annually. Each project consisted of the design of a new manufacturing facility, the selection, installation, and integration of equipment, and the supervision of startup activities. In addition, TMS experts are consultants to more than 100 clients, many of whom own TMS-designed facilities.

The broad technical basis of TMS in the areas of mechanical, electrical, and industrial engineering and its wide-ranging experience are its most important assets.

Management believes that the company is an industry leader in automatic assembly, material handling, industrial robots, command and control, and computer-integrated manufacturing. TMS is using subcontractors mainly in software development and, when necessary, for fabrication, because it does not have any shops or manufacturing facilities.

Recently, management has decided to expand its line of operations and services into the area of recycling and waste management. New regulations in many states are forcing the designers of manufacturing plants to analyze and solve problems related to waste generation and disposal.

Your team has been selected by TMS-Nashville to work on this new line of business. Your first assignment is to analyze the needs and opportunities in your geographical area. On the bases of a literature search and conversations with local manufacturers, environmentalists, and politicians, making whatever assumptions you believe are necessary, write a report and prepare a presentation that answers the following questions:

1. How well does this new line of business fit into TMS operations? What are the existing or potential opportunities?
2. How should a waste management project be integrated into TMS's current organizational structure?
3. What are the problems that TMS might encounter should it embark on this project? How might these problems affect the project? How might they affect TMS's other business activities?
4. If a project is approved in waste management, then what would its major life-cycle phases be?

Any assumptions regarding TMS's financial position and borrowing power, personnel, previous experience, and technological capabilities relating, for example, to computer-aided design, should be stated explicitly.

DISCUSSION QUESTIONS

1. Explain the difference between a project and a batch-oriented production system.
2. Describe three projects, one whose emphasis is on technology, one with emphasis on cost, and one with emphasis on scheduling.
3. Identify a project that is "risk free." Explain why this project is not subject to risk (low probability of undesired results, low cost of undesired results, or both).
4. In the text, it is stated that a project manager needs a blend of technical, administrative, and interpersonal skills. What attributes do you believe are desirable in an engineering specialist working on a project in a matrix organization?
5. Write a job description for a project manager.
6. Identify a project with which you are familiar, and describe its life-cycle phases and between 5 and 10 of the most important activities in each phase of its life cycle.

7. Find a recent news article on an ongoing project, evaluate the management's performance, and explain how the project could be better organized and managed.

8. Analyze the factors that affect the success of projects as a function of the project's life cycle. Explain in which phase of the life cycle each factor is most important, and why.

9. In a matrix management structure, the person responsible for a specific activity on a specific project has two bosses. What considerations in a well-run matrix organization reduce the resulting potential for conflict?

10. Outline a strategy for effective communication between project personnel and the customer (client).

11. Select a project and discuss what you think are the interfaces between the engineers and managers assigned to the project.

12. The project plan is the basis for monitoring, controlling, and evaluating the project's success once it has started. List the principal components or contents of a project plan.

EXERCISES

1.1 What type of production system would be associated with the following processes?

a. A production line for window assemblies
b. A special order of 150 window assemblies
c. Supplying 1,000 window assemblies per month throughout the year

1.2 You decided to start a self-service restaurant. Identify the stages of this project and the type of production system involved in each stage, from startup until the restaurant is running well enough to sell.

1.3 Select two products and two services and describe the needs that generated them. Give examples of other products and services that could satisfy those needs equally well.

1.4 You have placed an emergency order for materials from a company that is located 2,000 miles away. You were told that it will be shipped by truck and will arrive within 48 hours, the time at which the materials are needed. Discuss the issues surrounding the probability that the shipment will reach you within the 48 hours. How would things change if shipment were by rail?

1.5 Your plumber recommends that you replace your cast iron pipes with copper pipes. He claims that although the price for the job is $7,000, he has to add $2,000 for unforeseen expenses. Discuss his proposal.

1.6 In statistical analysis, the coefficient of variation is considered to be a measure of uncertainty. It is defined as the ratio of the standard deviation to the mean. Select an activity, say driving from your home to school, generate a frequency distribution for that activity, and calculate its mean and the standard deviation. Analyze the uncertainty.

1.7 Specify the type of uncertainties involved in completing each of the following activities successfully.

a. Writing a term paper on a subject that does not fall within your field of study
b. Undertaking an anthropological expedition in an unknown area
c. Driving to the airport to pick up a friend
d. Buying an item at an auction

1.8 Your professor told you that the different departments in the school of business are organized in a matrix structure. Functional areas include organizational behavior, mathematics (operations research and statistics), and computer science. Develop an organization chart that depicts these functions along with the management, marketing, accounting, and finance departments. What is the product of a business school? Who is the customer?

1.9 Provide an organizational structure for a school of business administration that reflects either a functional orientation or a product orientation.

1.10 Assume that a recreational park is to be built in your community and that the city council has given you the responsibility of selecting a project manager to lead the effort. Write a job description for the position. Generate a list of relevant criteria that can be used in the selection process, and evaluate three fictitious candidates (think about three of your friends).

1.11 Write an RFP soliciting proposals for preparing your master's thesis. The RFP should take into account the need for tables, figures, and multiple revisions. Make sure that it adequately describes the nature of the work and what you expect so that there will be no surprises once a contract is signed.

1.12 Explain how you would select the best proposal submitted in Exercise 1.11. That is, what measures would you use, and how would you evaluate and aggregate them with respect to each proposal?

1.13 The following list of activities is relevant to almost any project. Identify the phase in which each is typically performed, and order them in the correct sequence.

a. Developing the network
b. Selecting participating organizations
c. Developing a calendar
d. Developing corrective plans
e. Executing activities
f. Developing a budget
g. Designing a project
h. Recommending improvement steps
i. Monitoring actual performance
j. Managing the configuration
k. Allocating resources to activities
l. Developing the WBS
m. Estimating the LCC
n. Getting the customer's approval for the design
o. Establishing milestones
p. Estimating the activity duration

1.14 Drawing from your personal experience, give two examples for each of the following situations.

a. The original idea was attractive but not sufficiently important to invest in.
b. The idea was compelling but was not technically feasible.
c. The idea got past the selection process but was too expensive to implement.
d. The idea was successfully transformed into a completed project.

1.15 List two projects with which either you or your organization is involved that are currently in each of the various life-cycle phases.

1.16 Select three national, state, or local projects (e.g., construction of a new airport) that were completed successfully and identify the factors that affect their success. Discuss the attending risks, uncertainty, schedule, cost, technology, and resources usage.

1.17 Identify three projects that have failed, and discuss the reasons for their failure.

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Appendix 1A

Engineering Versus Management

1A.1 Nature of Management

Practically everyone has some conception of the meaning of the word *management* and to some extent understands that it requires talents that are distinct from those needed to perform the work being managed. Thus, a person may be a first-class engineer but unable to manage a high-tech company successfully. Similarly, a superior journeyman may make an inferior foreman. We all have read about cases in which an enterprise failed not because the owner did not know the field, but because he was a poor manager. To cite just one example, Thomas Edison was perhaps the foremost inventor of the last century, but he lost control of the many businesses that grew from his inventions because of his inability to plan and to direct and supervise others.

So what exactly is management, and what does a good manager have to know? Although there is no simple answer to this question, there is general agreement that, to a large extent, management is an art grounded in application, judgment, and common sense. To be more precise, it is the art of getting things done through other people. To work effectively through others, a manager must be able to perform competently the seven functions listed in Table 1A.1. Of those, planning, organizing, staffing, directing, and controlling are fundamental. If any of these five functions is lacking, then the management process will not be effective. Note that these are necessary but not sufficient functions for success. Getting things done through people requires the manager also to be effective at motivating and leading others.

The relative importance of the seven functions listed in Table 1A.1 may vary with the level of management. Top management success requires an emphasis on planning, organizing, and controlling. Middle-level management activities are more often concerned with staffing, directing, and leading. Lower-level managers must excel at motivating and leading others.

1A.2 Differences between Engineering and Management

Many people start out as engineers and, over time, work their way up the management ladder. As Table 1A.2 shows, the skills required by a manager are very different from those normally associated with engineering (Badawy and Trystram 1995, Eisner 2002).

TABLE 1A.1 Functions of Management

Functions	Description
Planning	The manager first must decide what must be done. This means setting short- and long-term goals for the organization and determining how they will be met. Planning is a process of anticipating problems, analyzing them, estimating their likely impacts, and determining actions that will lead to the desired outcomes, objectives, or goals.
Organizing	Establishing interrelationships between people and things in such a way that human and material resources are effectively focused toward achieving the goals of the enterprise. Organizing involves grouping activities and people, defining jobs, delegating the appropriate authority to each job, specifying the reporting structure and interrelationships between these jobs, and providing the policies or other means for coordinating these jobs with each other.
Staffing	In organizing, the manager establishes positions and decides which duties and responsibilities properly belong to each. Staffing involves appraising and selecting candidates, setting the compensation and reward structure for each job, training personnel, conducting performance appraisals, and performing salary administration. Turnover in the workforce and changes in the organization make it an ongoing function.
Directing	Because no one can predict with certainty the problems or opportunities that will arise, duties must naturally be expressed in general terms. Managers must guide and direct subordinates and resources toward the goals of the enterprise. This involves explaining, providing instructions, pointing out proper directions for the future, clarifying assignments, orienting personnel in the most effective directions, and channeling resources.
Motivating	A principal function of lower management is to instill in the workforce a commitment and enthusiasm for pursuing the goals of the organization. Motivating refers to the interpersonal skills to encourage outstanding human performance in others and to instill in them an inner drive and a zeal to pursue the goals and objectives of the various tasks that may be assigned to them.
Leading	This means encouraging others to follow the example set for them, with great commitment and conviction. Leading involves setting examples for others, establishing a sense of group pride and spirit, and instilling allegiance.
Controlling	Actual performance will normally differ from the original plan, so checking for deviations and taking corrective actions is a continuing responsibility of management. Controlling involves monitoring achievements and progress against the plans, measuring the degree of compliance with the plans, deciding when a deviation is significant, and taking actions to realign operations with the plans.

TABLE 1A.2 Engineering Versus Management

What engineers do	What managers do
Minimize risks, emphasize accuracy and mathematical precision	Take calculated risks, rely heavily on intuition, take educated guesses, and try to be "about right"
Exercise care in applying sound scientific methods, on the basis of reproducible data	Exercise leadership in making decisions under widely varying conditions, based on sketchy information
Solve technical problems on the basis of their own individual skills	Solve techno-people problems on the basis of skills in integrating the talents and behaviors of others
Work largely through their own abilities to get things done	Work through others to get things done

Engineering involves hands-on contact with the work. Managers are always one or more steps removed from the shop floor and can influence output and performance only through others. An engineer can derive personal satisfaction and gratification in his or her own physical creations, and from the work itself. Managers must learn to be fulfilled through the achievements of those whom they supervise. Engineering is a science. It is characterized by precision, reproducibility, proven theories, and experimentally verifiable results. Management is an art. It is characterized by intuition, studied judgments, unique events, and one-time occurrences. Engineering is a world of things; management is a world of people. People have feelings, sentiments, and motives that may cause them to behave in unpredictable or unanticipated ways. Engineering is based on physical laws, so that most events occur in an orderly, predictable manner.

1A.3 Transition from Engineer to Manager

Engineers are often propelled into management out of economic considerations or a desire to take on more responsibility. Some organizations have a dual career ladder that permits good technical people to remain in the laboratory and receive the same financial rewards that attend supervisory promotions. This type of program has been most successful in research-intensive environments such as those found at the IBM Research Center in Yorktown Heights and the Department of Energy research laboratories around the United States.

Nevertheless, when an engineer enters management, new perspectives must be acquired and new motivations must be found. He or she must learn to enjoy leadership challenges, detailed planning, helping others, taking risks, making decisions, working through others, and using the organization. In contrast to the engineer, the manager achieves satisfaction from directing the work of others (not things), exercising authority (not technical knowledge), and conceptualizing new ways to do things (not doing them). Nevertheless, experience indicates that the following three critical skills are the ones that engineers find most troublesome to acquire: (1) learning to trust others, (2) learning how to work through others, and (3) learning how to take satisfaction in the work of others.

The step from engineering to management is a big one. To become successful managers, engineers usually must develop new talents, acquire new values, and broaden their point of view. This takes time, on-the-job and off-the-job training, and careful planning. In short, engineers can become good managers only through effective career planning.

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Chapter 2

Process Approach to Project Management

2.1 INTRODUCTION

A project is an organized set of activities aimed at accomplishing a specific, nonroutine, or low-volume task such as designing an e-commerce website or building a hypersonic transport. Projects are aimed at meeting the objectives and expectations of their stakeholders. Because of the need for specialization, as well as the number of hours usually required, most projects are undertaken by multidisciplinary teams. In some cases, the team members belong to the same organization, but often, at least a portion of the work is assigned to subcontractors, consultants, or partner firms. Leading the effort is the project manager, who is responsible for the successful completion of all activities.

Coordination between the individuals and organizations involved in a project is a complex task and a major component of the project manager's job. To ensure success, integration of deliverables produced at different geographical locations, at different times, by different people, in different organizations is required.

Projects are typically performed under time pressure, limited budgets, tight cash flows, and uncertainty using shared resources. The triple constraint of time, cost, and scope (i.e., project deliverables that are required by the end-customers or end-users) requires the project manager to repeatedly make tradeoffs between these factors with the implicit goal of balancing risks and benefits. Moreover, disagreements among stakeholders on the best course of action to follow can lead to conflicting direction and poor resource allocation decisions. Thus, a methodology is required to support the management of projects. Early efforts in developing such a methodology focused on specific tools for different aspects of the problem. Tools for project scheduling, such as the Gantt chart and the critical path method, were developed along with tools for resource allocation, project budgeting, and project control. Each is covered in considerable detail in the chapters that follow.

Nevertheless, although it is important to gain an appreciation of these tools, each is limited in the view that it provides the project manager. For example, tools for scheduling rarely address problems related to configuration management, and tools for budgeting typically do not address problems associated with quality. The integration of these tools in a way that supports decision making at each stage in a project's life cycle is essential for understanding the dynamics of the project environment. This chapter identifies the relevant management processes and outlines a framework for applying them to both single and multiple projects.

A project management process is a collection of tools and techniques that are used on a predefined set of inputs to produce a predefined set of outputs. The processes are interconnected and interdependent. The full collection forms a methodology that supports all of the aspects of project management throughout a project's life cycle—from the initiation of a new project to its (successful) completion and termination.

The framework that we propose to organize and study the relevant processes is based on the ten knowledge areas identified by the Project Management Institute (PMI) and published as the Project Management Body of Knowledge (PMBOK). PMI also conducts a certification program based on the PMBOK. A Project Management Professional certificate can be earned by passing an exam and accumulating relevant experience in the project management discipline.

The benefit gained from implementing the full set of project management processes has been evident in many organizations. Although each project is a one-time effort, process-oriented management promotes learning and teamwork through the use of a common set of tools and techniques. A detailed description of their use is provided in the remainder of the book. Each chapter deals with a specific knowledge area and highlights the tools and techniques in the form of mathematical models, templates, charts, and checklists used in the processes developed for that area.

2.1.1 Life-Cycle Models

Because a project is a transitory effort designed to achieve a specific set of goals, it is convenient to identify the phases that accompany the transformation of an idea or a concept into a product or system. The collection of such phases is defined as the *project life cycle*.

A life-cycle model is a set of stages or phases through which a family of projects goes, in which each phase may be performed sequentially or concurrently. The project life cycle defines the steps required to achieve the project goals as well as the contents of each step. The end of each phase often serves as a checkpoint or milestone for assessing progress, as the actual status of the project is compared with the original plan in an effort to identify deviations in cost, schedule, and performance so that any necessary corrective action can be taken.

For software projects, the spiral life-cycle model proposed by Boehm (1988) and further refined by Muench (1994) has gained widespread popularity. The model, shown in Figure 2.1, is very useful for repetitive development in which a project goes through

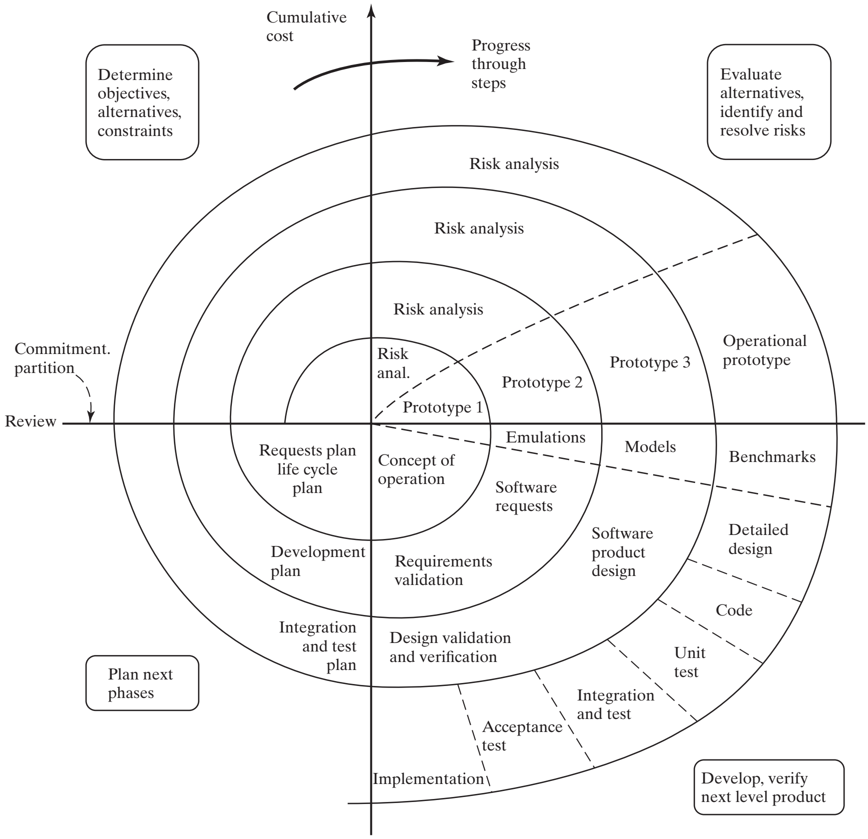

Figure 2.1 Spiral life-cycle model.

the same phases several times, each time becoming more complete; that is, closer to the final product. It has two main distinguishing features. The first is a cyclic approach for incrementally expanding a system's definition and degree of implementation while decreasing its level of risk. The other is a set of anchor point milestones for ensuring stakeholder commitment to feasible and mutually satisfactory solutions. The general idea is to ensure that the riskier aspects of the project are completed first to avoid failures in an advanced phase.

Construction projects also have their own set of life-cycle models, such as the one proposed by Morris (1988). In this model, a project is divided into four stages to be performed in sequence.

Stage I (Feasibility) This stage terminates with a go/no go decision for the project. It includes a statement of goals and objectives, conceptual design, high-level feasibility studies, the formulation of strategy, and the approval of both the design and the strategy by upper management.

Stage II (Planning and Design) This stage terminates with the awarding of major contracts. It includes detailed design, cost and schedule planning, contract definitions, and the development of the road map for execution.

Stage III (Production) This stage terminates with the completion of the facility. It includes construction, installation of utilities, equipment acquisition and setup, landscaping, roadwork, interior appointments, and operational testing.

Stage IV (Turnover and Startup) This stage terminates with full operation of the facility. It includes final testing and the development of a maintenance plan.

Clearly this model does not fit research and development (R&D) projects or software projects because of the sequential nature in which the work is performed. In R&D projects, for example, it is often necessary to undertake several activities in parallel with the hope that at least one will turn out to meet technological and cost objectives.

Other life-cycle models include:

- *Waterfall model*. Each phase is completed before the initiation of the following phase. This model is most relevant for information technology projects.
- *Incremental release model*. In the early phases, an imperfect version of the project is developed with the goal of maximizing market share. Toward the later phases, a final version of the product emerges. This is a special case of the spiral model.
- *Prototype model*. In the early phases, the rudimentary functions associated with the user interface are developed before the product itself is finalized. This model is most appropriate for information technology projects.

By integrating the ideas of project processes and the project life cycle, a methodology for project management emerges. The methodology is a collection of processes whereby each process is associated with a phase of the project life cycle. The project manager is responsible for identifying individuals who have the necessary skills and experience and for assigning them to the appropriate processes. A project's likelihood of success increases when the definition of inputs and outputs of each process is clear and when team members are clear about the lines of authority, individual responsibilities, and overall project objectives. Clear communication of the overall project's objectives as well as clear delineation of major work streams is necessary to ensure a well-coordinated flow of information and good communications between project participants.

Life-cycle models are indispensable project management tools. They provide a simple, yet effective, means of monitoring and controlling a project at each stage of its development. As each phase comes to an end, all results are documented and all deliverables are certified with respect to quality and performance standards.

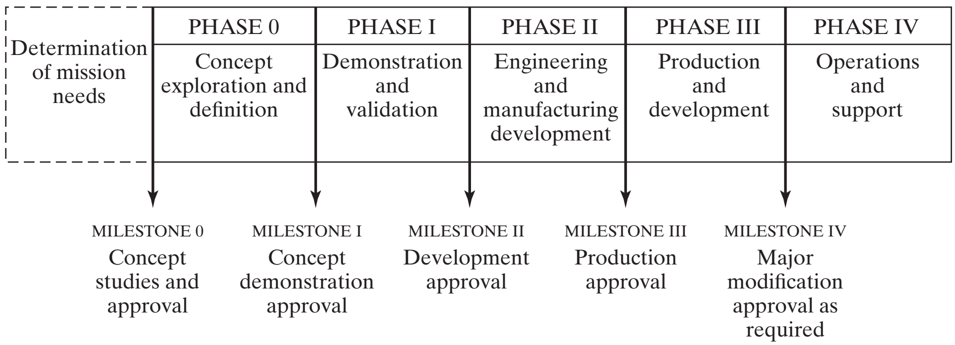

Figure 2.2 DOD life-cycle model.

2.1.2 Example of a Project Life Cycle

The DOD uses a simple life-cycle model for systems acquisition (US DOD 5000.2 1993). Its components are shown in Figure 2.2. The project starts only after the determination of mission needs and approval is given. At the end of stage IV the system is taken out of service. This is the end of the life cycle.

2.1.3 Application of the Waterfall Model for Software Development

A waterfall model captures the relevant phases of software development effort through a series of stages. There are specific objectives to be accomplished in each stage, and each activity must be deemed successful for work to proceed to the subsequent phase. The process is usually considered non-iterative. Each phase requires the delivery of particular documentation (contract data requirements list). In addition, many of the phases require successful completion of a government review process. Critics of the waterfall model, in fact, find that the model is geared to recognize documents as a measure of progress rather than actual results.

The nine major activities are as follows:

1. Systems concept/system requirements analysis
2. Software requirements analysis
3. Software parametric cost estimating
4. Preliminary design
5. Detailed design
6. Coding and computer software unit testing
7. Computer software component integration and testing
8. Computer software configuration item testing
9. System integration and operational testing

A schematic of the process, representing concurrent hardware and software development, is given in Figure 2.3.

An alternative approach to software development involves the use of incremental builds. With this approach, software development begins with the design of certain core functions to meet critical requirements. Each successive software build (iteration on product development) provides additional functions or enhances performance. Once system requirements are defined and preliminary system design is complete, each build

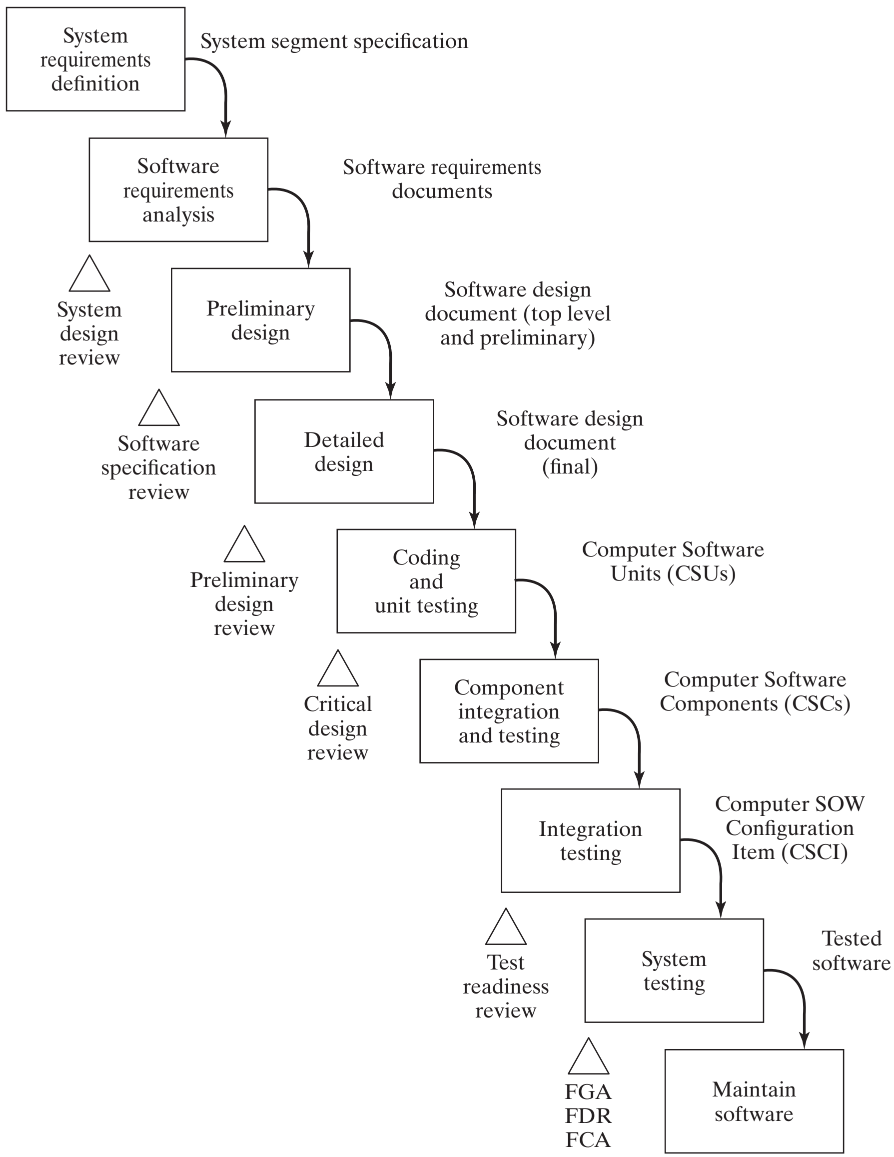

Figure 2.3 Waterfall model.

may follow the waterfall pattern for subsequent development phases. Each successive build will usually have to be integrated with previous builds.

2.2 PROJECT MANAGEMENT PROCESSES

A process is a group of activities designed to transform a set of inputs into the desired outputs. The transformation consists of the following three elements:

1. Data and information
2. Decision making
3. Implementation and action

A well-defined set of processes, supported by an appropriate information system (composed of a database and a model base) and implemented by a team trained in performing the processes, is a cornerstone in modern project management.

The following discussion is based on the work of Shtub (2001).

2.2.1 Process Design

The design of a process must address the following issues.

1. Data required to support decisions, including:
   - data sources
   - how the data should be collected
   - how the data should be stored
   - how the data should be retrieved
   - how the data should be presented as information to decision makers
2. Models required to support decisions. A model is a simplified representation of reality that is used in part to transform data into useful information. When a problem is too complicated to solve or some information is missing, simplifying assumptions are made and a model is developed. There are many types of models including mathematical, physical, and statistical. The model—the simplified presentation of reality—is analyzed and a solution is obtained. Sensitivity analysis is then used to evaluate the applicability of the solution found to the real problem and its sensitivity to the simplifying assumptions. Consider, for example, a simple way of estimating the time required to travel a given distance. Assuming a constant speed and movement in a straight line, one possibility would be: time = distance/speed. This simple algebraic model is frequently used, although most vehicles do not travel at a constant speed or in a straight line. In a similar way, a variety of models are used in project management, including:
   - models that support routine decisions
   - models that support ad-hoc decisions
   - models used for project control

Their value depends on how useful their estimates are in practice.

3. Data and models integration:
   - How data from the database are analyzed by the models
   - How information generated by the models is transferred and presented to decision makers

2.2.2 PMBOK and Processes in the Project Life Cycle

A well-defined set of processes that apply to a large number of projects is discussed in the PMBOK published by the PMI. Although some of the PMBOK processes may not apply to all projects, and others may need to be modified before they can be applied, the PMBOK is a widely accepted, widely known source of information. The processes are classified in two ways.

1. By project phase:
   - initiating processes
   - planning processes
   - executing processes
   - monitoring and controlling processes
   - closing processes
2. By knowledge areas or management functions:
   Knowledge areas are:
   - Project Integration Management
   - Project Scope Management
   - Project Time Management
   - Project Cost Management
   - Project Quality Management
   - Project Human Resource Management
   - Project Communications Management
   - Project Risk Management
   - Project Procurement Management
   - Project Stakeholder Management

2.3 PROJECT INTEGRATION MANAGEMENT

2.3.1 Accompanying Processes

Project integration management involves six processes:

1. Project charter development—This process involves some sort of cost-benefit analysis that leads to a go/no go decision regarding a proposed project. A project charter is created at the conclusion of this phase, and a project manager is

selected. The charter defines the business or societal need that the project addresses, the project timeline, and the budget. Considerations like the fit of the proposed project to the organization strategy, stakeholders' needs and expectations, competition, technological and economic feasibility are important in this process.

2. Project plan development—gathering results of various planning processes and integrating it all into an acceptable plan.
3. Management and directing project execution—implementation of the project plan during the project execution.
4. Monitoring and controlling the project work during execution—an effort to identify deviations from the project plan in order to take corrective actions when needed.
5. Integrated change control—coordination of changes in scope, schedule, budget, and other parts of the plans for the entire project.
6. Project closing—the last process in the project life cycle ensuring that the project work was done, deliverables are accepted, and all contracts with different stakeholders are terminated.

The purpose of these processes is to ensure coordination across the various work streams of the project.

Integration management is concerned with the identification, monitoring, and control of all interfaces between the various components of a project, including:

1. Human interface—the personnel associated with the various aspects of the project such as the project team members, subcontractors, consultants, stakeholders, and customers.
2. Scope interface—if the scope is not defined properly, then some required work may not be performed or work that is not required may be done.
3. Time interface—adequate resources must be provided to avoid delays and late deliverables.
4. Communication interface—Timely transfer of the right information to the right stakeholders at the right time is critical to project success.
5. Technological interface—since in most projects the work content is divided among project participants, the interfaces between the deliverables supplied by the participants must be managed throughout the project to ensure smooth integration of the parts into the final deliverables as specified.

Proper integration management requires proper communication between members of the project's stakeholders; indeed, one of the knowledge areas is communication management. The life-cycle model plays an important role. The project plan is developed in the early phases of the project, whereas execution of the plan and change control occurs during the later phases.

2.3.2 Description

Project charter development. Many alternative project proposals may exist. On the basis of an appropriate set of evaluation criteria and a selection methodology, the best alternative is chosen, a project charter is issued, and a project manager is selected.

Projects are initiated in response to a need typically arising at a level in the organization that is responsible for setting strategic goals. Research has shown that the most important criterion guiding organizations in choosing projects is financial. Projects are selected for implementation when they support clear business goals and have an attractive rate of return or net present value. A second factor that is likely to trigger a new project is an advance in technology. In the electronics industry, for example, the steady reduction in cost and increase in performance of integrated circuits and memory chips has forced firms to offer new products on a semiannual basis, just to remain competitive.

In summary, projects are initiated when:

1. a defined need arises
2. there is strategic support and a willingness to undertake the project
3. the technology is compelling
4. there are available resources

Potential projects can be classified in several ways:

1. External versus internal projects; that is, projects performed for customers outside the organization versus customers within the organization
2. Projects that are initiated to:
   a. address a business opportunity
   b. solve a problem
   c. follow a directed order
3. Due date and completion time
4. Organizational priority

The project plan. The project plan and its execution are the major outputs of this process. The plan is based on inputs from other processes such as scope planning, schedule development, resource planning, and cost estimating, along with historical information and organizational policies. It is updated continuously on the basis of corrective actions triggered by approved change requests and analysis of performance measures. As a tool for coordination, the documents that define the plan must address:

1. The time dimension—when is each stage performed
2. The scope dimension—what should be achieved
3. The human dimension—who does what
4. The risk dimension—how to deal with uncertainty

5. The resource dimension—the plan must ensure availability of resources
6. The information and communication dimension—the way data is collected, analyzed, stored, and communicated to stakeholders must be addressed as part of the project plan

The primary purpose of the plan is to guide the execution of the project. It assists the project manager in leading the project team and in achieving the project's goals. Critical characteristics are fluidity and flexibility, allowing changes to be incorporated easily as they occur. The corresponding document typically consists of the following parts:

1. Preface, including a general review, goals, outputs, scope of work to be done, and technical specifications
2. Project organization description—interfaces, organizational structure, responsibilities
3. Management processes—for example, procurement, reporting, and monitoring
4. Technical processes—for example, design and verification
5. Execution—the way work will be done, scheduling (i.e., timeline) and budget information, resource allocation, and information flow

A project plan should reflect the needs and expectations of stakeholders. Therefore, a project manager should perform an analysis, prior to formally proposing a project idea, to determine stakeholders' principal concerns and perspectives and understand the organization's underlying unmet needs.

This information can be used to develop guidelines for managing the relationship between project personnel and the stakeholders. The level of influence and the needs and expectations of any particular stakeholder may have a significant impact on the success or failure of the project. Moving in a direction that is at crossroads with an influential stakeholder can spell doom.

Execution of the plan. Execution of the project plan produces the deliverables. For integration management to be successful, a project manager must be skilled in the three areas listed below. Some of these skills are innate, whereas others can be learned.

1. The technology that is used by the project is referred to as the product scope. Often the project manager can delegate responsibilities for technological issues to a team member with detailed expertise. Most of the effort of the project manager, then, is related to integration—seeing that the pieces come together properly.
2. The organizational factor—the project manager must understand the nature of the organization, the human interrelations, the common types of interactions, and so on. Organizational understanding can be expressed as follows.
   a. Human resources (HR) framework—the focus is on creating harmony among the organizational needs, needs of the project participants, and the project requirements.

b. Cultural framework—the focus is on understanding the organizational culture; that is, the values of the organization.

c. Symbolic framework—the focus is on positions and responsibilities, coordination, and monitoring. The organizational breakdown structure (OBS) and the work breakdown structure (WBS) aid in defining this framework.
The project manager's authority is invested through the WBS but also through the political, HR, and cultural frameworks.

d. Political framework—begins with the assumption that the project organization is a coalition of different stakeholders. Key points to bear in mind are internal struggle and governing power. Because of the transitory nature of a project, the project manager must use the stakeholders' power to advance project goals. Stakeholders can, typically, be divided into two groups.

i. Stakeholders with an interest in the failure of the project
ii. Stakeholders with an interest in the success of the project

The project manager must identify all of the stakeholders and their political influence, their objectives, and their ability to affect the project. Once again, a project manager should spend some time to determine the significant needs and requirements of the chief stakeholders.

3. The business factor—the project manager must understand all aspects of the business associated with the project.

In terms of personal characteristics, the most successful project managers are:

1. Efficient
2. Decisive
3. Supportive of team members' decisions
4. Confident
5. Articulate communicators
6. Highly motivated
7. Technologically oriented
8. Able to deal with high levels of uncertainty

Project execution involves the management and administration of the work described in the project plan. Usually most of the budget, time, and resources are spent during the execution phase. When the focus of the project is on new product development, success is often determined by the depth and details of the plan. As the saying goes, "measure twice, cut once." Vital tools and techniques for project implementation are as follows:

1. Authorization management system—enables the project manager to verify that an authorized team member is performing a specific task at the correct point in time.

2. Status review meetings—prescribed meetings for information exchange regarding the project.
3. Project management software—decision support software (including a database and a model base) to help the project manager plan, implement, and control all aspects of the project, including budgets, personnel, schedule, and other resources.
4. Monitoring system—software, spreadsheets, or other mechanisms for comparing budget outlays, work performed, and resources consumed over time with the original plan.

Integrated change control. Once a project launches, changes to the original project plan are inevitable. A procedure must be put in place to identify, quantify, and manage the changes throughout the project life cycle. The main targets of change control are:

1. Evaluation of the change requests to determine whether the benefits of the change will be sufficient to justify the corresponding disruption and expense;
2. Determining that a change has occurred;
3. Managing the actual changes when and as they occur.

The original project scope must be maintained by continuously managing changes to the baseline. This is accomplished either by rejecting new change proposals or by approving changes and incorporating them into a revised project baseline.

As described in greater detail in Chapter 8, change control makes use of the following modules in the configuration management system.

1. *Configuration identification*. Conceptually, each configuration item should be coded in a way that facilitates reference to its accompanying documents. Any changes approved in the configuration item should trigger a corresponding change in the documents, thus ensuring the correct description of the element.
2. *Change management*. A change is initiated via an engineering change request (ECR). The ECR contains the basis of the change along with a statement of the effect that it will have on activity times, schedules, and resource usage, as well as any new risks that may result.

To guarantee that each type of change is handled by the proper authority, a change classification system should be put in place. The most important changes are handled by the change control board (CCB) that represents all of the stakeholders. After a review, a change request can be accepted or rejected by the board. Once a request is accepted, an engineering change order (ECO) is issued. The ECO contains all relevant information, such as the nature of the change, the party responsible for its execution, and the time when the change is to take place.

2.4 PROJECT SCOPE MANAGEMENT

2.4.1 Accompanying Processes

Project scope management consists of the following six processes:

1. *Plan scope management.* The scope management plan is part of the project plan. This process focuses on the preparation of the scope management plan and the requirement management plan, as both are part of the project plan.
2. *Requirements Gathering*. The driving force of any project is the needs and expectations of the stakeholders that are translated into requirements.
3. *Define Scope*. The project scope is the work content of the project. This work content and the way it should be performed are described in a document that defines a project's scope.
4. *Create WBS*. The work content is broken into work packages. Each work package is assigned to a work package manager who can provide information on the time and effort required to perform the work for planning purposes and is also responsible for the execution of the work.
5. *Validate Scope*. To ensure that the project work was performed as required and the deliverables satisfy the requirements, inspection and testing are conducted as part of the validation process.
6. *Control Scope*. The actual work performed and the project deliverables are monitored throughout the project life cycle to ensure stakeholders' satisfaction. When needed, corrective actions are taken to update the project plan or the requirements.

The purpose of these processes is to ensure that the project includes all work (and only that work) required for its successful completion. Scope management relates to:

- the product scope—defined as the features and functions to be included in the product or service that translate into specific project scope
- the project scope—encompasses the project management processes defined as the work that must be done in order to deliver the product scope

Management of a project's scope is similar for many projects, although the product scope is context-specific.

2.4.2 Description

Scope management encompasses the effort required to perform the work associated with a project, as well as the processes required to produce the intended products or services.

The scope management processes address the statement of work (SOW), and work breakdown structure (WBS), respectively. An outline of what is included in each follows.

SOW. The SOW gives information on:

1. Scope of work—what work should be completed and how;
2. Where will the work take place (at what physical location);
3. Duration of execution—initial schedule along with milestones for every product;
4. Applicable standards;
5. Product allocation;
6. Acceptance criteria;
7. Additional requirements—transportation needs, special documentation, insurance requirements, safety and security.

WBS. The WBS decomposes the project into subprojects. Each subproject should be described with full detail of owner, schedule, activities, how each is to be performed and when, and so on. It is advisable to have a WBS template, especially for organizations with many similar projects. The template specifies how to divide the project into the work packages.

A disconcerting issue related to scope management is "scope creep," in which new features and performance requirements are added to the project without a proper change management process. By adhering to the management processes described in this chapter, scope creep can be minimized.

2.5 PROJECT TIME MANAGEMENT

2.5.1 Accompanying Processes

Time management establishes the schedule for tasks and activities defined in the work packages. The following seven processes are included:

1. *Plan Schedule Management.* This process, which is part of the project plan, focuses on the preparation of a schedule management plan.
2. *Define Activities.* This process focuses on the preparation of a list of activities required to complete the project along with the attribute of each activity and, when applicable, specific dates or milestones of the project.
3. *Sequence Activities.* This process focuses on the precedence relationship among activities, including technological precedence relationships and managerial precedence relationships. In some cases, a lead or a lag is part of the precedence relationship.
4. *Estimate Activity Resources.* This process focuses on the resources required to perform the project activities, including human resources, material, machine, equipment, etc.
5. *Estimate Activity Durations.* This process deals with the estimate of the duration of the activities. In many projects, activity duration is a function of the resources assigned to perform the activity, and it is possible to reduce the duration of some activities by adding resources (a process known as activity crashing).

6. *Develop Schedule.* Various tools and techniques are used to integrate the information on activities, their duration, precedence relations, and resources into a schedule that specifies the dates resources will perform each activity. Network-based models are widely used to perform this process, including the Critical Path Method and the Critical Chain.
7. *Control Schedule.* The actual duration of activities as well as their start and finish dates are monitored throughout the project life cycle to ensure timely completion of the project and its milestones. When needed, corrective actions are taken to update the project plan or the schedule.

The purpose of time management is to ensure the timely completion of the project. The schedule defines what is to be done, when it is to be done, and by what resources. The schedule is used throughout the project to synchronize people, resources, and organizations involved and as a basis for control. When activities slip beyond their due dates, at least two major problems may arise:

1. Time and money are often interchangeable. As projects are pushed beyond their due date, time-related costs are incurred.
2. Most contracts specify rigid due dates, possibly with penalties for late deliveries. Alternatively, early deliveries may have incentives associated with them.

Scheduling issues can create conflicts in some organizations, especially during the implementation phase and specifically in organizations that have a matrix structure. By implementing proper processes for project management, conflicts can be minimized.

2.5.2 Description

Project work content is defined in the SOW and then translated into the WBS. Each work package in the WBS is decomposed into a set of activities that reflect its predefined scope. Estimating the duration of each activity is a major issue in time management. Activity durations are rarely known with certainty and are estimated by either point estimates or probability distributions. The work package manager is the best source of these estimates because he or she knows the technology. Sometimes an estimate can be derived from a database of similar activities. A problem is created when organizations do not maintain time-related records or do not associate parameters with an activity. The absence of parameterized data often precludes its use in deriving time estimates.

In developing the schedule, precedence relations among activities are defined, and a model, such as a Gantt chart or network, is constructed. Both technological and managerial precedence relations may be present. The former are drawn from the physical attributes of the product or system being developed. The latter emerge from procedures dictated by the organization; for example, issuing a purchase order usually requires that a low-ranking manager give his or her approval before the senior officer signs the final forms. Whereas managerial precedence relations can be sidestepped in some instances, say, if the project is late, technological precedence relations are invariant.

An initial schedule is the basis for estimating costs and resource requirements. After a blueprint is developed, constraints imposed by due dates, cash flows, resource availability, and resource requirements of other projects can be added. Further tuning of the schedule may be possible by changing the combination of resources (these combinations are known as modes) assigned to activities. In constructing a graph of cost versus duration, the modes correspond to the data points. Such graphs have two endpoints: (1) minimum cost (at maximum duration) and (2) maximum cost (at minimum duration). Implicit in this statement is the rule that the shorter the activity duration, the higher the cost.

As a first cut, the project manager normally uses the minimum cost–maximum duration point for each activity to determine the earliest finish time of the project. If the result is not satisfactory, then different modes for one or more activities may be examined. If the result still is not satisfactory, then more sophisticated methods can be applied to determine the optimal combination of costs and resources for each activity. Fast-tracking some activities is also possible by repositioning them in parallel or overlapping them to a certain degree. In any case, the schedule is implemented by performing the activities in accordance with their precedence relations. Uncertainty, though, calls for a control mechanism to detect deviations and to decide how to react to change requests. The schedule control system is based on performance measures such as actual completion of deliverables (milestones), actual starting times of activities, and actual finishing times of activities. Changes to the baseline schedule are required whenever a change in the project scope is implemented.

2.6 PROJECT COST MANAGEMENT

2.6.1 Accompanying Processes

Project cost management involves four processes:

1. *Plan Cost Management.* The cost management plan is part of the project plan. This process focuses on the preparation of a cost management plan.
2. *Estimate Costs.* This process requires information about activities, the project schedule, and resources assigned to perform project activities to estimate the cost of the project.
3. *Determine Budget.* Funding for the estimated costs is crucial. This process is based on aggregation of costs of individual activities and work packages into a cost baseline and matching the available funds to the estimated costs based on the policies of the organization and its ability to provide the needed funds.
4. *Control Costs.* The actual cost of activities as well as the project and product scope may change during the life cycle of the project and, therefore, they are monitored to ensure that the project budget is realistic and satisfies stakeholders' needs and expectations. When needed, corrective actions are taken to update the project plan or the budget.

These processes are designed to provide an estimate of the cost required to complete the project scope, to develop a budget based on availability of funds, management policies, and strategy, and to ensure that the project is completed within the approved budget and approved changes to the budget.

2.6.2 Description

To complete the project activities, different resources are required depending on whether the work is to be done internally or by outside contractors. Labor, equipment, and information, for example, are required for in-house activities, whereas money is required for outsourcing. The work packages derived from the SOW contain plans for using resources and suggest different operational modes for each activity.

There are various methods of estimating activity costs, from detailed accounting procedures to guesswork. Formal accounting procedures can be tedious and time consuming and perhaps a waste of time in case the project is discarded. Thus, early in the project life cycle, rough order-of-magnitude estimates are best, although they are not likely to be accurate.

Estimates of the amount of resources required for each activity, as well as the timing of their use, are based on the activity list and the schedule. Resource allocation is performed at the lowest level of the WBS—the work package level—and requirements are rolled up to the project level and then to the organizational level. A comparison of resource requirements and resource availability along with corporate strategies and priorities forms the basis of the allocation decisions at the organizational level. Resource planning results in a detailed plan specifying which resources are required for each work package. By applying the resource cost rates to the resource plan and adding overhead and outsourcing expenses, a cost estimate of the project is developed. This provides a basis for budgeting. As determined by the schedule, cost estimates are time-phased to allow for cash flow analysis. Additional allocations may also be made in the form of, say, a management reserve, to buffer against uncertainty. The resulting budget is the baseline for project cost control.

Because of uncertainty, cost control is required to detect deviations and to decide how to react to get the project back on track and within budget. Change requests require a similar response. The cost control system is based on performance measures, such as actual cost of activities or deliverables (milestones), and actual cash flows. Changes to the baseline budget are required whenever a change in the project scope is implemented.

2.7 PROJECT QUALITY MANAGEMENT

2.7.1 Accompanying Processes

Project quality management consists of three processes:

1. *Plan Quality Management.* The quality management plan is part of the project plan. This process focuses on the preparation of a quality management plan.
2. *Perform Quality assurance.* This process is focusing on analyzing the quality requirements and building the processes, tools, and techniques that guarantee that the project and its deliverables will satisfy these requirements.

3. *Control Quality.* This process is based on a comparison between quality requirements and results of tests and audits to verify that quality requirements are met and to recommend corrective actions in case the results of quality testing show substandard results.

The purpose of these processes is to ensure that the finished product satisfies the needs for which it was undertaken. Garvin (1987) suggested the following eight dimensions for measuring quality.

1. *Performance*. This dimension refers to the product or service's primary characteristics, such as the acceleration, cruising speed, and comfort of an automobile or the sound and the picture clarity of a TV set. Understanding of the stakeholder's performance requirements and the design of the product or service to meet those requirements are key factors in quality-based competition.
2. *Features*. This is a secondary aspect of performance that supplements the basic functions of the product or service. Features could be considered "bells and whistles." The flexibility afforded a customer to select desired options from a long list of possibilities contributes to the quality of the product or service.
3. *Reliability*. This performance measure reflects the probability of a product's malfunctioning or failing within a specified period of time. It affects both the cost of maintenance and downtime of the product.
4. *Conformance*. This is the degree to which the design and operating characteristics of the product or service meet established standards.
5. *Durability*. This is a measure of the economic and technical service duration of a product. It relates to the amount of use that one can get from a product before it has to be replaced due to technical or economical considerations.
6. *Serviceability*. This measure reflects the competence and courtesy of the agent performing the repair work, as well as the speed and ease with which it is done. The reliability of a product and its serviceability complement each other. A product that rarely fails and—on those occasions when it does—can be repaired quickly and inexpensively has a lower downtime and better serves its owner.
7. *Aesthetics*. This is a subjective performance measure related to how the product feels, tastes, looks, or smells and reflects individual preferences.
8. *Perceived quality*. This is another subjective measure related to the reputation of the product or service. Reputation may be based on past experience and partial information, but, in many cases, the customers' opinions are based on perceived quality as a result of the lack of accurate information on the other performance measures.

2.7.2 Description

Until the mid-1980s, quality was defined as meeting or exceeding a specific set of performance measures. Since then, the need to understand user requirements and application requirements has been on the rise. Quality starts with understanding stakeholders' requirements. Stakeholders require products that carry different grades at maximum achievable quality. Quality is the proper match for the desired requirements at the expected grade. The product should have specific characteristics.

Quality management starts with the definition of standards or performance levels for each dimension of quality. On the basis of the scope of the project, quality policy, standards, and regulations, a quality management plan is developed. The plan describes the organizational structure, responsibilities, procedures, processes, and resources needed to implement quality management; that is, how the project management team will implement its quality policy to achieve the required quality levels. Checklists and metrics or operational definitions are also developed for each performance measure so that actual results and performance can be evaluated against stated requirements.

To provide confidence that the project will achieve the required quality level, a quality assurance process is implemented. By continuously reviewing (or auditing) the actual implementation of the plan developed, quality assurance systematically seeks to increase the effectiveness and efficiency of the project and its results. Actual results are monitored and controlled. The quality control process forms the basis of acceptance (or rejection) decisions at various stages of development.

2.8 PROJECT HUMAN RESOURCE MANAGEMENT

2.8.1 Accompanying Processes

HR management during the life cycle of a project is primarily concerned with the following four processes:

1. *Plan Human Resource Management.* The human resource management plan is part of the project plan. This process focuses on the preparation of a human resource management plan.
2. *Acquire Project Team.* The process of obtaining the project team members from inside or outside the performing organization.
3. *Develop Project Team.* The process of developing shared understanding among project team members regarding project goals and the way to achieve those goals together.
4. *Manage Project Team.* The process of leading the project team during the project life cycle to achieve project goals by working together resolving conflicts and creating synergy among team members.

Collectively, these processes are aimed at making the most effective use of people associated with the project. The temporary nature of the project structure and organization, the frequent need for multi-disciplinary teams, and the participation of people from different organizations transform into a need for team building, motivation, and leadership if goals are to be met successfully.

2.8.2 Description

The work content of the project is allocated among the performing organizations by integrating the project's WBS with its OBS (Organizational Breakdown Structure). As mentioned, work packages—specific work content assigned to specific organizational units—are defined at the lowest level of these two hierarchical structures. Each work package is a building block; that is, an elementary project with a specific scope, schedule, budget, and quality objectives. Organizational planning activities are required to ensure that the total work content of the project is assigned and performed at the work package level, and that the integration of the deliverables produced by the work packages into the final product is possible according to the project plan. The organizational plan defines roles and responsibilities, as well as staffing requirements and the OBS of the project.

On the basis of the organizational plan, manpower assessments are made along with staff assignments. The availability of staff is compared with project requirements, and gaps are identified. These gaps are filled by the project manager working in conjunction with the HR department of the firm or agency. The assignment of available staff to the project and the acquisition of new staff result in the creation of a project team that may be a combination of full-time employees assigned full time to the project, full-timers assigned part time, and part-timers. Subcontractors, consultants, and other outside resources may be part of the team also.

The assignment of staff to the project is the first step in the team development process. To succeed in achieving project goals, teamwork and a team spirit are essential ingredients. The transformation of disparate individuals who are assigned to a project into a high-performance team requires leadership, communication skills, and negotiation skills, as well as the ability to motivate people, to coach and to mentor them, and to deal with conflicts in a professional, yet effective manner.

2.9 PROJECT COMMUNICATIONS MANAGEMENT

2.9.1 Accompanying Processes

The three processes associated with project communications management are:

1. *Plan Communication Management.* The Communication Management plan is part of the project plan. This process focuses on the preparation of a communication management plan to satisfy the needs of stakeholders for information.
2. *Manage Communication.* The process of collecting data, storing and retrieving the data, and processing it to create useful information that is distributed according to the Communication Management plan.
3. *Control Communication.* The process of monitoring the information distributed to stakeholders throughout the project life cycle and comparing it to the needs for information of the stakeholders to identify gaps and to take corrective actions when needed.

These processes are required to ensure “timely and appropriate generation, collection, dissemination, storage, and ultimate disposition of project information” (PMBOK). Each is tightly linked with organizational planning. Communication between team members, with stakeholders, and with external parties and systems can take many forms. For example, it can be formal or informal, written or verbal, and planned or ad hoc.

The decisions regarding communication channels, the information that should be distributed, and the best form of communication for each type of information are crucial in supporting teamwork and coordination.

2.9.2 Description

Communications planning is the process of selecting the communication channels, the modes of communication, and the contents of the communication between project participants, stakeholders, and the environment. Taking into account information needs, available technology, and constraints on the availability and distribution of information, the communications management plan specifies the frequency and methods by which information is collected, stored, retrieved, transmitted, and presented to the parties involved in the project. On the basis of the plan, data collection as well as data storage and retrieval systems can be implemented and used throughout the project life cycle. The project communication system that supports the transmission and presentation of information should be designed and established early to facilitate the transfer of information.

Information distribution is based on the communication management plan and occurs throughout the project life cycle. As one can imagine, documentation of ongoing performance with respect to costs, schedule, and resource usage is important for several reasons. In general, performance reporting provides stakeholders with information on the actual status of the project, current accomplishments, and forecasts of future project status and progress. It is also essential for project control because deviations between plans and actual progress trigger corrective actions. In addition to the timely distribution of information, historical records are kept to enable post-project analysis in support of organizational and individual learning.

To facilitate an orderly closure of each phase of the project, information on actual performance levels of all activities is collected and compared with the project plan. If a product is the end result, then performance information is similarly collected and compared with the product specifications at each phase of the project. This verification process ensures an ordered, formal acceptance of the project's deliverables by the stakeholders and provides a means for record keeping that supports organizational learning.

Communications planning should answer the following questions:

1. What information is to be provided?
2. Who will be the correspondent?
3. When and in what form is the information to be provided?
4. What templates are to be used?
5. What are the methods for gathering the information to be provided?
6. With what frequency will the information be passed?
7. What form will the communication take—formal, informal, handwritten, oral, hard copy, email?

Information distribution is the implementation of the communication program. If the program is lacking appropriate definition, then it is possible to create a situation of information overload in which too much irrelevant information is passed to project participants at too great a frequency. When this happens, essential information may be overlooked, ignored, or lost. To be more precise regarding the appropriateness of various communication channels, we have:

- *Informal communication.* This is the result of an immediate need for information that was not addressed by the communication plan.
- *Verbal communication.* This is vital in a project setting. The project manager must make sure that team meetings are held on a scheduled basis.

Performance reporting is an important part of communication. It enables the project manager to compare the actual status of each activity with the baseline. This provides the foundations for the change control process and allows for the collection and aggregation of knowledge.

2.10 PROJECT RISK MANAGEMENT

2.10.1 Accompanying Processes

Risk is an unwelcome but inevitable part of any project or new undertaking. Risk management includes six processes:

1. *Plan Risk Management.* The risk management plan is part of the project plan. This process focuses on the preparation of the risk management plan.
2. *Identify Risks.* The process of determining risk events that might impact the project success.
3. *Perform Qualitative Risk Analysis.* The process of assessing the likelihood and impact of identified risk events in order to prioritize and focus on the most significant risks.
4. *Perform Quantitative Risk Analysis.* The process of estimating the probability and impact of identified risk events and applying numerical analysis in order to assess overall project risk.
5. *Plan Risks Response.* The process of selecting risk events for mitigation and deciding the best way to mitigate those risks as well as developing contingency and risk response plans and setting reserves for residual risks and risks that are not mitigated.
6. *Control risk.* The process of monitoring identified risks and identification of new risks throughout the project life cycle as a trigger for activation of contingency plans and a basis for corrective actions and changes.

These processes are designed to identify and evaluate possible events that could have a negative impact on the project. Tactics are developed to handle each type of disruption identified, as well as any uncertainty that could affect project planning, monitoring, and control.

2.10.2 Description

All projects have some inherent risk as a result of the uncertainty that accompanies any new nonrepetitive endeavor. In many industries, the riskier the project, the higher the payoff. Thus, risk is at times beneficial because it has the potential to increase profits (i.e., "upside"). Risk management is not risk avoidance, but a method to control risks so that, in the long run, projects provide a net benefit to the organization.

A decision maker's attitude toward risk may be described as either risk averse, risk prone, or risk natural. For different circumstances and payoffs, the same decision maker can fall into any of these categories. In Chapter 3, we discuss how to construct individual utility functions that capture risk attitudes in specific situations. In project management, these utility functions should reflect the inclination of the organization. Risks can affect the scope, quality, schedule, cost, and other goals of the project such as client satisfaction.

Major risks should be handled by performing a Pareto analysis to assess their magnitude. As a historical footnote, Villefredo Pareto studied the distribution of wealth in the 18th century in Milan and found that 20% of the city's families controlled approximately 80% of its wealth. His findings proved to be more general than the initial purpose of his study. In many populations, it turns out that a small percentage of the population (say, 15%–25%) accounts for a significant portion of a measured factor (say, 75%–85%). This phenomenon is known as the Pareto rule. Using this rule it is possible to focus one's attention on the most important items in a population. In risk management, by focusing on the 10%–20% of the risks with the highest magnitude, it is possible to take care of approximately 80% of the total risk impact on the project.

In a Pareto analysis, events that might have the most severe effect on the project are identified first, for example, by examining the history of similar projects. A risk checklist is then created with the help of team members and outside experts. Next, the magnitude of each item on the list is assessed in terms of impact and probability. Multiplying these terms together gives the expected loss for that risk. When probability estimates are not readily available, methods such as simulations and expert judgments can be used.

A risk event is a discrete random occurrence that cannot be factored into the project plan explicitly. Risk events are identified on the basis of the potential difficulty that they impose on (1) achieving the project's objectives (the characteristics of the product or service), (2) meeting the schedule and budget, and (3) satisfying resource requirements. The environment in which the project is performed is also a potential source of risk. Historical information is an important input in the risk identification process. In high-tech projects, for example, knowledge gaps are a common source of risk. Efforts to develop, use, or integrate new technologies necessarily involve uncertainty and, hence, risk. External sources of risk include new laws, transportation delays, raw material shortages, and labor union problems. Internal difficulties or disagreements may also generate risks.

The probability of risk events and their magnitude and effect on project success are estimated during the risk quantification process. The goal of this process is to rank risks in order of the probability of occurrence and the level of impact on the project. Thus, a high risk is an event that is highly probable and may cause substantial damage.

On the basis of the magnitude of risk associated with each risk event, a risk response is developed. Several responses are used in project management, including:

- Risk elimination—in some projects it is possible to eliminate some risks altogether by using, for example, a different technology or a different supplier.
- Risk reduction—if risk elimination is too expensive or impossible, then it may be possible to reduce the probability of a risk event or its impact or both. A typical example is redundancy in R&D projects when two mutually exclusive technologies are developed in parallel to reduce the risk that a failure in development will harm the project. Although only one of the alternative technologies will be used, the parallel effort reduces the probability of a failure.
- Risk sharing—it is possible in some projects to share risks (and benefits) with some stakeholders such as suppliers, subcontractors, partners, or even the client. Buying insurance is another form of risk sharing.
- Risk absorption—if a decision is made to absorb the risk, then buffers in the form of management reserve or extra time in the schedule can be used. In addition, it may be appropriate to develop contingency plans to help cope with the consequences of any disruptions.

Because information is collected throughout the life cycle of a project, new information is used to update the risk management plan continuously. A continuous effort is required to identify new sources of risk, to update the estimates regarding probabilities and impacts of risk events, and to activate the risk management plan when needed. By constantly monitoring progress and updating the risk management plan, the impact of uncertainty can be reduced and the probability of project success can be increased. Being on the lookout for symptoms of risk is the first step in warding off trouble before it begins. One way to do this is to formulate a list of the most prominent risks to be checked periodically. Because risks change with time, the list must be updated continuously and new estimates of their impact and probability of occurrence must be derived.

2.11 PROJECT PROCUREMENT MANAGEMENT

2.11.1 Accompanying Processes

Procurement management for projects consists of the following four processes:

1. *Plan Procurement Management.* The procurement management plan is part of the project plan. This process focuses on the preparation of the procurement management plan.
2. *Conduct Procurement.* The process of selecting the sellers and signing contracts with them.
3. *Control Procurement.* The process of managing the relationship with the seller throughout the procurement process after signing the contract. Includes the management of changes and the monitoring of the contract performances.
4. *Close Procurement.* The process of completing the procurement process.

These processes accompany the acquisition of goods and services from outside sources, such as consultants, subcontractors, and third-party suppliers. The decision to procure goods and services from the outside (the "make or buy" decision) has a short-term or tactical-level (project-related) impact as well as a long-term or strategic-level (organization-related) impact. At the strategic level, core competencies should rarely be outsourced, even when such action can reduce the project cost, shorten its duration, reduce its risk, or improve quality. At the tactical level, outsourcing can alleviate resource shortages, help in closing knowledge gaps, off-load certain financial risks, and increase the probability of project success. Management of the outsourcing process from supplier selection to contract closeout is another important part of the project manager's job.

2.11.2 Description

The decision on which parts of a project to purchase from outside sources, and how and when to do it, is critical to the success of most projects. This is because significant parts of many projects are candidates for outsourcing, and the level of uncertainty and consequent risk is different from the corresponding measures associated with activities performed in-house. To gain a competitive advantage from outsourcing, the planning, execution, and control of outsourcing procedures must be well-defined and supported by data and models.

The first step in the process is to consider which parts of the project scope and product scope to outsource. This decision is related to capacity and know-how and can be crucial in achieving project goals; however, a conflict may exist between project goals and the goals of the stakeholders. For example, subcontracting may help a firm in a related industry develop the skills and capabilities that would give it a competitive advantage at some future time. This was the case with IBM, which outsourced the development of the Disk Operating System to Microsoft and the development of the central processing unit to Intel. The underlying analysis should take into account the cost, quality, speed, risk, and flexibility of in-house development versus the use of subcontractors or suppliers to deliver the same goods and services. The decisions should also take into account the long-term or strategic factors discussed earlier. Some additional considerations are:

- the prospect of ultimately producing a less-expensive product with higher quality
- the lack of in-house skills or qualifications as defined by prevailing laws and regulations
- the ability to shift risks to the supplier

Once the decision to outsource is made, the following questions must be addressed:

- Should the purchase be made from a single supplier, or should a bid be issued?
- Should the purchase be for a single project or for a group of projects?
- Should finished products or parts be purchased or just the labor hours and have the work done in-house?

- How much should be purchased if, for example, quantity discounts are available?
- When should the purchase be made? There is a tradeoff between time at which a spending commitment is made and the risk associated with delaying the purchase.
- Should the idea of shared purchases be considered whereby joint orders are placed with (competing) organizations to receive quantity discounts or better contractual terms?

Once a decision is made to outsource, the solicitation process begins. This step requires an exact definition of the goods or services to be purchased, the development of due dates and cost estimates, and the preparation of a list of potential sources. Various types of models can be used to support the process by arraying the alternatives and their attributes against one another and allowing the decision maker to input preferences for each attribute. The use of simple scoring models, such as those described in Chapter 5, or more sophisticated methods, such as those described in Chapter 6, can help stakeholders reach a consensus by making the selection process more objective.

In conjunction with selecting a vendor, a contractual agreement is drawn up that is based on the following items:

1. Memorandum of understanding. This is a non-obligatory legal document that provides the foundations for the contract. It is preliminary to the contract.
2. SOW—description of required work to be purchased. The SOW offers the vendor a better understanding of the customer's expectations.
3. Product technical specifications.
4. Acceptance test procedure.
5. Terms and conditions—defines the contractual terms.

The contract is a legal binding document that should specify the following:

1. What—scope of work (deliverables)
2. Where—location of work
3. When—period of performance
4. Schedule for deliverables
5. Applicable standards
6. Acceptance criteria—the criteria that must be satisfied for the project to be accepted
7. Special requirements related to testing, documentation, standards, safety, and so on

Solicitation can take many forms. One extreme is a request for proposal (RFP) advertised and open to all potential sources; a direct approach to a single preferred (or only) source is another extreme. There are many options in between, such as requests for letters of inquiry, qualification statements, and pre-proposals. The main output of the solicitation process is to generate one or more proposals—from the outside—for the goods or services required.

A well-planned solicitation planning process followed by a well-managed solicitation process is required for the next step—source selection—to be successful. Source selection is required whenever more than one acceptable vendor is available. If a proper selection model is developed during the solicitation planning process and all the data required for the model are collected from the potential vendors during the solicitation process, the rest is easy. On the basis of the evaluation criteria and organizational policies, proposals are evaluated and ranked to identify the top candidates. Negotiations with a handful of them follow to get their best and final offer. The process is terminated when a contract is signed. If, however, solicitation planning and the solicitation process do not yield a clear set of criteria and a manageable selection model, then source selection may become a difficult and time-consuming process; it may not end with the best vendor selected or the best possible contract signed. It is difficult to compare proposals that are not structured according to clear RFP requirements; in many cases, important information may be missing.

Throughout the life cycle of a project, contracts are managed as part of the execution and change control efforts. Deliverables, such as test results, prototype models, subassemblies, documentation, hardware and software are submitted and evaluated, payments are made; and, when necessary, change requests are issued. When these are approved, changes are made to the contract. Contract management is equivalent to the management of a work package performed in-house; therefore, similar tools are required during the contract administration process.

Contract closeout is the final process that signals formal acceptance and closure. On the basis of the original contract and all of the approved changes, the goods or services provided are evaluated and, if accepted, payment is made and the contract is closed. Information collected during this process is important for future projects and vendor selection.

2.12 PROJECT STAKEHOLDERS MANAGEMENT

2.12.1 Accompanying Processes

Stakeholders management for projects consists of the following four processes:

1. *Identify Stakeholders.* This process identifies and maps the individuals and parties that may impact the project or may be impacted by the project. The needs and interests of important and influential stakeholders early on in the project life cycle are the basis for setting project objectives, goals, and constraints.
2. *Plan Stakeholders Management.* Based on the analysis of needs and interests of important and influential stakeholders, a stakeholders management plan is developed specifying how each stakeholder should be engaged throughout the project life cycle.
3. *Manage Stakeholders Engagement.* Throughout the life cycle of the project the stakeholders management plan is executed by communicating and working with

the stakeholders according to the plan. Information is distributed to the stakeholders and collected from them, their concerns, needs, and expectations are analyzed, and appropriate actions are taken.

4. *Control Stakeholders Engagement.* Due to uncertainty, stakeholders needs and expectations may change as well as their interests and level of influence on the project. Throughout the life cycle of the project important stakeholders are monitored, and the stakeholders management plan is updated and adjusted based on new information that becomes available.

These processes are key to setting project objectives, goals, and constraints early on in the project life cycle and developing/updating project plans to achieve those objectives, goals, and constraints. Stakeholders may be part of the performing organization; they may come from outside the performing organization, may support the project, or may oppose the project and try to stop it or to limit its success. Therefore, specific attention to developing plans to manage the stakeholders is crucial to improving the probability of project success.

2.12.2 Description

Projects are performed to satisfy the needs and expectations of some stakeholders. Stakeholders management is therefore an important and, yet, a very difficult task. Frequently, the needs and expectations of different stakeholders are in conflict and, sometimes, satisfying one group of stakeholders means that another group will not be satisfied or, even worse, will oppose the project.

Mapping of stakeholders is the first step—an effort to understand who they are, what are their needs, expectations, and interests, their power to influence the project, and their desire to be involved in the project and their expected level of engagement in the project. Based on the mapping, a strategy for managing each stakeholder is developed. Some influential stakeholders who are very interested in the project may be partners and take part in the decision-making process, while other stakeholders will be satisfied if they get specific information during the project life cycle to guarantee their support. The stakeholders management plan should translate this strategy into specific actions like setting regular meetings with some stakeholders and providing some specific information by email or phone in specific points of time to other stakeholders.

The stakeholders management plan is an important part of the project plan, and it should specify who is responsible for the ongoing relationship with each of the stakeholders, what should be done, and when.

An important aspect of a stakeholders management plan is the ongoing effort to monitor and control the stakeholders already identified and to update the list of stakeholders when new stakeholders are identified. This activity is required because the needs and expectations of stakeholders may change throughout the project life cycle, as well as their level of interest in the project and their ability to influence it. Changes in the market, the economic and political environment, and technological changes may all introduce new stakeholders to the project. The earlier these new players are identified and managed, the better it is.

2.13 THE LEARNING ORGANIZATION AND CONTINUOUS IMPROVEMENT

2.13.1 Individual and Organizational Learning

To excel as a project manager, an individual must have expertise in a number of arenas—planning, initiation, execution, supervision—and an ability to recognize when each phase of a project has been completed successfully and the next phase is ready to begin. If such an individual has facility with all aspects of the managerial process, then he or she will be in a prime position to educate, challenge, stimulate, direct, and inspire those whose work he or she is overseeing. A good project manager will be able to serve as a powerfully effective role model and as a source of knowledge and inspiration for those less experienced. In essence, organizational growth and development can be enhanced by way of this "trickle-down" effect from a project manager who enjoys his or her work and takes pride in doing it well; is reliable, committed, and disciplined; can foster development of a strong work ethic and a sense of prideful accomplishment in those whom he or she is managing; and is a font of knowledge, a master strategist, and a visionary who never loses sight of the long-term goal.

The ability of groups to improve performance by learning parallels the same abilities found in individuals. Katzenbach and Smith (1993) explained how to combine individual learning with team building, a key component of any collective endeavor. Just as it is important for each person to learn and master his or her assignment in a project, it is equally important for the group to learn how to work as a team. By establishing clear processes with well-defined inputs and outputs and by ensuring that those responsible for each process master the tools and techniques necessary to produce the desired output, excellence in project management can be achieved.

2.13.2 Workflow and Process Design as the Basis of Learning

The one-time, nonrepetitive nature of projects implies that uncertainty is a major factor that affects a project's success. In addition, the ability to learn by repetition is limited because of the uniqueness of most projects. A key to project management success is the exploitation of the repetitive parts of the project scope. By identifying repetitive processes (both within and between projects) and by building an environment that supports learning and data collection, limited resources can be more effectively allocated. Reuse of products and procedures is also a key to project success. For example, in software projects, the reuse of modules and subroutines reduces development time and cost.

A valuable step in the creation of an environment that supports learning is the design and implementation of a workflow management system—a system that embodies the decision-making processes associated with each aspect of the project. Each process, discussed in this chapter, should be studied, defined, and implemented within a workflow management system. Definitional elements include the trigger or initiation mechanism of the process, inputs and outputs, skills and resource requirements, activities performed, data required, models used, relative order of execution, termination conditions, and, finally, an enumeration of results or deliverables. The workflow management system uses a workflow enactment system or workflow process engine that can create, manage, and execute multiple process instances.

By identifying processes that are common to more than one project within an organization, it is possible to implement a workflow system that supports and even automates those processes. Automation means that the routing of each process is defined along with the input information, processing tools and techniques, and output information. Although the product scope may vary substantially from project to project, when the execution of the project scope is supported by an automatic workflow system, the benefits are twofold: (1) the level of uncertainty is reduced because processes are clearly defined and the flow of information required to support those processes is automatic, and (2) learning is enabled. In general, a well-structured process can be taught easily to new employees or learned by repetition. For the organization that deals with many similar projects, efficiency is greatly enhanced when the same processes are repeated, the same formats are used to present information, and the same models are used to support decision making. The workflow management system provides the structure for realizing this efficiency.

TEAM PROJECT

Thermal Transfer Plant

Develop two project life-cycle models for the plant. Focus on the phases in the model and answer the following questions.

1. What should be done in each phase?
2. What are the deliverables?
3. How should the output of each phase be verified?

Discuss the pros and cons of each life-cycle model and select the one that you believe is best. Explain your choice.

DISCUSSION QUESTIONS

1. Explain what a project life cycle is.
2. Draw a diagram showing the spiral life-cycle model for a particular project.
3. Draw a diagram showing the waterfall life-cycle model for a particular project.
4. Discuss the pros and cons of the spiral project life-cycle model and the waterfall project life-cycle model.
5. How are the processes in the PMBOK related to each other? Give a specific example.
6. How are the processes in the PMBOK related to the project life cycle? Give a specific example.
7. If time to market is the most important competitive advantage for an organization, then what life-cycle model should it use for its projects? Explain.
8. What are the main deliverables of project integration?
9. What are the relationships between a learning organization and the project management processes?
10. What are the characteristics of a good project manager?

EXERCISES

2.1 Find an article describing a national project in detail. On the basis of the article and on your understanding of the project, answer the questions below. State any assumptions that you feel are necessary to provide answers.

a. Who were the stakeholders?
b. Was it an internal or external project?
c. What were the most important resources used in the project? Explain.
d. What were the needs and expectations of each stakeholder?
e. What are the alternative approaches for this project?
f. Was the approach selected for the project the best, in your opinion? Explain.
g. What were the risks in the project?
h. Rank the risks according to severity.
i. What was done or could have been done to mitigate those risks?
j. Was the project a success? Why?
k. Was there enough outsourcing in the project? Explain.
l. What lessons can be learned from this project?

2.2 Find an article that discusses workflow management systems (e.g., Stohr and Zhao 2001) and explain the following:

a. What are the advantages of workflow systems?
b. Under what conditions is a workflow system useful in a project environment?
c. Which of the processes described in the PMBOK are most suitable for workflow systems?
d. What are the disadvantages of using a workflow system in a project environment?

2.3 On the basis of the material in this chapter and any outside sources you can find, answer the following.

a. Define what is meant by a "learning organization."
b. What are the building blocks of a learning organization?
c. What are the advantages of a learning organization?
d. What should be done to promote a learning organization in the project environment?

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Chapter 5

Portfolio Management—Project Screening and Selection

5.1 COMPONENTS OF THE EVALUATION PROCESS

Every new project starts with an idea. Typically, new ideas arrive continuously from a variety of sources, such as customers, suppliers, upper management, and shop floor personnel. Details of the steps involved in processing these ideas and the related analyses are highlighted in Figure 5.1.

Depending on the scope and estimated costs, management may simply be interested in determining the merit of the idea or it may want to determine how best to allocate a budget among a portfolio of projects. If the organization is a consulting firm or an outside contractor, then it may want to decide on the most advantageous strategy for responding to requests for proposals (RFPs).

Of course, there are many different types of projects, so the evaluation criteria and accompanying methodology should reflect the particular characteristics of the sponsoring or responding organization. The usual divisions are public sector versus private sector, research and development (R&D) versus operations, and internal customer versus external customer. Project size, expected duration, underlying risks, and required resources are some of the factors that must weigh on the decision.

Regardless of the source or nature of the customer, screening is usually the first step. A proposed project is analyzed in a preliminary manner in light of the most prominent criteria or prevailing conditions. This should be a quick and inexpensive exercise. The results may suggest, for example, that no further effort is warranted as a result of uncertainty in the technology or the lack of a well-defined market. If some promise exists, then the project may be temporarily backlogged in deference to more attractive contenders. At some time in the future when conditions are more favorable, it may be desirable to re-visit the go/no go decision, or the project may be deemed so urgent or beneficial to the organization that it is placed at the top of the priority list. Alternatively,

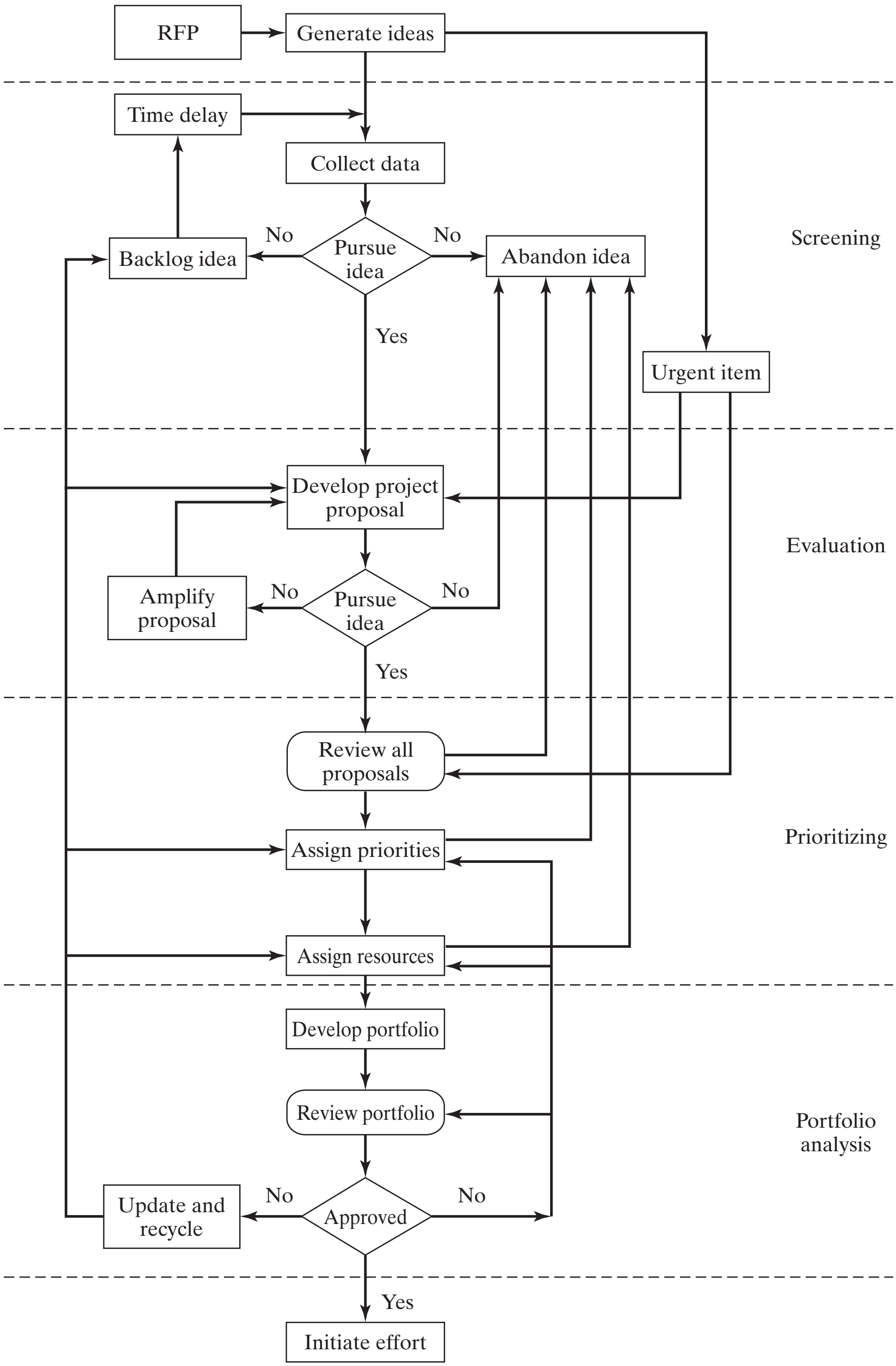

Figure 5.1 Project evaluation and selection process.

results of the project screening process may indicate that the proposed project possesses some merit and deserves further investigation.

If a project passes the organization screening process for evaluating new project ideas, then a more in-depth analysis should be performed with the goal of narrowing uncertainties associated with the project's costs, benefits, and risks. In contrast to the screening process, the evaluation process usually involves extensive and in-depth data collection, the solicitation of expert opinion, sample computations, and perhaps technological forecasting. As with the screening process, several courses of action might be suggested. The proposal may be rejected or abandoned for lack of merit, it may be backlogged for later retrieval and analysis, or it may be found to be acceptable and placed on a candidate list for a comparative analysis. In some cases, it may be initiated immediately.

When the results of the evaluation process indicate that a proposal passes an acceptance threshold but that it is not clearly superior to other candidates, each proposal should be assessed and ranked competitively. The relative strengths and weaknesses of each candidate project are examined carefully, and a weighted ranking is obtained. Ideally, the ranking would indicate not only the most preferred project but also the degree to which it is preferred over the other contenders. A number of assessment methodologies are presented in Sections 5.3 through 5.7 and Chapter 6.

If the ranking of a particular proposal is high enough, then resources may tentatively be assigned. However, the decision to fund and initiate work on a proposal involves the full consideration of the available human and financial resources within the organization. The level of available funds and personnel skill types and the commitments to the current portfolio of activities must be factored into the decision. It may be that the new idea is so meritorious that it should replace one or more ongoing projects. If this is the case, then some ongoing project(s) will be terminated or halted temporarily so that resources can be freed up for the new project. Portfolio models have been developed to aid in making these decisions. A portfolio model determines the best way to allocate available resources among competing alternatives, including new candidates and ongoing projects. An example of such a model is presented in Chapter 13.

Portfolio models are used only when multiple projects compete for the same resources. In the remainder of this chapter, we discuss methods for screening and prioritizing alternatives when resources limit the size of the portfolio.

5.2 DYNAMICS OF PROJECT SELECTION

As Figure 5.1 suggests, project selection can be a very dynamic process. Screening, evaluation, prioritizing, and portfolio analysis decisions may be made at various points, and new ideas may not even go through these steps in sequence. An idea may be shelved or abandoned at any point in time. New information and changed circumstances may reverse a previous decision to reject or abandon a project. For example, efforts to develop lightweight portable computers were given a new impetus with the dramatic improvement in flat-screen display technology. Alternatively, new information or changed circumstances may cause a previously backlogged project to be rejected. The drastic reduction in the price of imported oil in the early 1980s dealt a death blow to some exotic alternative energy projects, such as coal gasification and shale oil reclamation.

The available budget or labor skills within an organization may constrain the project selection process. A meritorious project may be delayed if insufficient budget is available to fund it. Alternatively, a project may be phased, and certain portions initiated while others are postponed until the financial situation becomes more favorable. Customer complaints, competitive threats, or unique opportunities may occasion an urgent need to pursue a particular idea. Depending on the urgency, the project may receive only a cursory screening and evaluation and may go directly into the portfolio.

Screening, evaluation, prioritizing, and portfolio decisions may be repeated several times over the life cycle of a project in response to emerging technologies and changing environmental, financial, or commercial circumstances. The advent of a new RFP, a change in competitive pressures, and the appearance of a new technology are some factors that may cause management to reevaluate an ongoing project. Moreover, with each advance that is recorded, new technical information that may influence other efforts and proposed ideas will be forthcoming. As current projects near completion, key personnel and equipment may be released so that they can be used on another project, perhaps one that was previously backlogged for lack of appropriate resources.

In general, evaluation and selection of new product ideas and project proposals is a complex process, consisting of many interrelated decisions. The complexities involve the variety of data that must be collected and the difficulty of unequivocally measuring and assessing candidate projects on the basis of information derived from these data. Much of the resultant information is subjective and uncertain in nature. Many ideas and proposals exist only as embryonic thoughts and are propelled forward by the sheer force of the sponsor's enthusiasm. The presence of various organizational and behavioral factors tends to politicize the decision-making process. In many cases, the potential costs and benefits of a project play only a small role in the final decision. For example, an extensive two-year analysis of LANDSAT, an earth-orbiting satellite with advanced resource monitoring capabilities, concluded that the benefits to the user community would fall significantly short of the expected costs associated with operating and maintaining the system over its 10-year lifetime, even under the most optimistic of scenarios (Bard 1984). Nevertheless, pressure from National Aeronautics and Space Administration (NASA) and its congressional allies, who saw LANDSAT as a high-profile, nonmilitary application of space technology that might actually return some benefits, persuaded the U.S. Department of the Interior to provide funding.

The more sophisticated analytical and behavioral tools that have been developed to aid managers in evaluating projects vary in their approach for handling nonquantitative aspects of the decision.

5.3 CHECKLISTS AND SCORING MODELS

The idea-generation stage of a project, when done properly, will often lead to more proposals than can realistically be pursued. Thus, a screening procedure designed to eliminate those proposals that are clearly infeasible or without merit must be established. Compatibility with the organization's objectives, existing product and service lines, and resources is a primary concern. It is also important to keep in mind that when comparing alternatives early on, a wide range of criteria should be introduced in the analysis. The fact that these criteria are often measured on differing scales makes the screening and evaluation much more difficult.

Of the several techniques available to aid in the screening process, perhaps the most commonly used are rating checklists. They are appropriate for eliminating the most undesirable proposals from further consideration. Because they require a relatively small amount of information, they can be used when the available data are limited or when only rough estimates have been obtained. Such methods should be viewed as expedient; they do not provide a great deal of depth and should be used with this caveat in mind.

Table 5.1 presents an illustration of a checklist. In constructing a checklist, it is necessary to identify the criteria or set of requirements that will be used in making the decision. In the next step, a (arbitrary) scoring scale is developed to measure how well a project does with respect to each criterion. Words such as "excellent" and "good" may be associated with the numerical values [see Gass (2001) for a more complete discussion of several issues related to the choice of scales and their effect on rankings].

In the example displayed in Table 5.1, the criteria include profitability, time to market, development risks, and commercial success. Each candidate is evaluated subjectively and scored using a 3-point scale. The built-in assumption is that each criterion is weighted equally. Total scores are displayed in the rightmost column. Typically, a cutoff point or threshold is specified below which the project is abandoned. Of those that exceed the threshold, the top contenders are held for further analysis, whereas the remainder are backlogged or shelved temporarily. Here, if 7 is specified as the threshold total score, then only projects A and C would be pursued.

An alternative means of displaying the information in Table 5.1 is a multidimensional diagram known as a polar graph (Canada et al. 1996), shown in Figure 5.2. In one sense, this type of representation is more efficient than a table because it allows the analyst quickly to ascertain the presence of dominance. For example, by noting that the performance measure surface of project B is completely within that of project A, we can conclude that B is no better than A on any dimension and thus can be discarded or backlogged.

Scoring models extend the logic of checklists by assigning a weight to each criterion that signifies the relative importance of one to the other (Baker 1974, Hobbs 1980, Souder and Mandakovic 1986). A weighted score is then computed for each candidate. In deriving the weights, a team approach should be used to head off disagreement after

TABLE 5.1 An Example of a Checklist for Screening Projects

	Criteria												
	Profitability			Time to market			Development risks			Commercial success			
Score:	3	2	1	3	2	1	3	2	1	3	2	1	Total score
Project A		×		×			×				×		10
Project B		×			×				×			×	6
Project C	×					×		×			×		8

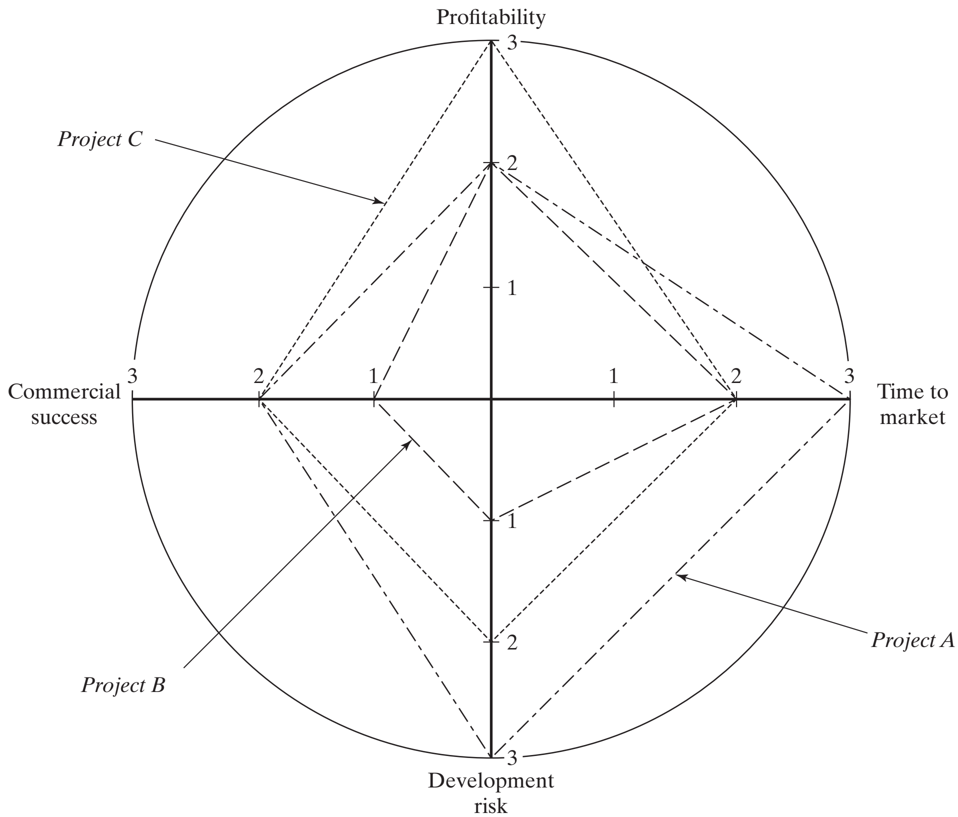

Figure 5.2 Multidimensional diagram for checklist example.

the assessment. One way of accomplishing this is to list all criteria in descending order of importance. Next, assign the least important (last-listed) criterion a value of 10, and assign a numerical weight to each criterion on the basis of how important it is relative to this one. A criterion considered to be twice as important as the least important criterion would be assigned a weight of 20. If team members cannot agree on specific values, then sensitivity analysis should be performed.

An example of the use of a scoring model for screening projects associated with the development of new products is shown in Table 5.2. Here eight criteria are to be rated on a numerical scale of 0 to 30, where 0 means poor and 30 means excellent. Because this scale is arbitrary, no significance should be placed on relative values. For convenience, the weights are scaled between 0 and 1. In general, the factor score for project j, call it T_j, is obtained by multiplying the relative weights, w_i for criterion i, by the ratings, s_{ij}, and summing. That is,

$$T_j = \sum_i w_i S_{ij} \tag{5.1}$$

In this example, the project under consideration received a factor score of 18.

TABLE 5.2 An Example of a Scoring Model for Screening Projects

Criteria	Relative weight	Rating: Excellent 30	Good 20	Fair 10	Poor 0	Factor score
Marketability	0.20	×				6
Risk	0.20		×			4
Competition	0.15		×			3
Value added	0.15				×	0
Technical opportunities	0.10	×				3
Material availability	0.10			×		1
Patent protection	0.05				×	0
Current products	0.05		×			1
Total	1.00					18

A variety of other formulas have been proposed for deriving the relative weights. Three of the simplest are presented below. More elaborate schemes are discussed in the next chapter.

1. *Uniform or equal weights.* Given N criteria, the weight for each is

$$w_i = \frac{1}{N}$$

2. *Rank sum weights.* If R_i is the rank position of criterion i (with 1 as the highest rank) and there are N criteria, then rank sum weights for each criterion may be calculated as

$$w_i = \frac{N - R_i + 1}{\sum_{k=1}^{N}(N - R_k + 1)}$$

where the denominator is the sum of the first N integers; that is, $N(N + 1)/2$.

3. *Rank reciprocal weights.* These weights may be calculated as

$$w_i = \frac{1/R_i}{\sum_{k=1}^{N} 1/R_k}$$

The advantage of a scoring model is that it takes into account the tradeoffs among the criteria, as defined by the relative weights. The disadvantage is that it lacks precision and relies on an arbitrary scoring system.

An environmental scoring form developed by Niagara Mohawk, a New York utility, is depicted in Table 5.3. Note that the procedure for assigning points is specified.

5.4 BENEFIT-COST ANALYSIS

Evaluation of the merits of alternative investment opportunities begins with technical feasibility. The next step involves a comparison at some minimum attractive rate of return (MARR) of the estimated stream of costs and benefits over the expected

TABLE 5.3 Environmental Scoring Form Used by Niagara Mohawk

Environmental attributes	Weight, *W*	Points, *P*: 0	1	2	3	4	5	Score, *W* × *P*
Air emissions								
Sulfur oxides (lb/MWh)	7	>6	4.0–6.0	2.5–3.9	1.5-2.4	0.5–1.4	<0.5	
Nitrogen oxides (lb/MWh)	16	>6	4.0–6.0	2.5–3.9	1.5–2.4	0.5–1.4	<0.1	
Carbon dioxide (lb/MWh)	3	>1500	1050–1500	650–1049	250–649	100–249	<100	
Particulates (lb/MWh)	1	>0.3	0.2–0.3	0.1–0.199	0.05–0.099	0.01–0.049	<0.01	
Water effects								
Cooling water flow (annual intake as % of lake volume)	1	80–100	60–79	40–59	20–39	5–19	<5	
Fish protection	1	None		Operational restrictions		Fish protection	No public water used provided	
NY State water quality classification of receiving water	1	A or better	B	C+	C+	D	No water use or municipal water/waste water utilized	
Land effects								
Acreage required (acres/MW)	1	0.3–0.5	0.2–0.29	0.1–0.19	0.05–0.09	0.01–0.05	<0.01	
Terrestrial	1	Unique ecological or historical value		Rural or low-density suburban		Industrial area	No land used	
Visual aesthetics	1	Highly visible		Within existing developed area		Not visible from public roads		
Transmission	2	New OH >5 miles	New OH 1–5 miles	New UG >5 miles	New UG 1–5 miles	Use existing facilities	Energy conservation	
Noise (L_{eq} − backgrd L_{90})	2	5–10			0–4.9		<0	
Solid waste disposal (lb/MWh)	2	>300	200–300	100–199	50–99	10–49	<10	
Solid waste as fuel (% of total Btu)	1	0	1–30	31–50	51–80	81–90	91–100	
Fuel delivery method	1	New RR spur	Truck and existing RR	New pipeline	Barge	Use existing pipeline	No fuel use	
Distance from receptor area (km)	1	<10	10–39	40–69	70–100	>100	Energy conservation	
						Total score (210 maximum) =		

economic life of each project. Engineering studies must be undertaken to establish the fundamental data. The estimated benefits and costs are then compared, usually on a present value basis, using a predetermined discount rate.

In the private sector, the firm generally pays all of the costs and receives all of the benefits, both quantitative and qualitative. Replacing an outdated piece of equipment is an example in which the returns are measurable, whereas constructing a new company cafeteria illustrates the opposite case. Where the activities of government are concerned, however, a different situation arises. Revenues are received through various forms of taxation and are supposed to be spent "in the public interest." Thus, the government pays but receives very few, if any, benefits. This can present all sorts of problems. For one, it means that the intended beneficiaries of a federal project will be very anxious to get the project approved and funded. Such situations may induce otherwise virtuous people to redefine the standards of acceptable ethical behavior. A second problem concerns the measurement of benefits, which are often widely disbursed. Other difficulties include the selection of an interest rate and choosing the correct viewpoint from which the analysis should be made. Finally, in the benefit-cost (B/C) analysis, where the B/C ratio is used to rank competing projects, there may be legitimate ambiguity in deciding what goes in the numerator and what goes in the denominator of the ratio.

At first glance, it would seem to be a simple matter of sorting out the consequences into benefits (for the numerator) or costs (for the denominator). This works satisfactorily when applied to projects for a firm or a person. In government projects it may be considerably more difficult to classify the various consequences, as shown in Example 5-1.

Example 5-1

On a proposed government project, the following consequences have been identified:

- Initial cost of project to be paid by government is \$100K.
- Present worth (PW) of future maintenance to be paid by government is \$40K.
- PW of benefits to the public is \$300K.
- PW of additional public users costs is \$60K.

Show the various ways of computing the B/C ratio.

Solution Putting the benefits in the numerator and all costs in the denominator gives

$$\text{B/C ratio} = \frac{\text{All benefits}}{\text{All costs}} = \frac{300}{100 + 40 + 60} = \frac{300}{200} = 1.5$$

An alternative computation is to consider user costs as disbenefits and to subtract them in the numerator rather than add them in the denominator:

$$\text{B/C ratio} = \frac{\text{public benefits} - \text{public costs}}{\text{government costs}} = \frac{300 - 60}{100 + 40} = \frac{240}{140} = 1.7$$

Still another variation would be to consider maintenance costs as disbenefits:

$$\text{B/C ratio} = \frac{300 - 60 - 40}{100} = \frac{200}{100} = 2.0$$

It should be noted that although three different B/C ratios may be computed, the net present value (NPV) does not change:

$$\text{NPV} = \text{PW of benefits} - \text{PW of costs} = 300 - 60 - 40 - 100 = 100. \qquad \blacksquare$$

There is no inherently correct way to compute the B/C ratio. Using the notation of Chapter 3, two commonly used formulations are given below:

1. *Conventional B/C*

$$\text{B/C} = \frac{\text{PW of benefits to user}}{\text{PW of total costs to supplier}} = \frac{\text{PW[B]}}{\text{PW[CR + (O + M)]}} \tag{5.2a}$$

or

$$\text{B/C} = \frac{\text{Annual worth (AW) of benefits to user}}{\text{AW of total costs to supplier}} = \frac{\text{B}}{\text{CR + (O + M)}} \tag{5.2b}$$

where

B = AW of benefits to user
CR = capital recovery cost (equivalent annual cost of initial investment, considering any salvage value)
O = equivalent uniform annual operating cost
M = equivalent uniform maintenance cost

2. *Modified B/C*

$$\text{B/C} = \frac{\text{PW[B} - \text{(O + M)]}}{\text{PW[CR]}} \quad \text{or} \quad \text{B/C} = \frac{\text{B} - \text{(O + M)}}{\text{CR}} \qquad \blacksquare$$

The modified method has become more popular with governmental agencies and departments over the last decade. Although both methods yield the same recommendation when comparing mutually exclusive alternatives, they may yield different rankings for independent investment opportunities. In either case, using PW, AW, or future worth (FW) should always provide the same results.

Example 5-2 (Single-Project Analysis)

An individual investment opportunity is deemed to be worthwhile if its B/C ratio is greater than or equal to 1. Consider the project of installing a new inventory control system with the following data:

Initial cost	\$20,000
Project life	5 years
Salvage value	\$4,000
Annual savings	\$10,000
Operating & Maintenance disbursements	\$4,400
MARR	15%

By interpreting annual savings as benefits, the conventional and modified B/C ratios based on annual equivalents are computed as follows:

$$\text{CR} = \$20{,}000(A/P, 15\%, 5) - \$4{,}000(A/F, 15\%, 5)$$
$$= 20{,}000(0.2983) - 4{,}000(0.1483) = \$5{,}373$$

$$\text{conventional B/C} = \frac{\text{B}}{\text{CR} + (\text{O} + \text{M})} = \frac{\$1{,}0000}{\$5{,}373 + \$4{,}400} = 1.02$$

$$\text{modified B/C} = \frac{\text{B} - (\text{O} + \text{M})}{\text{CR}} = \frac{\$10{,}000 - \$4{,}400}{\$5{,}373} = 1.04$$

Because either B/C is greater than 1, the investment is worthwhile. Nevertheless, there is an opportunity cost associated with the investment that may preclude other possibilities. The fact that the B/C of a project is greater than 1 does not necessarily mean that it should be pursued. ■

Example 5-3 (Comparing Mutually Exclusive Alternatives)

As was true for rate of return (ROR) calculations, when comparing a set of mutually exclusive alternatives by any B/C method, an incremental approach is preferred. The principles and criterion of choice as explained in Chapter 3 apply equally to B/C methods, the only difference being that each increment of cost (the denominator) must be justified by a B/C ratio ≥ 1.

Consider the data in Table 5.4a associated with the four alternative projects used in Example 3.9 to demonstrate the internal rate of return (IRR) method. Each is listed in increasing order of investment. The symbol Δ(B/C) means that the B/C ratio is being computed on the incremental cost. Once again, a MARR of 15% is used.

The output data in Table 5.4b confirm the results previously found using the IRR method. Alternative C would be chosen given that it is the most expensive project for which each increment of cost is justified (by B/C ratio ≥ 1).

TABLE 5.4 Input Data and Results for Incremental Analysis

	Project			
(a) Input data	A	B	C	D
Initial cost	\$20,000	\$30,000	\$35,000	\$43,000
Useful life	5 years	10 years	5 years	5 years
Salvage value	\$4,000	0	\$4,000	\$5,000
Annual receipts	\$10,000	\$14,000	\$20,000	\$18,000
Annual disbursements	\$4,400	\$8,600	\$9,390	\$5,250
Net annual receipts − disbursements	\$5,600	\$5,400	\$10,610	\$12,750
(b) Results	A	A → B	A → C	C → D
ΔInvestment	\$20,000	\$10,000	\$15,000	\$8,000
ΔSalvage	4,000	−4,000	0	1,000
ΔCR = ΔC	5,373	605	4,477	2,386
Δ(annual receipts − disbursements) = ΔB	5,600	−200	5,010	2,140
Δ(B/C) = ΔB/ΔC	1.04	−0.33	1.12	0.90
Is Δinvestment justified?	Yes	No	Yes	No

■

B/C studies within the public sector in particular may be approached from several points of view. The perspective taken may have a significant impact on the outcome of the analysis. Possible viewpoints include

1. That of the governmental agency conducting the study
2. That of the local area (e.g., town, municipality)
3. The nation as a whole
4. The targeted industry

Thus, it is essential that the analyst have clearly in mind which group is being represented before proceeding with the study. If the objective is to promote the general welfare of the public, then it is necessary to consider the impact of alternative policies on the entire population, not merely on the income and expenditures of a selected group. Practically speaking, however, without regulations, the best that can be hoped for is that the broader interests of the community will be taken into account. Most would agree, for example, that without environmental and health regulations and the attendant threat of prosecution, there would be little incentive for firms to treat their waste products before discharging them into local waterways.

The national viewpoint would seem to be the correct one for all federally funded public works projects; however, most such projects provide benefits only to a local area, making it difficult, if not impossible, to trace and evaluate quantitatively the national effects. The following example parallels an actual case history.

Example 5-4

The government wants to decide whether to give a $5,000,000 subsidy to a chemical manufacturer who is interested in opening a new factory in a depressed area. The factory is expected to generate jobs for 200 people and further stimulate the local economy through commercial ventures and tourist trade. The benefits as a result of jobs created and improved trade in the area are estimated at $1,000,000 per year. Six percent is considered to be a fair discount rate. The study period is 20 years. Calculate the B/C ratio to determine whether the project is worthwhile.

Solution $\text{PW of benefits} = \$1{,}000{,}000(P/A, 6\%, 20) = \$11{,}470{,}000$

$$\text{B/C ratio} = \frac{\$11{,}470{,}000}{\$5{,}000{,}000} = 2.3$$

Outcome. The plant was funded on the basis of the foregoing study, but pollution control equipment was not installed. During operations, raw by-products were dumped into the river, causing major environmental problems downstream. Virtually all of the fish died, and the river became a local health hazard. The retrofitting of pollution control equipment sometime later made the entire project uneconomical, and the plant eventually closed.

Conclusion. Because the full costs of the project were not taken into account originally, the results were overly optimistic and misleading. Had the proper viewpoint been established at the outset and all of the factors considered, the outcome might not have been so unfortunate. ■

5.4.1 Step-by-Step Approach

To conduct a benefit-cost (B/C) analysis for an investment project, it is important to complete the following steps:

1. Identify the problem clearly.
2. Explicitly define the set of objectives to be accomplished.
3. Generate alternatives that satisfy the stated objectives.
4. Identify clearly the constraints (e.g., technological, political, legal, social, financial) that exist with the project environment. This step will help narrow the alternatives generated.
5. Determine and list the benefits and costs associated with each alternative. Specify each in monetary terms. If this cannot be done for all factors, then this should be stated clearly in the final report.
6. Calculate the B/C ratios and other indicators (e.g., present value, ROR, initial investment required, payback period) for each alternative.
7. Prepare the final report comparing the results of the evaluation of each alternative examined.

5.4.2 Using the Methodology

As with any decision-making process, the first two steps above are to define the problem and related goals. This may involve identifying a particular problem to be solved (e.g., pollution) or agreeing on a specific program, such as landing an astronaut on the moon. Once this is done, it is necessary to devise a solution that is feasible, not only technically and economically but also politically.

Implicit in these steps is a twofold selection process: a macro-selection process whereby we choose from among competing opportunities or programs (should more federal funds be expended on space research or pollution cleanup and control?) and a micro-selection process whereby we strive to find the best of several alternatives (should we build a nuclear- or coal-fired plant?).

5.4.3 Classes of Benefits and Costs

Once a set of alternatives has been established, the detailed analysis can begin. The benefits and costs may be broken down into four classes: primary, secondary, external, and intangible. Primary refers to benefits and costs that are a direct result of a particular project. If a corporation manufactures videocassette recorders, then the primary costs are in production, and the primary benefits are in profits. In building a canal, the construction costs and the revenues generated from water charges are the primary elements.

"Secondary" benefits and costs are the marginal benefits and costs that accrue when an imperfect market mechanism is at work. In such instances, the market prices of a project's final goods and services do not reflect the "true" prices. The use of government funds to build and maintain airports is a good example. There is a hidden cost to society as well as a hidden benefit to the airlines and their more frequent customers. Increased noise pollution and traffic congestion around the airport are illustrative of the costs; benefits can be measured by lower airfares.

External benefits and costs are those that arise when a project produces a spillover effect on someone other than the intended group. Thus, a government subsidy to airports produces external benefits by indirectly boosting the local economy. Massive government spending on space has yielded extensive benefits to medical science and the microelectronics industry. Similarly, there are spillover effects of pollution that produce disutilities in the form of health costs and the loss of recreational facilities.

Intangible benefits and costs are those that are difficult, if not impossible, to measure on a monetary scale. Examples of intangible benefits include trademarks and goodwill, whereas examples of intangible costs include costs associated with increased urban congestion. If intangibles dominate the decision process, the value of multiple-criteria methods such as multi-attribute utility theory and the analytic hierarchy process, discussed in Chapter 6, increases.

After categorizing the benefits and costs in this manner, they should be allocated to the various stages in a project in which they are expected to occur. A typical project includes stages such as planning, implementation, operation, and closeout. This distinction is necessary for proper quantitative evaluation. For example, the costs associated with noise, traffic disruption, and hazards of subway construction may occur only in the implementation stage and must be discounted accordingly.

5.4.4 Shortcomings of the Benefit-Cost Methodology

Upon completion of the quantitative assessment of the various costs and benefits, the actual desirability of the project can be determined. Use of the B/C ratio to rank the best alternative can be deceptive, however, because it disguises the problem of scale. Two projects may have the same ratio yet involve benefits and costs that differ by millions of dollars, or one project may have a lower ratio than another and still possess greater benefits. Sometimes, therefore, projects will be selected simply on the basis of whether their benefits exceed their costs; yet again, scale must be considered, for two projects obviously can have the same net benefit, but one may be far more costly than the other.

As mentioned, another way to evaluate projects is to compare the expected ROR on investment with the interest rate on an alternative use of the funds. This criterion is implicit in most private-sector decisions but generally is neglected in the public sector, where tangible financial returns are not the sole criterion for investment allocations. Moreover, there is rarely a consensus on which discount rate should be used. Economists invariably dispute the choice, some arguing for the social rate of time preference, whereas others lean toward the prevailing interest rate. Except when a particular rate is specified by the decision maker, the NPV calculations should be repeated using several values to ascertain sensitivity effects.

The difficulty in agreeing on a discount rate is usually secondary to the problem of determining future costs and benefit streams. Uncertainties in long-term consequences may be large for extended time horizons of more than a few years, although frequently, all alternatives will suffer from a similar fate. Investigating questions of inter-temporal equity and methods for dealing with uncertain outcomes are central problems of research, and their logic must be pursued relentlessly. Moreover, all forms of decision making must resolve these questions, regardless of whether they are dealt with explicitly.

In practice, it is rare that any one criterion will suffice for making a sound decision. Several criteria, as well as their many variations, must be examined in the analysis. The important point, however, is that even if all relevant factors are addressed, the analysis will still possess a high degree of subjectivity, leaving room for both conscious and unacknowledged bias. This leads to the two major shortcomings of B/C analysis.

The first is the need and general failure to evaluate those items that are unquantifiable in monetary terms. The type of question that continually gets raised is, "How do you measure the value of harmony between labor and management?" or "What is the value of a pollution-free environment?" The development of indicators other than those that reflect dollar values explicitly present a considerable challenge to analysts. They must depart from the familiar criteria of economic efficiency as a prime mechanism of evaluation and venture into the unknown areas of social and environmental concerns. Interestingly enough, the nonquantifiable elements bear equally on the governmental, business, and consumer sectors of the economy. In short, these "unmeasurable" elements may be of utmost significance, as system indicators must be developed to evaluate their impact on the program. It is here where judgment and subjectivity come into play.

The second weakness in the practice of B/C analysis arises from the "judge and jury" characteristic. Invariably, the same organization (either in a private company or a government agency) that proposes and sponsors a particular project undertakes the analysis. Whether this is done internally or by a subcontractor is not important. Rather, the organization and its contractors will usually display similar attitudes and biases in their approach to a problem. Independent, unbiased assessments are needed if the process is to work correctly and produce believable results.

5.5 COST-EFFECTIVENESS ANALYSIS

When comparing two projects that have the same B/C ratio, the one that costs more will provide greater returns. In some situations, though, there may be a fixed or upper limit on the budget, so a project that is technically feasible may not be economically feasible even if it has a high B/C ratio. Economic barriers to entry are common in many fields, such as automotive or semiconductor manufacturing where the required initial investment may be as high as $1 billion.

In the case in which the budget is the limiting factor, a *cost-effectiveness* (C-E) study is often performed to maximize the value of an organization's investment. In a C-E study, the focus is the performance of the proposed system (i.e., project) as measured by a composite index that is necessarily subjective in nature. This is because incommensurable and qualitative factors such as development risk, maintainability, and ease of use all must be evaluated collectively.

In general, system effectiveness can be thought of as a measure of the extent to which a system may be expected to achieve a set of specific mission requirements. It is often denoted as a function of the system availability, dependability, and capability.

- *Availability* is defined as a measure of the system condition at the start of a mission. It is a function of the relationship among hardware, personnel, and procedures.
- *Dependability* is defined as a measure of the system condition at one or more points during mission operations.
- *Capability* accounts specifically for the performance spectrum of the system.

The term *effectiveness* can be difficult to define precisely. For a product or service, one definition would be the ability to deliver what is called for in the technical specification. Among the terms that are related to (or have been substituted for) *effectiveness* are *value, worth, benefit, utility, gain,* and *performance*. Unlike cost, which can be measured in dollars, effectiveness does not possess an intrinsic measure by which it can be uniquely expressed.

Government agencies, in particular, the U.S. Department of Defense, have been prominent users of C-E analyses. The following eight steps represent a common blueprint for conducting a C-E study:

1. Define the desired goals.
2. Identify the mission requirements.
3. Develop alternative systems.
4. Establish system evaluation criteria.
5. Determine capabilities of alternative systems.
6. Analyze the merits of each.
7. Perform sensitivity analysis.
8. Document results and make recommendations.

A critical step in the procedure is in deciding how the merits of each alternative will be judged. After the evaluation criteria or attributes are established, a mechanism is needed to construct a single measure of performance. Scoring models, such as those described in Section 5.3, are commonly used. Here, we assess the relative importance of each system attribute and assign a weight to each. Next, a numerical value, say between 0 and 100, is assigned to represent the effectiveness of each attribute for each system. Once again, these values are subjective ratings but may actually be based on simple mathematical calculations of objective measures, subjective opinion, or engineering judgments. Where an appropriate physical scale exists, the maximum and minimum values can be noted and a straight line between those boundaries can be used to translate outcomes to a scale of 0 to 100. The analyst must ensure that the actual value of the attribute corresponds to the subjective description; for example, $100 \geq$ excellent ≥ 80; $80 >$ good ≥ 60.

In many cases it is useful to compare attribute relative values graphically to determine whether any obvious errors exist in data entry or logic. Figure 5.3 provides a visual comparison of the ratings of each of five attributes for four systems. The corresponding data are displayed in Table 5.5.

At this point in the analysis, two sets of numbers have been developed for each attribute i: the normalized weights, w_i, and the perceived effectiveness assigned to each system j for each attribute i, s_{ij}. To arrive at a composite measure of effectiveness, T_j, for each system j, we could use Eq. (5.1). The highest value of T would indicate the system with the best overall performance.

If this system were within budget and none of its attribute values were below a predetermined threshold, then it would represent the likely choice. Nevertheless, effectiveness alone does not tell the entire story, and, whenever possible, the analysis should

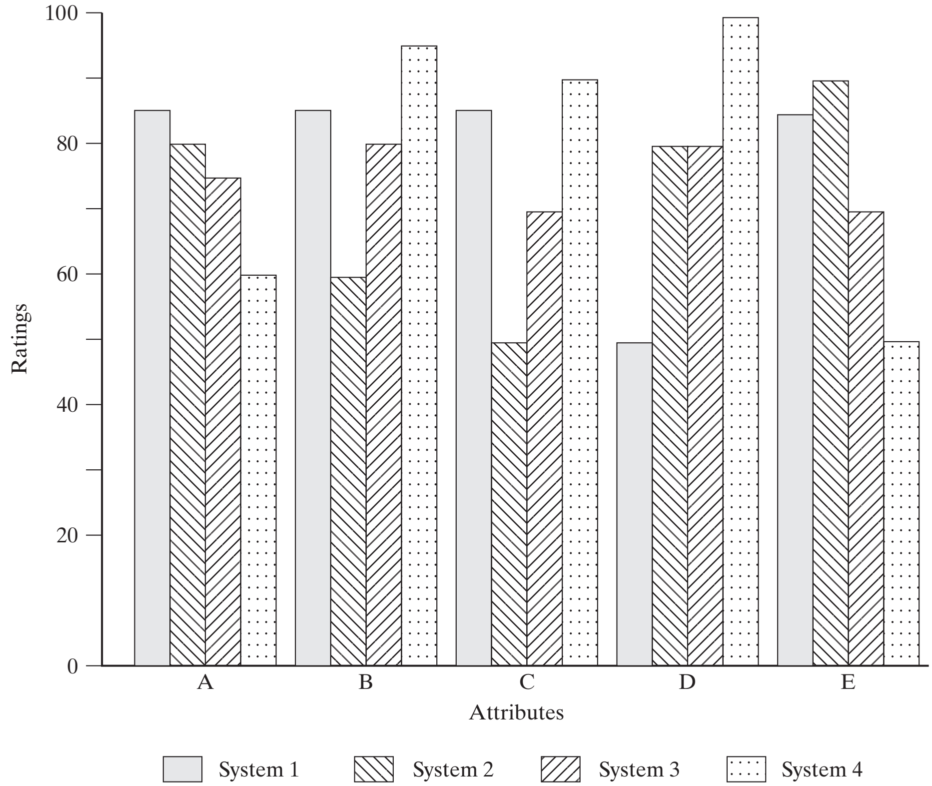

Figure 5.3 Relative effectiveness of systems.

TABLE 5.5 Data for C-E Analysis

Attribute	Weight	System 1 EFF	System 1 WT	System 2 EFF	System 2 WT	System 3 EFF	System 3 WT	System 4 EFF	System 4 WT
A. Efficiency	0.32	85	27.2	80	25.6	75	24.0	60	19.2
B. Speed	0.24	85	20.4	60	14.4	80	19.2	95	22.8
C. User Friendly	0.24	85	20.4	50	12.0	70	16.8	90	21.6
D. Reliability	0.12	50	6.0	80	9.6	80	9.6	99	11.9
E. Expandability	0.08	85	6.8	90	7.2	70	5.6	50	4.0
Total effectiveness			80.8		68.8		75.2		79.5
Costs			$450K		$250K		$300K		$350K

be extended to include costs as well. In a similar manner, cost factors can be combined into a single measure to compare with effectiveness. Typically, procurement, installation, and maintenance costs are considered. When the planning horizon extends beyond one year, the effects of time should be included through appropriate discounting. Table 5.5 contains this information.

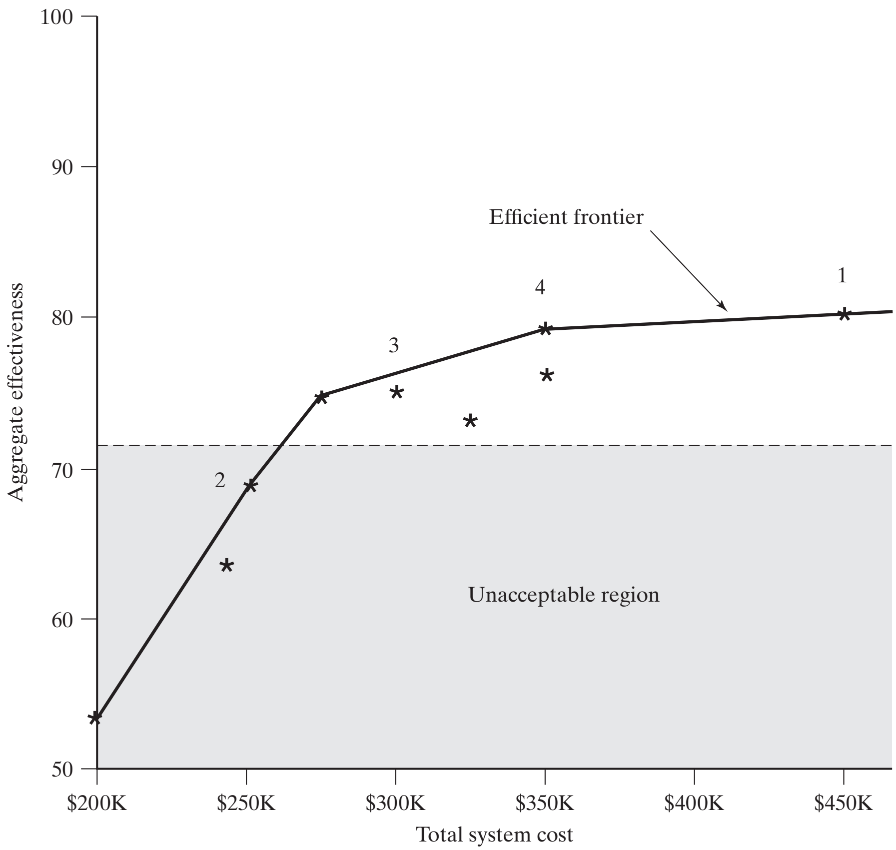

Figure 5.4 Relationship between system effectiveness and cost.

The final step of the C-E methodology compares system effectiveness and costs. A graphical representation may be helpful in this regard. Figure 5.4 plots the two variables for each system (the unlabeled points represent systems not contained in Table 5.5). The outer envelope denotes the *efficient frontier*. Any system that is not on this curve is dominated by one or a combination of two or more systems, implying that it is inferior from both a cost and an effectiveness point of view. Systems that fall below the dashed line (predetermined threshold) are arbitrarily deemed unacceptable. Finally, note the relationship between systems 1 and 4. Although system 1 has the highest effectiveness rating, it is only marginally better than system 4. The fact that it is almost 30% more expensive, however, makes its selection problematic, as an incremental analysis would indicate.

5.6 ISSUES RELATED TO RISK

In designing, building, and operating large systems, engineers must address such questions as, "What can go wrong, and how likely is it to happen?" "What range of consequences might there be, when, and how could they be averted or mitigated?" "How much risk should be tolerated or accepted during normal operations, and how can it be measured, reduced, and managed?"

Formal risk analysis attempts to quantify answers to these questions (Bell 1989, Kaplan and Garrick 1981). In new systems, it is coming to be accepted as a way of comparing the risks inherent in alternative designs, spotlighting the high-risk portion of a system, and pointing up techniques for attenuating those risks. For older systems, risk analysis conducted after systems have been built and operated have often revealed crucial design faults. One such fault cost the lives of 167 workers on the British oil production platform Piper Alpha in the North Sea several years ago. A simple gas leak in the $3 billion rig led to a devastating explosion. The platform had a vertical structure, and risk analysis was not done on the design. Workers' accommodations were on top, above the lower compartments, which housed equipment for separating oil from natural gas. The accommodations were thought to be immune to mishap, but as a post-accident computer simulation revealed, the energy from the explosion in the lower level coupled to the platform's frame. Stress waves were dissipated effectively into the water below, but in short order, reflections at the steel–air interface at the upper levels expanded, weakened, and shattered the structure. In contrast, Norwegian platforms, which are designed using government-mandated risk analysis, are long and horizontal like aircraft carriers, with workers' accommodations at the opposite end of the structure from the processing facilities and insulated from them by steel doors.

Analysts define risk as a combination of the probability of an undesirable event and the magnitude of every foreseeable consequence (e.g., damage to property, loss of money, and delay in implementation). The consequences considered can range in seriousness from mild setback to catastrophic. Some related definitions are given in Table 5.6.

The first step in risk analysis is to tabulate the various stages or phases of a system's mission and list the risk sensitivities in each phase, including technical, human,

TABLE 5.6 Some Definitions Related to Risk

Term	Definition
Failure	Inability of a product or system to perform its required function.
Quality Assurance	Probability that a product or system will perform its intended function when tested.
Reliability	Probability that a product or system will perform its intended function for a specified time duration (assuming under normal conditions).
Risk	A blend of the probability of failure and the monetary outcome (or equivalent) associated with failure.
Risk Assessment	Processes and procedures for identifying and quantifying risks.
Risk Management	Techniques used to minimize risk either through reducing the probability of a failure or reducing the impact of a failure.
Uncertainty	A measure of the limits of knowledge in a technical area; for example, uncertainty may be expressed by a statistical confidence interval (a measure of sampling accuracy).

and economic risks. The time at which a failure occurs may mitigate its consequences. For example, a failure in an air traffic control system at a major airport would disrupt local air traffic far more at weeknight rush hour than on a Sunday morning. Similarly, a failure in a chemical processing plant would be more dangerous if it interfered with an intermediate reaction that produced a toxic chemical than if it occurred at a stage when the by-products were more benign.

Next, for each phase of the mission, the system's operation should be diagrammed and the logical relationships of the components and subsystems during that phase determined. The most useful techniques for the job are failure modes and effects analysis (FMEA), event tree analysis, and fault tree analysis (Kumamoto and Henley 2001). The three complement one another, and when taken together, help engineers identify the hazards of a system and the range of potential consequences. The interactions are particularly important because one piece of equipment might be caused to fail by another's failure to, say, supply fuel or current.

For engineers and managers, the chief purpose of risk analysis—defining the stages of a mission, examining the relationships between system parts, and quantifying failure probabilities—is to highlight any weakness in a design and identify those that contribute most heavily to delays or losses. The process may even suggest ways of minimizing or mitigating risk.

A case in point is the probabilistic risk analysis on the U.S. space shuttle's auxiliary power units, completed for NASA in December 1987 by the engineering consulting firm Pickard, Lowe & Garrick. The auxiliary power units, among other tasks, throttle the orbiter's main engines and operate its wing ailerons. NASA engineers and managers, using qualitative techniques, had formerly judged fuel leaks in the three auxiliary fuel units "unlikely" and the risks acceptable, without fully understanding the magnitude of the risks that they accepted, even though a worst-case consequence could be the loss of the vehicle. One of the problems with qualitative assessment is that subjective interpretation of words such as "likely" and "unlikely" allows opportunity for errors in judgment about risk. For example, NASA had applied the word "unlikely" to risks that ranged from 1:250 to 1:20,000.

The probabilistic risk analysis revealed that although the probability of individual leaks was low, there were so many places where leaks could occur that five occurred in the first 24 shuttle missions. Moreover, in the ninth mission on November 28, 1983 the escaping fuel self-ignited while the orbiter was hurtling back to earth and exploded after it had landed.

The probabilistic analysis pinpointed the fact that an explosion was more likely to occur during landing than during launch, when the auxiliary power units are purged with nitrogen to remove combustible atmospheric oxygen. It also suggested several ways of reducing the risk, such as changing the fuels or placing fire barriers between the power units.

5.6.1 Accepting and Managing Risk

Once the risks are determined, managers must decide what levels are acceptable on the basis of economic, political, and technological judgments. The decision can be controversial because it necessarily involves subjective judgments about costs and benefits of the project, the well-being of the organization, and the potential damage or liability.

Naturally, risk is tolerated at a higher level if the payoffs are high or critical to the organization. In the microcomputer industry, for example, where product lifetimes may be no greater than 1 or 2 years and new products and upgrades are being introduced continually, companies must keep pace with the competition or forfeit market share. Whatever the level of risk finally judged acceptable, it should be compared with and, if necessary, used to adjust the risks calculated to be inherent in the project. The probability of failure may be reduced further by redundant or standby subsystems or by parallel efforts during development. Also, managers should prepare to counter the consequences of failure or setbacks by devising contingency plans or emergency procedures.

5.6.2 Coping with Uncertainty

Two sources of uncertainty still need to be considered: one intrinsic in probability theory and the other born of all-too-human error. First, the laws of chance exclude the prediction of when and where a particular failure may occur. That remains true even when enough statistical information about the system's operation exists for a reliable estimate of how likely it is to fail. The probability of failure, itself, is surrounded by a band of uncertainty that expands or shrinks depending on how much data are available and how well the system is understood. This statistical level of confidence is usually expressed as a standard deviation about the mean or a related measure. Finally, if the system is so new that few or no data have been recorded for it and analogous data from similar systems must be used to get a handle on potential risks, then there is uncertainty over how well the estimate resembles the actual case.

At the human interface, the challenge is to design a system so that it will not only operate as it should, but also leave the operator little room for erroneous judgment. Additional risk can be introduced if a designer cannot anticipate which information an operator may need to digest and interpret under the daily pressures of the job, especially when an emergency starts to develop.

From an operational point of view, poor design can introduce greater risk, sometimes with tragic consequences. After the U.S.S. *Vincennes* on July 3, 1988, mistook Iran Air Flight 655 for an enemy F-14 and shot down the airliner over international waters in the Persian Gulf, Rear Admiral Eugene La Roque blamed the calamity on the bewildering complexity of the Aegis radar system. He is quoted as saying that "we have scientists and engineers capable of devising complicated equipment without any thought of how it will be integrated into a combat situation or that it might be too complex to operate. These machines produce too much information and don't sort the important from the unimportant. There's a disconnection between technical effort and combat use."

All told, human behavior is not nearly as predictable as that of an engineered system. Today, there are many techniques for quantifying with fair reliability the probability of slips, lapses, and misperceptions. Still, remaining uncertainty in the prediction of individual behavior contributes to residual risk in all systems and projects.

5.6.3 Non-probabilistic Evaluation Methods when Uncertainty Is Present

When considering a capital investment, there are four major sources of uncertainty that are nearly always present in engineering economic studies:

1. Inaccuracy of the cash flow estimates, especially benefits related to new products or technology.
2. Relationship between type of business and future health of the company. Certain lines of business are inherently unstable, such as oil drilling, entertainment, and luxury goods.
3. Type of physical plant and equipment involved. Some structures have definite economic lives and market values, whereas others are unpredictable. The cost of specialized plants and equipment is often difficult to estimate, especially for first-time projects.
4. Length of the project and study period. As the length increases, so does the variability in the estimates of operations and maintenance costs, as well as presumed benefits.

As discussed in Chapter 3, breakeven analysis and sensitivity analysis are two simple ways of addressing uncertainty. Other approaches include *scenario analysis*, *risk-adjusted MARR*, and *reduction of useful life*. Breakeven analysis is commonly used when the selection process is dependent on a single factor, such as capacity, sales, or ROR, and only two alternatives are being considered. In this case, we identify the one whose marginal benefit is greater and solve for the value of the factor that makes the two alternatives equally attractive. Above the breakeven point, the alternative with the greater marginal benefit is preferable.

Sensitivity analysis is aimed at assessing the relative magnitude of a change in the measure of interest, such as NPV, caused by one or more changes in estimated factors, such as interest rate and useful life. The results can often be visualized graphically, as shown in the following example.

Example 5-5 (Sensitivity Analysis)

Your office is considering the acquisition of a new workstation, but there is some uncertainty about which model to buy and the expected cash flows. Before making the investment, your supervisor has asked you to investigate the NPV of a generic system over a range of ± \$40% with respect to (a) capital investment, (b) annual net cash flow, (c) salvage value, and (d) useful life. The following data characterize the investment:

Capital investment	−\$11,500
Annual revenues	\$5,000
Annual expenses	−\$2,000
Estimated salvage value	\$1,000
Useful life	6 years
MARR	10%

Solution The first step is to compute the NPV for the given data.

$$\text{Baseline NPV} = -\$11{,}500 + \$3{,}000(P/A, 10\%, 6) + \$1{,}000(P/F, 10\%, 6) = \$2{,}130$$

(a) When initial investment varies by $\pm p\%$,

$$NPV(p) = -(1 + p/100)(\$11{,}500) + \$3{,}000(P/A, 10\%, 6) + \$1000(P/F, 10\%, 6)$$

(b) When revenues vary by $\pm p\%$,

$$NPV(p) = -\$11{,}500 + (1 + p/100)(\$3{,}000)(P/A, 10\%, 6) + \$1{,}000(P/F, 10\%, 6)$$

(c) When salvage value varies by $\pm p\%$,

$$NPV(p) = -\$11{,}500 + \$3{,}000(P/A, 10\%, 6) + (1 + p/100)(\$1{,}000)(P/F, 10\%, 6)$$

(d) When the useful life varies by $\pm p\%$,

$$NPV(p) = -\$11{,}500 + \$3{,}000[P/A, 10\%, 6(1 + p/100)] + \$1{,}000[P/F, 10\%, 6(1 + p/100)]$$

Plotting the functions NPV(p) for $-40\% \leq p \leq +40\%$, gives rise to what is known as a spider chart, as shown in Figure 5.5. A frame of references is provided by the baseline result. ■

Scenario analysis, or optimistic-pessimistic estimation, is used to establish a range of values for the measure of interest. Typically, the optimistic estimate is defined to have only a 5% chance of being exceeded by the actual outcome, whereas the pessimistic estimate is defined so that it is exceeded approximately 95% of the time.

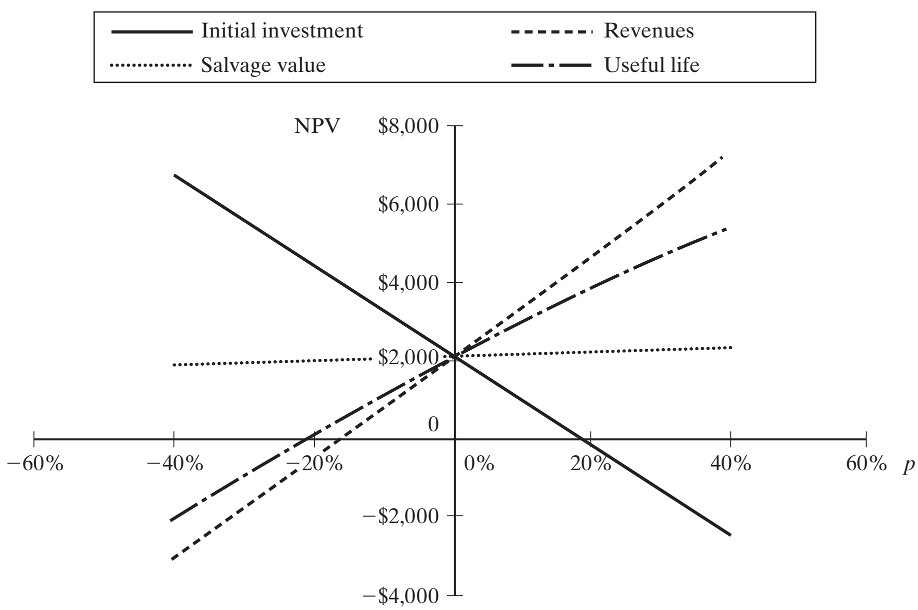

Figure 5.5 Spider chart for sensitivity analysis.

Example 5-6 (Scenario Analysis)

An ultrasound inspection device for which optimistic, most likely, and pessimistic estimates are given below is being considered for purchase. If the MARR is 8%, then what course of action would you recommend? Base your answer on net annual worth (NAW).

Measure	Optimistic (O)	Most likely (M)	Pessimistic (P)
Capital investment	−$150,000	−$150,000	−$150,000
Annual revenues	$110,000	$70,000	$50,000
Annual costs	−$20,000	−$43,000	−$57,000
Salvage value	$0	$0	$0
Useful life	18 years	10 years	8 years
NAW	$73,995	$4,650	−$33,100

Solution Whether to accept or reject the purchase is somewhat arbitrary, and would depend strongly on the decision maker's attitude toward risk. A conservative approach would be to

accept the investment if NAW(P) $>$ 0
reject the investment if NAW(O) $<$ 0
or do more analysis

Applying this rule tells us that more information is needed. One possible approach at this point is to evaluate all combinations of outcomes and see how many are above some threshold, say $50,000, and below, say $0. Following this idea, we note that annual revenues, annual costs, and the useful life are the independent inputs that vary from one scenario to another. This means that there are $3^3 = 27$ possible outcomes. The NAW of each is listed in the table below rounded to the nearest $1,000. For example, the first block of 9 data entries represents the results when the annual revenues and useful life are varied over the three scenarios, whereas the annual costs are held fixed at the optimistic estimate.

	Annual costs								
	O			M			P		
	Useful life			Useful life			Useful life		
Annual revenues	O	M	P	O	M	P	O	M	P
O	74	68	64	51	45	41	37	31	27
M	34	28	24	11	5	1	−3	−9	−13
P	14	8	4	−9	−15	−19	−23	−29	−33

The computations indicate that the NAW $>$ $50,000 in 4 of 27 scenarios and NAW $<$ $0 in 9 out of 27. Coupled with the results for the strictly optimistic, most likely, and pessimistic scenarios, this might not be sufficient for a positive decision. ■

The risk-adjusted MARR method involves the use of higher discount rates for those alternatives that have a relatively high degree of uncertainty and lower discount rates for projects that are at the other end of the spectrum. A higher-than-usual MARR implies that distance cash flows are less important than current or near-term cash flows. This approach is widely used in practice but contains many pitfalls, the most serious being that the uncertainty is not made explicit. As a consequence, the analyst should first try other methods.

Example 5-6 (Risk-Adjusted MARRs)

As an analyst for an investment firm, you are considering two alternatives that have the same initial cost and economic life but different cash flows, as indicated in the table below. Both are affected by uncertainty to some degree; however, alternative P is thought to be more uncertain than alternative Q. If the firm's risk-free MARR is 10%, then which is the better investment?

End-of-year, k	Alternative P	Alternative Q
0	−$160,000	−$160,000
1	$120,000	$20,827
2	$60,000	$60,000
3	$0	$120,000
4	$60,000	$60,000

Solution At the risk-free MARR of 10%, both alternatives have the same NPV = $39,659. All else being equal, alternative Q should be chosen because it is less uncertain. To take into account the degree of uncertainty, we now use a prescribed risk-adjusted MARR of 20% for P and 17% for Q. Performing the same computations, we get

$$\begin{aligned} NPV_P(20\%) &= -\$160{,}000 + \$120{,}000(P/F, 20\%, 1) + \$60{,}000(P/F, 20\%, 2) \\ &\quad + \$60{,}000(P/F, 20\%, 4) = \$10{,}602 \\ NPV_Q(17\%) &= -\$160{,}000 + \$20{,}827(P/F, 17\%, 1) \\ &\quad + \$60{,}000(P/F, 17\%, 2) + \$120{,}000(P/F, 17\%, 3) \\ &\quad + \$60{,}000(P/F, 17\%, 4) = \$8{,}575 \end{aligned}$$

implying that alternative P is preferable. This is a reversal of the first result.

Figure 5.6 plots the NPV of the two alternatives as a function of the MARR. The breakeven point is 10%. For MARRs beyond 10%, P is always the better choice. ■

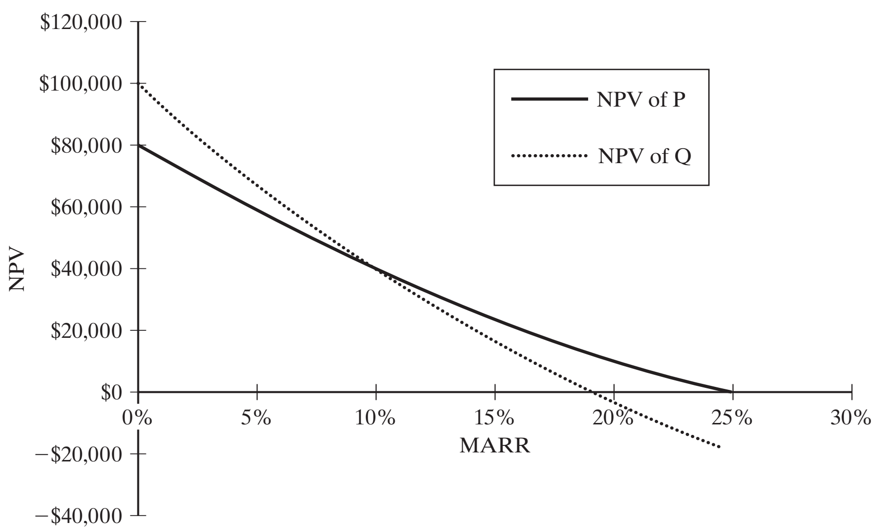

Figure 5.6 NPV comparisons for risk-adjusted MARRs.

Another technique used to compensate for uncertainty is based on truncating the project life to something less than its estimated useful life. By dropping from consideration those revenues and costs that may occur after the reduced study period, heavy emphasis is placed on rapid recovery of investment capital in the early years. Consequently, this method is closely related to the payback technique discussed in Chapter 3.

Implementation can by carried out in one of two ways. The first is to reduce the project life by some percentage and discard all subsequent cash flows. The NPV of the alternatives are then compared for the shortened life. The second is to determine the minimal life of the project that will produce an acceptable ROR. If this life is within the expectations of the decision maker, say, in terms of the maximum payback period, then the project is viewed as acceptable.

Example 5-7 (Reduction of Useful life)

A proposed new product line requires $2,000,000 in capital over a 2-year period. Estimated revenues and expenses over the product's anticipated 8-year commercial life are shown in Table 5.7. The company's maximum payback period is 4 years (after taxes), and its effective tax rate is 40%. The investment will be depreciated by the modified accelerated cost recovery system (MACRS) using a 5-year class life.

The company's management is concerned about the financial attractiveness of this venture should unforeseen circumstances arise (e.g., loss of market or technological breakthroughs by the competition). They are very leery of investing a large amount of capital in this product because competition is fierce and companies that wait to enter the market may be able to purchase improved technology. You have been given the task of assessing the downside profitability of the product when the primary concern is its staying power (life) in the marketplace. If the after-tax MARR is 15%, then what do you recommend? State any necessary assumptions.

Solution The first step is to compute the after-tax cash flow (ATCF). To do this, we assume that the salvage value of the investment is zero, that the MACRS deductions are unaffected by the useful life of the product, and that they begin in the first year of commercial operations (year 1). The results are given in Table 5.7.

Next we compute the ROR of the investment as a function of the product's presumed life. For the first 2 years, the undiscounted ATCF is negative so there is no ROR. In year 3, the ROR is 10.3% and climbs to 29.4% if the full commercial life is realized. A plot of the after-tax ROR versus the actual life of the product line is shown in Figure 5.7. To make

TABLE 5.7 Data and Results for Reduction of Useful Life Example

	End of year ($M)									
Cash flows	−1	0	1	2	3	4	5	6	7	8
Initial investment	−0.9	−1.1	0	0	0	0	0	0	0	0
Annual revenues	0	0	1.8	2	2.1	1.9	1.8	1.8	1.7	1.5
Annual expenses	0	0	−0.8	−0.9	−0.9	−0.9	−0.8	−0.8	−0.8	−0.7
ATCF	−0.9	−1.1	0.76	0.92	0.88	0.7	0.7	0.65	0.54	0.48
ROR	—	—	—	—	10.3%	18.6%	23.6%	26.6%	28.3%	29.4%

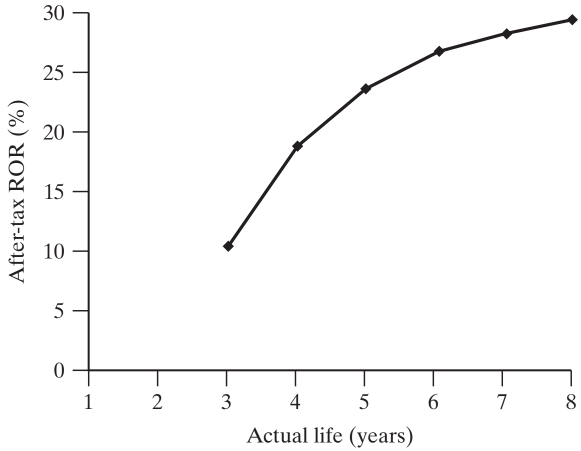

Figure 5.7 After-tax parametric analysis for product.

at least 15% per year after taxes, the product line must last 4 or more years. It can be quickly determined from the data in the table that the simple payback period is 3 years. Consequently, this venture would seem to be worthwhile as long as its actual life is at least 4 years. ■

5.6.4 Risk-Benefit Analysis

Risk-benefit analysis is a generic term for techniques that encompass risk assessment and the inclusive evaluation of risk, costs, and benefits of alternative projects or policies. Like other quantitative methods, the steps in risk-benefit analysis include specifying objectives and goals for the project options, identifying constraints, defining the scope and limits for the study itself, and developing measures of effectiveness of feasible alternatives. Ideally, these steps should be completed in conjunction with a responsible decision maker, but, in many cases, this is not possible. It therefore is incumbent upon the analyst to take exceptional care in stating assumptions and limitations, especially because risk-benefit analysis is frequently controversial.

The principal task of this methodology is to express numerically, insofar as possible, the risks and benefits that are likely to result from project outcomes. Calculating these outcomes may require scientific procedures or simulation models to estimate the likelihood of an accident or mishap, and its probable consequences. Finally, a composite assessment that aggregates the disparate measures associated with each alternative is carried out. The conclusions should incorporate the results of a sensitivity analysis in which each significant assumption or parameter is varied in turn to judge its effect on the aggregated risks, costs, and benefits.

One approach to risk assessment is based on the three primary steps of systems engineering, as shown in Figure 5.8 (Sage and White 1980). These involve the *formulation*, *analysis*, and *interpretation* of the impacts of alternatives on the needs, and the institutional and value perspectives of the organization. In risk formulation,

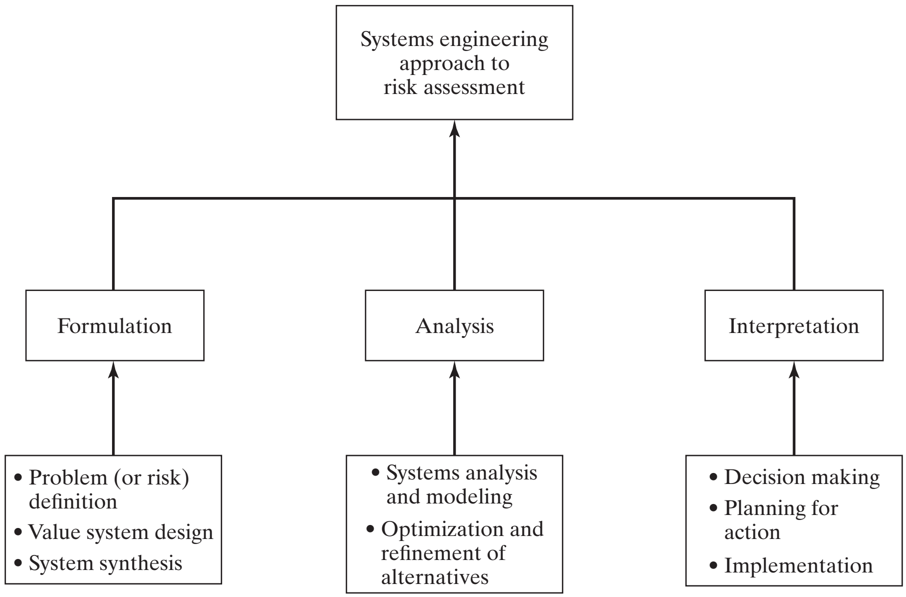

Figure 5.8 Systems engineering approach to risk assessment.

we determine or identify the types and scope of the anticipated risks. A variety of systemic approaches, such as the nominal group technique, brainstorming, and the Delphi method, are especially useful at this stage (Makridakis et al. 1997). It is important to identify not only the risk elements but also the elements that represent needs, constraints, and alternatives associated with possible risk reduction with and without technological innovation. This can be done only in accordance with a value system.

In the analysis step, we forecast the failures, mishaps, and other consequences that might accompany the development and implementation of the project. This will include estimation of the probabilities of outcomes and the associated magnitudes. Many methods, such as cross-impact analysis, interpretive structural modeling, economic modeling, and mathematical programming, are potentially useful at this step. The inputs are those elements determined during problem formulation.

In the final step, we attempt to give an organizational or political interpretation to the risk impacts. This includes specification of individual and group utilities for the final evaluation. Decision making follows. The economic methods of B/C analysis are most commonly used at this point. Extension to include the results of the risk assessment, however, is not trivial. A principal problem is that risks and benefits may be measured in different units and therefore may not be strictly additive. Rather than trying to convert everything into a single measure, it may be better simply to present the risks and net benefits in their respective units or categories.

To aid in interpreting the results, risk-return graphs, similar to the C-E graph displayed in Figure 5.4, can be drawn to highlight the efficient frontier. Risk profiles may also be useful. Figure 5.9 illustrates a perspective provided by a risk analysis profile. Projects

1 and 2 are most likely to yield lifetime profits of $100,000 and $200,000, respectively. So, for some decision makers, project 2 might be considered superior if the B/C ratio were favorable. Nevertheless, it is worth probing the data a bit more. Project 2 has a finite probability of returning a loss but a higher expected profit than project 1. The probability that project 2 will yield lower profits than project 1 is known as the downside risk and can be found by a breakeven analysis. Given these data, a risk-averse person would be inclined to select project 1, which has a big chance (0.50) of realizing a moderate profit of at least $100K, with little chance of anything much less or much greater; that is, project 1 has a small variance. A gambler would lean toward project 2, which has a small chance at a very large profit.

The types of risk profiles contained in Figure 5.9 make the consequences of outcomes more visible and enable a decision maker to behave in a manner consistent with his or her attitude toward risk, be it conservative or freewheeling. Generally speaking, the amount of data needed to construct a graph such as Figure 5.9 is small

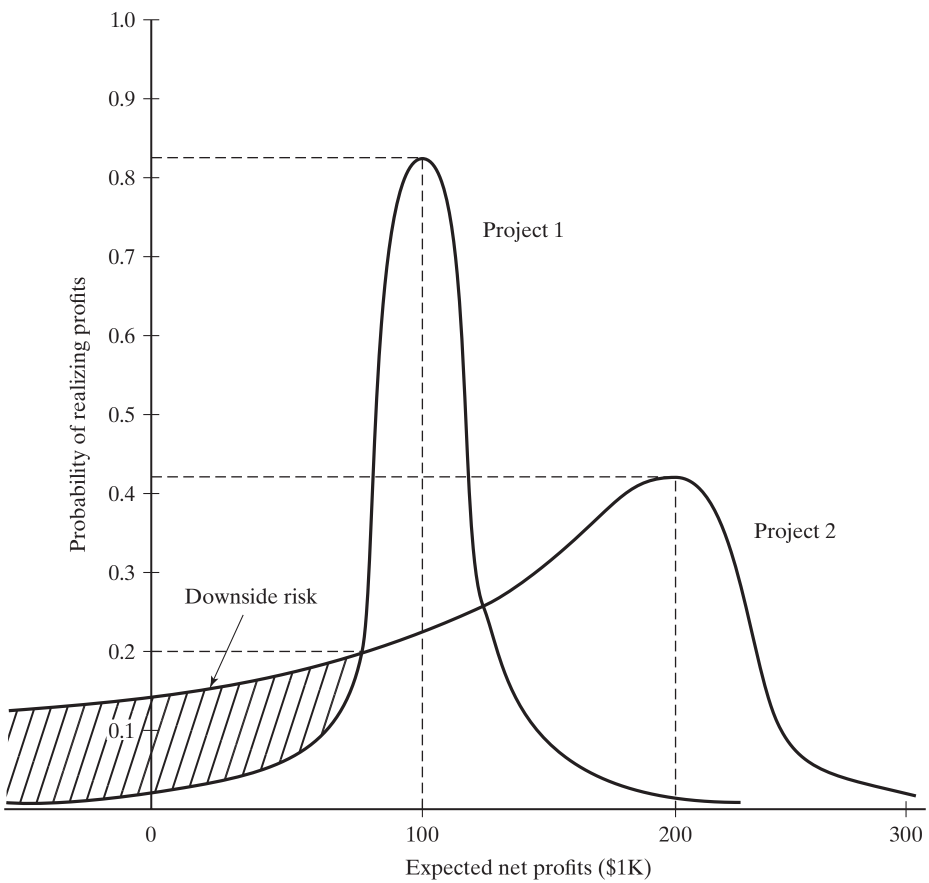

Figure 5.9 Illustration of risk profile.

and relatively easy to obtain if a historical database exists. It can be solicited from the engineers and marketing personnel who are familiar with an organization's previous projects. If no collective experience can be found within the organization, then more subjective or arbitrary procedures would be required. A number of software packages are available to help with the construction effort.

5.6.5 Limits of Risk Analysis

The ultimate responsibility for project selection and implementation goes beyond any risk assessment and rests squarely on the shoulders of top management. Although formal analysis can reveal unexpected vulnerabilities in large complex projects, it remains an academic exercise unless the managers take the results seriously and ensure that the project is managed conscientiously. Safety must be designed into a system from the beginning, and good operating practice is essential to the success of any continuing program of risk management. Controversy still rages, for example, over whether the vent-gas scrubber—a key element in the safety system of the Union Carbide pesticide plant in Bhopal, India that exploded in 1984, killing more than 3,000 people—was designed adequately to handle a true emergency. But even if it had been, neither it nor a host of other safety features were maintained in working order.

For risks to be ascertained at all, project managers must agree on the value of assessing them in engineering design. It has often been said that you can degrade the performance of a system by poor quality control, but you cannot enhance a poor design by good quality control. At the point at which project managers are responsible for crucial decisions, risk assessment is one more tool that can help them weigh alternatives so that their choices are informed and deliberate rather than isolated or worse, repetitions of past mistakes.

5.7 DECISION TREES

Decision trees, also known as decision flow networks and decision diagrams, may depict and facilitate analysis of problems that involve sequential decisions and variable outcomes over time. They make it possible to look at a large, complicated problem in terms of a series of smaller simple problems while explicitly considering risk and future consequences.

A decision tree is a graphical method of expressing, in chronological order, the alternative actions that are available to a decision maker and the outcomes determined by chance. In general, they are composed of the following two elements, as shown in Figure 5.10.

1. *Decision nodes.* At a decision node, usually designated by a square, the decision maker must select one alternative course of action from a finite set of possibilities. Each possible course of action is drawn as a branch emanating from the right side of the square. When there is a cost associated with an alternative, it is written along the branch. Each alternative branch may result in a payoff, another decision node, or a chance node.

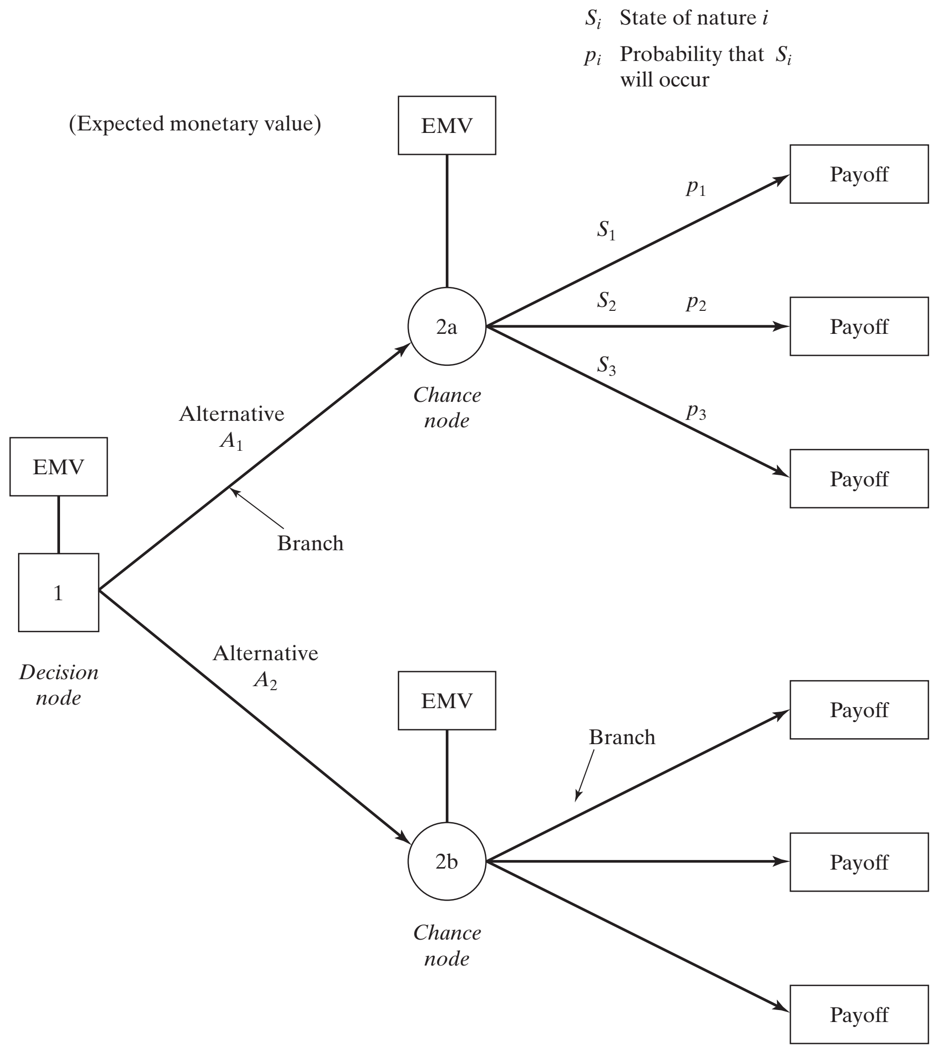

Figure 5.10 Structure of decision tree.

2. *Chance nodes.* A chance node, designated as a circle, indicates that a random event is expected at this point in the process; that is, one of a finite number of states of nature may occur. The states of nature are shown on the tree as branches to the right of the chance nodes. The corresponding probabilities are similarly written above the branches. The states of nature may be followed by payoffs, decision nodes, or more chance nodes.

Constructing a Tree. A tree is started on the left of the page with one or more decision nodes. From these, all possible alternatives are drawn branching out to the right.

Then, a chance node or second decision node, associated with either subsequent events or decisions, respectively, is added. Each time a chance node is added, the appropriate states of nature with their corresponding probabilities emanate rightward from it. The tree continues to branch from left to right until the final payoffs are reached. The tree shown in Figure 5.10 represents a single decision with two alternatives, each leading to a chance node with three possible states of nature.

Finding a Solution. To solve a tree, it is customary to divide it into two segments: (1) chance nodes with all their emerging states of nature (Figure 5.11a) and (2) decision nodes with all their alternatives (Figure 5.11b). The solution process starts with those segments that end in the final payoffs, at the right side of the tree, and continues to the left, segment by segment, in the reverse order from which it was drawn.

1. *Chance node segments.* The expected monetary value (EMV) of all of the states of nature that emerge from a chance node must be computed (multiply payoffs by probabilities and sum the results). The EMV is then written above the node inside a rectangle (labeled a "position value" in Figure 5.10). These expected values are considered as payoffs for the branch to the immediate left.
2. *Decision node segments.* At a decision point, the payoffs given (or computed) for each alternative are compared and the best one is selected. All others are discarded. The corresponding branch of a discarded alternative is marked by the symbol ‖ to indicate that the path is suboptimal.

This procedure is based on principles of dynamic programming and is commonly referred to as the "rollback" step. It starts at the endpoints of the tree where the

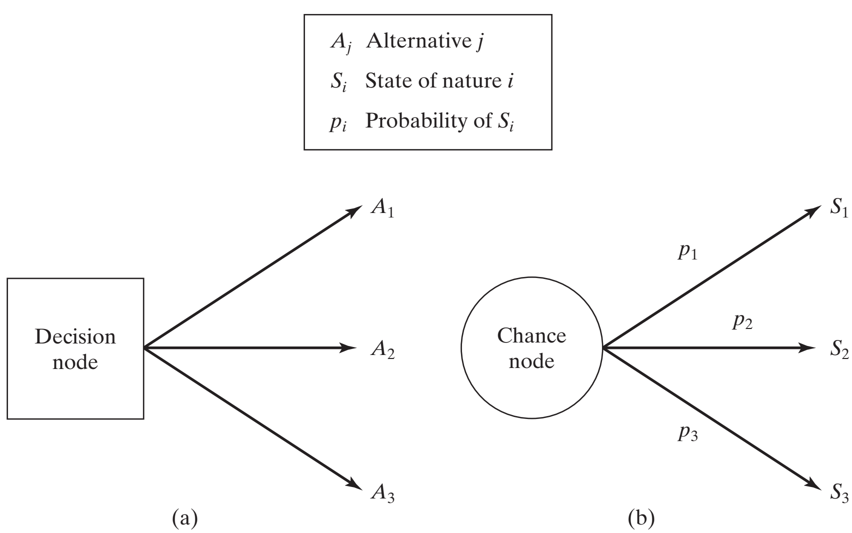

Figure 5.11 Segments of tree.

expected value at each chance node and the optimal value at each decision node are computed. Suboptimal choices at each decision node are dropped, with the rollback continuing until the first node of the tree is reached. The optimal policy is recovered by identifying the choices made at each decision node that maximize the value of the objective function from that point onward.

Example 5-8 (Deterministic Replacement Problem)

The most basic form of a decision tree occurs when each alternative results in a single outcome; that is, when certainty is assumed. The replacement problem defined in Figure 5.12 for a 9-year planning horizon illustrates this situation. The numbers above the branches represent the returns per year for the specified period should the replacement be made at the corresponding decision point. The numbers below the branches are the costs associated with that decision. For example, at node 3, keeping the machine results in a return of \$3K per year for 3 years, and a total cost of \$2K.

As can be seen, the decision as to whether to replace the old machine with the new machine does not occur just once, but recurs periodically. In other words, if the decision is made to keep the old machine at decision point 1, then later, at decision point 2, a choice again has to be made. Similarly, if the old machine is chosen at decision point 2, then a choice has to be made at decision point 3. For each alternative, the cash inflow and duration of the project is shown above the branch, and the cash investment opportunity cost is shown below the branch. At decision point 2, for example, if a new machine is purchased for the remaining 6 years, then the net benefits from that point on are (6 yr)(\$6.5K/yr) returns −\$17.0K opportunity cost = \$22.0K net benefits. Alternatively,

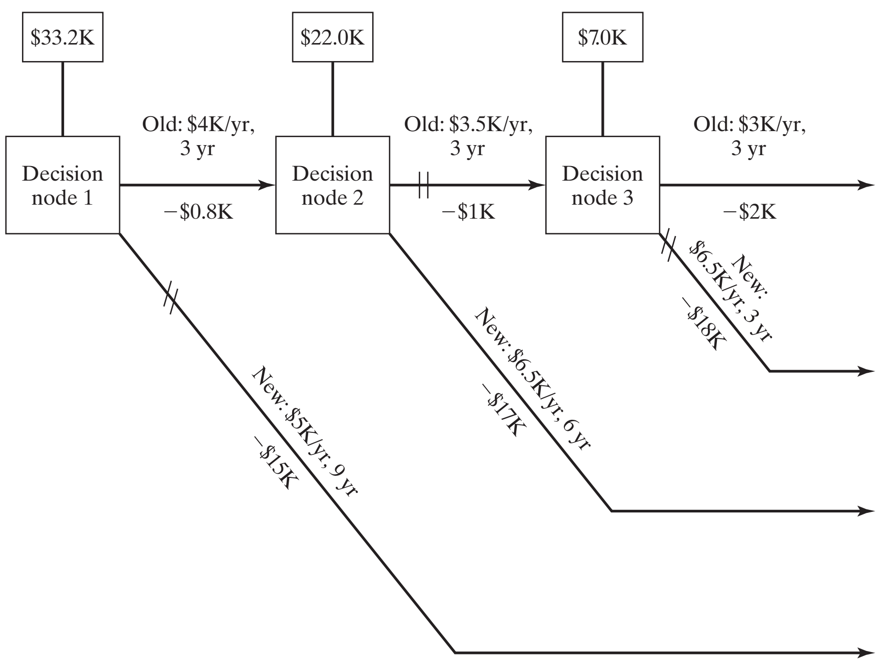

Figure 5.12 Deterministic replacement problem.

TABLE 5.8 Computational Results for Replacement Problem in Figure 5.12

Decision point	Alternative	Monetary outcome		Choice
3	Old	(\$3K/yr)(3 yr) − \$2K	= \$7.0K	Old
	New	(\$6.5K/yr)(3 yrs) − \$18K	= \$1.5K	
2	Old	\$7K + (\$3.5K/yr)(3 yr) − \$1K	= \$16.5K	
	New	(\$6.5K/yr)(6 yr) − \$17K	= \$22.0K	New
1	Old	\$22.0K + (\$4K/yr)(3 yr) − \$0.8K	= \$33.2K	Old
	New	(\$5K/yr)(9 yr) − \$15K	= \$30.0K	

■

if the old machine is kept at decision point 2, then we have (\$3.5K/yr)(3 yr) returns −\$1.0K opportunity cost +\$7K net benefits associated with decision point 3 = \$16.5K net benefits.

For this problem, one is concerned initially with which alternative to choose at decision point 1, but an intelligent choice here should take into account the later alternatives and decisions that stem from it. Hence, the correct procedure in analyzing this type of problem is to start at the most distant decision point, determine the best alternative and quantitative result of that alternative, and then roll back to each successive decision point, repeating the procedure until finally the choice at the initial or present decision point is determined. By this procedure, one can make a present decision that directly takes into account the alternatives and expected decisions of the future.

For simplicity in this example, timing of the monetary outcomes first will be neglected, which means that a dollar has the same value regardless of the year in which it occurs. Table 5.8 displays the necessary computations and implied decisions. Note that the monetary outcome of the best alternative at decision point 3 (\$7.0K for the "old") becomes part of the outcome for the old alternative at decision point 2. That is, if the decision at node 2 is to continue to use the current machine rather than replace it, then the monetary value associated with this decision equals the EMV at node 3 (\$7K) plus the transition benefit from node 2 to 3 (\$3.5/yr × 3 yr − \$1K = \$9.5K), or \$16.5K. Similarly, the best alternative at decision point 2 (\$22.0K for the "new") becomes part of the outcome for the "old" alternative at decision point 1.

By following the computations in Table 5.7, one can see that the answer is to keep the old machine now and plan to replace it with a new machine at the end of 3 years (at decision point 2). In practice, an organization would re-evaluate the decision on a rolling, annual basis and may, in fact, replace the machine prior to three years or may delay machine replacement beyond three years. ■

Example 5-9 (Timing Considerations)

For decision tree analyses, which involve working from the most distant decision point to the nearest decision point, the easiest way to take into account the timing of money is to use the present value approach and thus discount all monetary outcomes to the decision points in question. To demonstrate, Table 5.9 gives the computations for the same replacement problem of Figure 5.9 using an interest rate of 12% per year.

Note from Table 5.8 that when taking into account the effect of timing by calculating PWs at each decision point, the indicated choice is not only to keep the old at decision point 1, but also to keep the old at decision points 2 and 3. This result is not surprising because the high interest rate tends to favor the alternatives with lower initial investments,

TABLE 5.9 Computations for Replacement Problem with 12% Interest Rate

Decision point	Alternative	Monetary outcome		Choice
3	Old	$\$3K(P/A, 12\%, 3) - \$2K$ $= \$3K(2.402) - \$2K$	$= \$5.21K$	Old
	New	$\$6.5K(P/A, 12\%, 3) - \$18K$ $= \$6.5K(2.402) - \$18K$	$= -\$2.39K$	
2	Old	$\$3.5K(P/A, 12\%, 3) - \$1K$ $+ \$5.21K(P/F, 12\%, 3)$ $= \$3.5K(2.402) - \$1K$ $+ \$5.21K(0.7118)$	$= \$11.11K$	Old
	New	$\$6.5K(P/A, 12\%, 6) - \$17K$ $= \$6.5K(4.111) - \$17K$	$= \$9.72K$	
1	Old	$\$4K(P/A, 12\%, 3) - \$0.8K$ $+ \$11.11K(P/F, 12\%, 3)$ $= \$4K(2.402) - \$0.8K$ $+ \$11.11K(0.7118)$	$= \$16.71K$	Old
	New	$\$5.0K(P/A, 12\%, 9) - \$15K$ $= \$5.0K(5.328) - \$15K$	$= \$11.64K$	

and it also tends to place less weight on long-run returns. When the interest rate drops to 10%, the solution is the same as that for Example 5.8. ■

Example 5-10 (Automation Decision Problem with Random Outcomes)

In this problem, the decision maker must decide whether to automate a given process. Depending on the technological success of the automation project, the results will turn out to be poor, fair, or excellent. The net payoffs for these outcomes (expressed in NPVs and including the cost of the equipment) are −\$90K, \$40K, and \$300K, respectively. The initially estimated probabilities that each outcome will occur are 0.5, 0.3, and 0.2. Figure 5.13 is a decision tree depicting this simple situation. The calculations for the two alternatives are

Automate: $-\$90K(0.5) + \$40K(0.3) + \$300K(0.2) = \$27K$

Don't automate: \$0

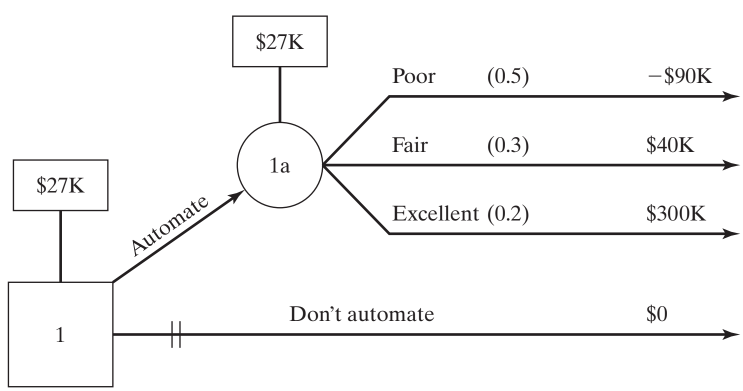

Figure 5.13 Automation problem before consideration of technology study.

These calculations show that the best choice for the firm is to automate on the basis of an expected NPV of $27K versus $0 if it does nothing. Nevertheless, this may not be a clear-cut decision because of the possibility of a $90K loss. Depending on the decision maker's attitude toward risk and confidence in the given data, he or she might want to gather more information.

Suppose that it is possible for a decision maker to conduct a technology study for a cost of $10K. The study will disclose that the enabling technology is "shaky," "promising," or "solid" corresponding to ultimate outcomes of "poor," "fair," and "excellent," respectively. Let us assume that the probabilities of the various outcomes, given the technology study findings, are as shown in Figure 5.14, which is a decision tree for the entire problem.

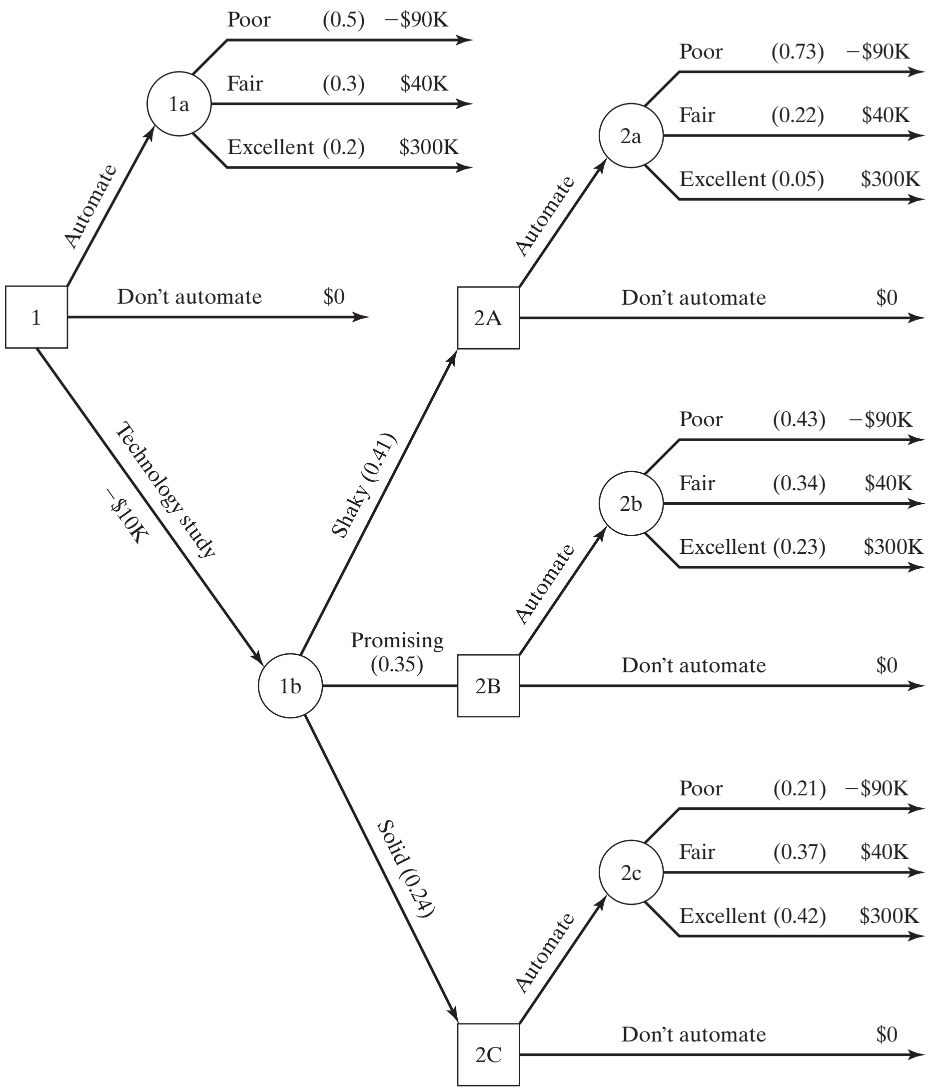

Figure 5.14 Automation problem with technology study taken into account.

This diagram shows expected future events (outcomes), along with their respective cash flows and probabilities of occurrence. The calculation of these probabilities requires the use of Bayes' theorem given in Appendix 5A at the end of this chapter and discussed in a later subsection. To use Bayes' theorem, it is necessary to know all conditional probabilities of the form P(study outcome | state); e.g., P(shaky | poor) or P(excellent | promising).

The rectangular blocks represent (decision) points in time at which the decision maker must elect to take one and only one of the paths (alternatives) available. These decisions are normally based on a quantifiable measure, such as money, which has been determined to be the predominant "cost" or "reward" for comparing alternatives. As mentioned, the general approach is to find the action or alternative that will maximize the expected NPV equivalent of future cash flows at each decision point, starting with the furthest decision point(s) and then rolling back until the initial decision point is reached.

Once again, the chance (circular) nodes represent points at which uncertain events (outcomes) occur. At a chance node, the expected value of all paths that lead (from the right) into the node can be calculated as the sum of the anticipated value of each path multiplied by its respective probability. (The probabilities of all paths that lead into a node must sum to 1.) As the project progresses through time, the chance nodes are automatically reduced to a single outcome on the basis of the "state of nature" that occurs at that time.

The solution to the problem in Figure 5.14 is given in Table 5.10. It can be noted that the alternative "technology study" is shown to be best with an expected NPV of \$34.62K. (To check the solution in Table 5.10, perform the rollback procedure on Figure 5.14, indicating which branches should be eliminated.) ■

5.7.1 Decision Tree Steps

Now that decision trees (diagrams) have been introduced and the mechanics of using them to arrive at an initial decision have been illustrated, the steps involved can be summarized as follows:

1. Identify the points of decision and alternatives available at each point.
2. Identify the points of uncertainty and the type or range of possible outcomes at each point (layout of decision flow network).

TABLE 5.10 Expected NPV Calculations for the Automation Problem

Decision point	Alternative	Expected monetary outcome		Choice
2A	Automate	−\$90K(0.73) + \$40K(0.22) + \$300K(0.05)	= −\$41.9K	
	Don't automate		= \$0	Don't automate
2B	Automate	−\$90K(0.43) + \$40K(0.34) + \$300K(0.23)	= \$43.9K	Automate
	Don't automate		= \$0	
2C	Automate	−\$90K(0.21) + \$40K(0.37) + \$300K(0.42)	= \$121.9K	Automate
	Don't automate		= \$0	
1	Automate	(see calculations above)	= \$27K	
	Don't automate		= \$0	
	Technology study	\$0(0.41) + \$43.9K(0.35) + \$121.9K(0.24) − \$10K	= \$34.62K	Technology study

3. Estimate the values needed to conduct the analysis, especially the probabilities of different outcomes and the costs/returns for various outcomes and alternative actions.
4. Remove all dominated branches.
5. Analyze the alternatives, starting with the most distant decision point(s) and working back, to choose the best initial decision.

In Example 5.9, we used the expected NPV as the decision criterion. However, if outcomes can be expressed in terms of utility units, then it may be appropriate to use the expected utility as the criterion. Alternatively, the decision maker may be willing to express his or her certain monetary equivalent for each chance outcome node and use that as the decision criterion.

Because a decision tree can quickly become unmanageably large, it is often best to start out by considering only major alternatives and outcomes in the structure to get an initial understanding or feeling for the issues. Secondary alternatives and outcomes can then be added if they are significant enough to affect the final decision. Incremental embellishments can also be added if time and resources are available.

5.7.2 Basic Principles of Diagramming

The proper diagramming of a decision problem is, in itself, very useful to the understanding of the problem, as well as being essential to performing the analysis correctly. The placement of decision points and chance nodes from the initial decision point to any subsequent decision point should give an accurate representation of the information that will and will not be available when the decision maker actually has to make the choice associated with the decision point in question. The tree should show the following:

1. All initial or immediate alternatives among which the decision maker wishes to choose.
2. All uncertain outcomes and future alternatives that the decision maker wishes to consider because they may directly affect the consequences of initial alternatives.
3. All uncertain outcomes that the decision maker wishes to consider because they may provide information that can affect his or her future choices among alternatives and hence, indirectly affect the consequences of initial alternatives.

It should also be noted that the alternatives at any decision point and the outcomes at any payoff node must be:

1. Mutually exclusive; that is, no more than one can possibly be chosen.
2. Collectively exhaustive; that is, when a decision point or payoff node is reached, some course of action must be taken.

In Figure 5.14, decision nodes 2A, 2B, and 2C are each reached only after one of the mutually exclusive results of the technology study is known; and each decision node reflects all alternatives to be considered at that point. Furthermore, all possible outcomes to be considered are shown, as the probabilities sum to 1.0 for each chance node.

5.7.3 Use of Statistics to Determine the Value of More Information

An alternative that frequently exists in an investment decision is to conduct further research before making a commitment. This may involve such action as gathering more information about the underlying technology, updating an existing analysis of market demand, or investigating anew future operating costs for particular alternatives.

Once this additional information is collected, the concepts of Bayesian statistics provide a means of modifying estimates of probabilities of future outcomes, as well as a means of estimating the economic value of further investigation study. To illustrate, consider the one-stage decision situation depicted in Figure 5.15, in which each alternative has two possible chance outcomes: "high" or "low" demand. It is estimated that each outcome is equally likely to occur, and that the monetary result expressed as PW is shown above the arrow for each outcome. Again, the amount of investment for each alternative is written below the respective lines. On the basis of these amounts, the calculation of the expected monetary outcomes minus the investment costs (giving expected NPV) is as follows:

$$\text{Old system: } E[\text{NPV}] = \$45\text{M}(0.5) + \$27.5\text{M}(0.5) - \$10\text{M} = \$26.25\text{M}$$
$$\text{New FMS: } E[\text{NPV}] = \$80\text{M}(0.5) + \$48\text{M}(0.5) - \$35\text{M} = \$29.0\text{M}$$

which indicates that the new flexible manufacturing system (FMS) should be selected.

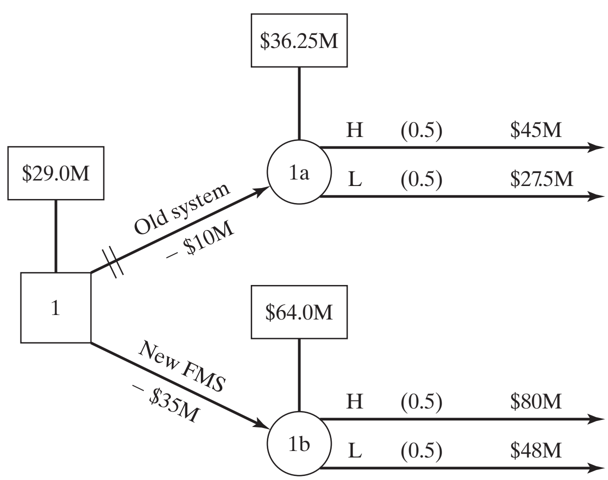

Figure 5.15 One-stage FMS replacement problem.

To demonstrate the use of Bayesian statistics, suppose that one is considering the advisability of undertaking a fresh intensive investigation before deciding on the "old system" versus the "new FMS." Suppose also that this new study would cost $2.0M and will predict whether the demand will be high (h) or low (ℓ). To use the Bayesian approach, it is necessary to assess the conditional probabilities that the investigation (technology study) will yield certain results. These probabilities reflect explicit measures of management's confidence in the ability of the investigation to predict the outcome. Sample assessments are

$$P(h|H) = 0.70, P(\ell|H) = 0.30, P(h|L) = 0.20, \text{and } P(\ell|L) = 0.80,$$

where H and L denote high and low actual demand as opposed to predicted demand. As an explanation, $P(h|H)$ means the probability that the predicted demand is high (h), given that the actual demand will turn out to be high (H).

A formal statement of Bayes' theorem is given in Appendix 5A along with a tabular format for ease of computation. Tables 5.11 and 5.12 use this format for revision of probabilities based on the assessment data above, and the prior probabilities of 0.5 that the demand will be high and 0.5 that the demand will be low [i.e., $P(H) = P(L) = 0.5$]. These probabilities are now used to assess the technology study

TABLE 5.11 Computation of Posterior Probabilities Given That Investigation-Predicted Demand is High (h)

(1) State (actual demand)	(2) Prior probability, P(state)	(3) Confidence assessment, $P(h\|\text{state})$	(4) $= (2) \times (3)$ Posterior joint probability	(5) $= (4)/\sum(4)$ Probability, $P(\text{state}\|h)$
H	0.5	0.70	0.35	0.78
L	0.5	0.20	0.10	0.22
			0.45	

TABLE 5.12 Computation of Posterior Probabilities Given That Investigation-Predicted Demand is Low (ℓ)

(1) State (actual demand)	(2) Prior probability, P(state)	(3) Confidence assessment, $P(\ell\|\text{state})$	(4) $= (2) \times (3)$ Posterior joint probability	(5) $= (4)/\sum(4)$ Probability, $P(\text{state}\|\ell)$
H	0.5	0.30	0.15	0.27
L	0.5	0.80	0.40	0.73
			0.55	

alternative. Figure 5.16 depicts the complete decision tree. Note that demand probabilities are entered on the branches according to whether the investigation indicates high or low demand.

The next step is to calculate the expected outcome for the technology study alternative. This is done by the standard decision tree rollback principle, as shown in Table 5.11. Note that the 0.45 and 0.55 probabilities that the investigation-predicated demand will be high and low, respectively, are obtained from the totals in column (4) of the Bayesian revision calculations depicted in Tables 5.11 and 5.12.

Thus, from Table 5.13, it can be seen that the "new FMS" alternative with an expected NPV of $29.0M is the best course of action by a slight margin. (As an exercise,

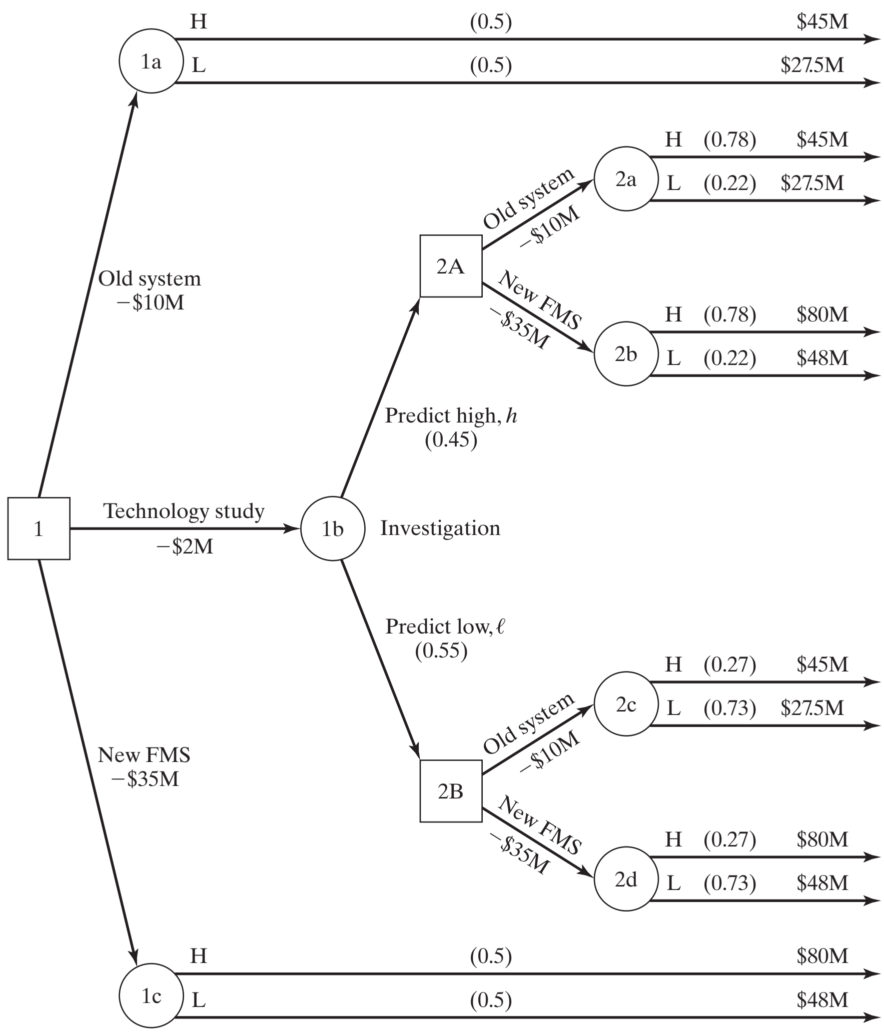

Figure 5.16 Replacement problem with alternative of technology study.

TABLE: 5.13 Expected NPV Calculations for Replacement Problem in Figure 5.13

Decision point	Alternative	Expected monetary outcome		Choice
2A	Old system	\$45M(0.78) + \$27.5M(0.22) − \$10M	= \$31.15M	
	New FMS	\$80M(0.78) + \$48M(0.22) − \$35M	= \$37.96M	New FMS
2B	Old system	\$45M(0.27) + \$27.5M(0.73) − \$10M	= \$22.23M	Old system
	New FMS	\$80M(0.27) + \$48M(0.73) − \$35M	= \$21.64M	
1	Old system	(see calculations above)	= \$26.25M	
	New FMS	(see calculations above)	= \$29.00M	New FMS
	Technology study	\$37.96M(0.45) + \$22.23M(0.55) − \$2M	= \$27.31M	

perform the calculations on Figure 5.16 and indicate the optimal path.) Although the figures used here do not reflect any advantages to this technology study, the benefit of gathering additional information can potentially be great.

In practice, firms will conduct market research or spot-market tests before launching a new product to a larger market audience. The research—with a representative sample of customers—will enable the firm to refine its probabilities of successfully launching a new product. The firm may learn, for instance, that a proposed, new product is not well-received by the research panel. In this case, the firm may abandon its broader "go to market" strategy for the new product and save itself from a more catastrophic financial loss. The decisions of (1) whether to conduct a spot-market test and (2) whether to go to market using a broad, national campaign can be modeled with decision trees, assuming that a finite set of possible outcomes, associated with each decision, can be stated and probabilities associated with each of the possible outcomes can be estimated.

5.7.4 Discussion and Assessment

One unique feature of decision trees is that they allow management to view the logical order of a sequence of decisions. They afford a clear graphical representation of the various courses of action and their possible consequences. By using decision trees, management can also examine the impact of a series of decisions (over many periods) on the goals of the organization. Such models reduce abstract thinking to a rational, visual pattern of cause and effect. When costs and benefits are associated with each branch and probabilities are estimated for each possible outcome, analysis of the tree can clarify choices and risks.

On the down side, the methodology has several weaknesses that should not be overlooked. A basic limitation of its representational properties is that only small and relatively simple decision models can be shown at the level of detail that makes trees so descriptive. Every variable added expands the tree's size multiplicatively. Although this problem can be overcome to some extent by generalizing the diagram, significant information may be lost in doing so. This loss is particularly acute if the problem structure is highly dependent or asymmetric.

Regarding the computational properties of trees, for simple problems in which the endpoints are pre-calculated or assessed directly, the rollback procedure is very efficient. However, for problems that require a roll-forward procedure, the classic tree-based algorithm has a fundamental drawback: it is essentially an enumeration technique. That is, every path through the tree is traversed to solve the problem and generate the full range of outputs. This feature raises the "curse of dimensionality" common to many stochastic models: for every variable added, the computational requirements increase multiplicatively. This implies that the number of chance variables that can be included in the model tends to be small. There is also a strong incentive to simplify the value model, because it is recalculated at the end of each path through the tree.

Nevertheless, the enumeration property of tree-based algorithms in theory can be reduced dramatically by taking advantage of certain structural properties of a problem. Two such properties are referred to as "asymmetry" and "coalescence." For more discussion and some practical aspects of implementation, consult Call and Miller (1990).

5.8 REAL OPTIONS

NPV has been criticized for not properly accounting for uncertainty and flexibility—that is, multistage development funding and abandonment options. Decision trees more accurately capture the multistage nature of development by using probability-based EMVs, but can be time consuming and overly complex when all potential courses of action are included. An alternative to decision trees is real options, a technique that applies financial options theory to nonfinancial assets and encourages managers to consider the value of strategic investments in terms of risks that can be held, hedged, or transferred.

Seen through a real options lens, NPV always undervalues potential projects, often by several hundred percent. Real-options analysis offers the flexibility to expand, extend, contract, abandon, or defer a project in response to unforeseen events that drive the value of a project up or down through time. It is good practice to consider these options at the outset of an investment analysis rather than only when trouble arises.

Recall that the NPV of a project is estimated by forecasting its annual cash flows during its expected life, discounting them back to the present at a risk-adjusted weighted average cost of capital, then subtracting the initial start-up capital expenditure. There's nothing in this calculation that captures the value of flexibility to make future decisions that resolve uncertainty.

Financial managers often overrule NPV by accepting projects with negative NPVs for "strategic reasons." Their intuition tells them that they cannot afford to miss the opportunity. In essence, they're intuiting something that has not been quantified in the project.

5.8.1 Drivers of Value

Like options on securities, real options are the right but not the obligation to take an action in the future at a predetermined price (the exercise or striking price) for a predetermined time (the life of the option). When you exercise a real option, you capture the difference between the value of the asset and the exercise price of the option. If a project is more successful than expected, then management can pay an "exercise price" to expand the project by making an additional capital expenditure. Management can also extend the life of a project by paying an exercise price. If the project does worse than expected, then it can be scaled back or abandoned. In addition, the initial investment does not have to be made today—it can be deferred.

The value of a real option is influenced by the following six variables:

1. *Value of the underlying project.* The option to expand a project (a call), for example, increases the scale of operations and therefore the value of the project at the cost of additional investment (the exercise price). Thus, the value of the project (without flexibility) is the value of what, in real-options language, is called the underlying risky asset. If we have flexibility to expand the project—in other words, an option to buy more of the project at a fixed price—then the value of the option to expand goes up when the value of the underlying project goes up.
2. *Exercise price/investment cost.* The exercise price is the amount of investment required to expand. The value of the option to expand goes up as the cost of expansion is reduced.
3. *Volatility of the underlying project's value.* Because the decision to expand is voluntary, you will expand only when the value of expansion exceeds the cost. When the value is less than the cost and there is no variability in the value, the option is worthless, but if the value is volatile, then there's a chance that the value can rise and exceed the cost, making the option valuable. Therefore, the value of flexibility goes up when uncertainty of future outcomes increases.
4. *Time to maturity.* The value of flexibility increases as the time to maturity lengthens because there's a greater chance that the value of expansion will rise the longer you wait.
5. *Risk-free interest rate.* As the risk-free rate of interest goes up, the present value of the option also goes up because the exercise price is paid in the future, and therefore, as the discount rate increases, the present value of the exercise price decreases.
6. *Dividends.* The sixth variable is the dividends, or the cash flows, paid out by the project. When dividends are paid, they decrease the value of the project and therefore the value of the option on the project.

5.8.2 Relationship to Portfolio Management

The flexible decision structure of options is valid in an R&D context. After an initial investment, management can gather more information about the status of a project and market characteristics and, on the basis of this information, change its course of action. The real option value of this managerial flexibility enhances the R&D project value, whereas a pure NPV analysis understates it. Five basic sources of flexibility have been identified (e.g., Trigeorgis 1997). A *defer option* refers to the possibility of waiting until more information has become available. An *abandonment option* offers the possibility to make the investment in stages, deciding at each stage, on the basis of the newest information, whether to proceed further or to stop (this is applied by venture capitalists). An *expansion* or *contraction option* represents the possibility to adjust the scale of the investment (e.g., a production facility) depending on whether market conditions turn out favorably or not. Finally, a *switching option* allows changing the mode of operation of an asset, depending on factor prices (e.g., switching the energy source of a power plant, switching raw material suppliers).

One key insight generated by the real options approach to R&D investment is that higher uncertainty in the payoffs of the investment increases the value of managerial flexibility, or the value of the real option. The intuition is clear—with higher payoff uncertainty, flexibility has a higher potential of enhancing the upside while limiting the downside. An important managerial implication of this insight is that the more uncertain the project payoff is, the more efforts should be made to delay commitments and maintain the flexibility to change the course of action. This intuition is appealing. Nevertheless, there is hardly any evidence of real options pricing of R&D projects in practice despite reports that Merck uses the method. Moreover, there is recent evidence that more uncertainty may reduce the option value if an alternative "safe" project is available.

This evidence represents a gap between the financial payoff variability, as addressed by the real options pricing literature, and operational uncertainty that pervades R&D. For example, R&D project managers encounter uncertainty about budgets, schedules, product performance, or market requirements, in addition to financial payoffs. The relationship between such operational uncertainty and the value of managerial flexibility (option value of the project) is not clear. For example, should the manager respond to increased uncertainty about product performance in the same way as to uncertainty about project payoffs, by delaying commitments? Questions such as this must be addressed on a case-by-case basis in full view of the scope and consequences of the attending risks.

TEAM PROJECT

Thermal Transfer Plant

On the basis of the evaluation of alternatives, Total Manufacturing Solutions, Inc. (TMS) management has adopted a plan by which the design and assembly of the rotary combustor will be done at TMS. Most of the manufacturing activity will be subcontracted except for the hydraulic power unit, which TMS decided to build "in-house."

There are three functions involved in charging and rotating the combustor. Two of them, the charging rams and the resistance door, naturally lend themselves to hydraulics. The third, turning the combustor, can be done either electromechanically (by an electric motor and a gearbox) or hydraulically. If the hydraulic method is chosen, then there are two alternatives: (1) use a large hydraulic motor as a direct drive or (2) use a small hydraulic motor with a gearbox. Figure 5.17 contains a schematic.

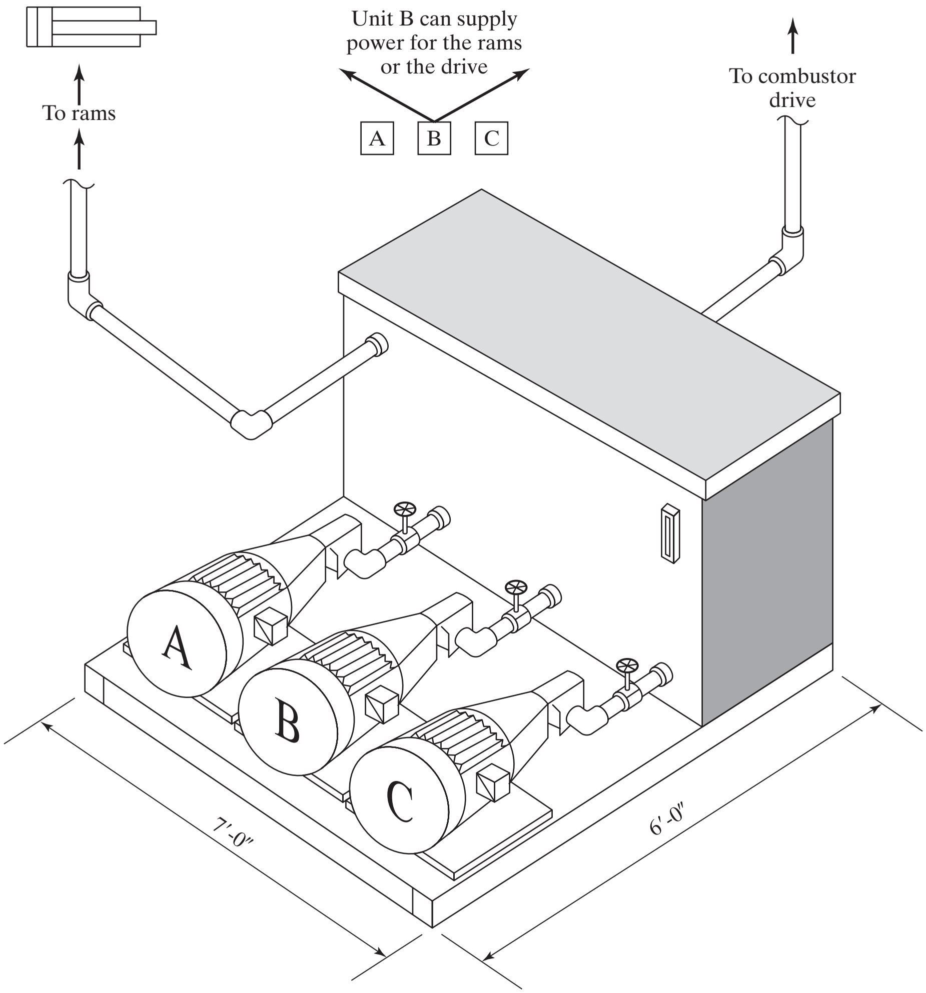

Figure 5.17 Hydraulic power unit.

TMS engineering has produced the following specifications for the hydraulic power unit:

Applicable documents, codes, standards, and requirements

National Electric Manufacturers Association (NEMA)

American National Standards Institute (ANSI)

Pressure Vessels Code, American Society of Mechanical Engineers (ASME) Section VIII

Hydraulic rams

Two hydraulic cylinders will be provided for the rams. The cylinders will be 8 in. bore × 96 in. stroke. They will operate at 1,500 psi, and will have an adjustable extension rate of 2 to 6 ft/min. They will retract in 15 seconds, will operate 180° out of phase, and will retract in the event of a power failure.

Combustor barrel drive

A single-direction, variable-speed drive will be provided for the combustor. The output of this drive will deliver up to 1.6 rpm and 7,500 ft-lb of torque.

Resistance door cylinder

This cylinder will be 6 in. bore × 48 in. stroke and will operate with a constant pressure of 200 psi.

Hydraulic power unit

- The hydraulic power unit will be skid mounted and ready for hookup to interfacing equipment. Mounting and lifting brackets will be manufactured as well.
- Hydraulic pumps will be redundant so that in the event of the failure of one, another can be started to take over its function. Accumulators will be added to retract the rams and close the resistance door in the event of a power failure.
- The hydraulic fluid is to be E. F. Houghton's Cosmolubric or equivalent. Although system operating pressure is to be 1,500 psi, the plumbing will be designed to withstand 3,000 psi. Water-to-oil heat exchangers shall be provided to limit reservoir temperature to 130°C.
- A method of controlling ram extension speed and combustor rpm within the specifications stated above will be provided. Control concepts may be analog (5 to 20 milliamperes) or digital.

Electrical

Electric motors will be of sufficient horsepower to drive the hydraulic pumps. Motors shall operate at 1,200 rpm, 220/440 volts, 3 phase, 60 hertz.

Solenoids and controls

Solenoids are to be 120 volt, 60 hertz and will have manual overrides. Any analog control function is to respond to a 5- to 20-milliampere signal.

Combustion drive

A single-direction, variable-speed drive will be provided for the combustor. The output of this drive will deliver up to 1.6 rpm and 7,500 ft-lb of torque. Three potential alternatives for the combustor drive are

- Electric motor and gearbox
- Hydraulic motor with gearbox (hydraulic power supplied by hydraulic power unit)
- Hydraulic motor with direct drive (hydraulic power supplied by hydraulic power unit)

Your team assignment is to select the most appropriate drive from these candidates. To do so, develop a scoring model or a decision tree and evaluate each alternative accordingly. State your assumptions clearly, regarding technological, economic, and other aspects and explain the methodology used to support your analysis.

Initial cost estimates available to your team are:

Ram cylinders (two required)	$5,948 each
Resistance door cylinder	$1,505
Hydraulic power unit	$50,000
Low-speed, high-torque motor	$22,780
High-speed motor with gear box	$7,000

DISCUSSION QUESTIONS

1. Where would ideas for new projects and products probably originate in a manufacturing company? What would be the most likely source in an R&D organization such as AT&T Laboratories or IBM's Watson Center?
2. Assume that you work in the design department of an aerospace firm and you are given the responsibility of selecting a workstation that will be used by each group in the department. How would you find out which systems are available? What basic information would you try to collect on these systems?
3. How can you extend a polar graph, similar to the one shown in Figure 5.2, to the case in which the criteria are individually weighted?
4. Identify a project that you are planning to pursue either at home or at work. List all of the components, decision points, and chance events. What is the measure of success for the project? Assuming that there is more than one measure, how can you reconcile them?
5. If you were evaluating a proposal to upgrade the computer-aided design system used by your organization, what type of information would you be looking for in detail? How would your answer change if you were buying only one or two systems as opposed to a few dozen?
6. Which factors in an organization do you think would affect the decision to go ahead with a project, such as automating a production line, other than the B/C ratio?
7. For years before beginning the project to build a tunnel under the English Channel, Great Britain and France debated the pros and cons. Speculate on the critical issues that were raised.
8. The project to construct a subway in Washington, D.C. began in the early 1970s with the expectation that it would be fully operational by 1980. A portion of the system opened in 1977, but as of 2004, approximately 5% remained unfinished. What do you think were the costs, benefits, and risks involved in the original planning? How important was the interest rate used in those calculations? Speculate on who or what was to blame for the lengthy delay in completion.
9. Where does quality fit into the B/C equation? Identify some companies or products that compete primarily on the basis of quality rather than price.
10. A software company is undecided on whether it should expand its capacity by using part-time programmers or by hiring more full-time employees. Future demand is the

critical factor, which is not known with certainty but can be estimated only as low, medium, or high. Draw a decision tree for the company's problem. What data are needed?

11. How could B/C analysis be used to help determine the level of subsidy to be paid to the operator of public transportation services in a congested urban area?

12. Why has the U.S. Department of Defense been the major exponent of C-E analysis? Give your interpretation of what is meant by "diminishing returns," and indicate how it might affect a decision on procuring a military system versus an office automation system.

13. In which type of projects does risk play a predominant role? What can be done to mitigate the attendant risks? Pick a specific project and discuss.

EXERCISES

5.1 Consider an important decision with which you will be faced in the near future. Construct a scoring model detailing your major criteria and assign weights to each. Indicate which data are known for sure and which are uncertain. What can be done to reduce the uncertainty?

5.2 Use a checklist and a scoring model to select the best car for a married graduate student with one child. State your assumptions clearly.

5.3 Assume that you have just entered the university and wish to select an area of study.

a. Using B/C analysis *only*, what would your decision be?
b. How would your decision change if you used C-E analysis? Provide the details of your analysis.

5.4 You have just received a job offer in a city 1,000 miles away and must relocate. List all possible ways of moving your household. Use two different analytic techniques for selecting the best approach, and compare the results.

5.5 Three new-product ideas have been suggested. These ideas have been rated as shown in Table 5.14.

a. Using an equal point spread for all five ratings (i.e., P = 1, F = 2, G = 3, VG = 4, E = 5), determine a weighted score for each product idea. What is the ranking of the three products?
b. Rank the criteria, compute the rank-sum weights, and determine the score for each alternative. Do the same using the rank reciprocal weights.
c. What are some of the advantages and disadvantages of this method of product selection?

TABLE 5.14

	Product[1]			
Criteria	A	B	C	Weight (%)
Development cost	P	F	VG	10
Sales prospects	VG	E	G	15
Producibility	P	F	G	10
Competitive advantage	E	VG	F	15
Technical risk	P	F	VG	20
Patent protection	F	F	VG	10
Compatibility with strategy	VG	F	F	20
				100

[1] P = poor, F = fair, G = good, VG = very good, E = excellent

5.6 Suppose that the products from Exercise 5.5 have been rated further as shown in Table 5.15.

TABLE 5.15

	Product		
	A	B	C
Probability of technical success	0.9	0.8	0.7
Probability of commercial success	0.6	0.8	0.9
Annual volume (units)	10,000	8,000	6,000
Profit contribution per unit	$2.64	$3.91	$5.96
Lifetime of product (years)	10	6	12
Total development cost	$50,000	$70,000	$100,000

a. Compute the expected return on investment over the lifetime of each product.
b. Does this computation change your ranking of the products over that obtained in Exercise 5.5?

5.7 The federal government proposes to construct a multipurpose water project. This project will provide water for irrigation and for municipal uses. In addition, there will be flood control benefits and recreation benefits. The estimated project benefits computed for 10-year periods for the next 50 years are given in Table 5.16.

The annual benefits may be assumed to be one tenth of the decade benefits. The O&M cost of the project is estimated to be $15,000 per year. Assume a 50-year analysis period with no net project salvage value.

TABLE 5.16

Purpose	First decade	Second decade	Third decade	Fourth decade	Fifth decade
Municipal	$ 40,000	$ 50,000	$ 60,000	$ 70,000	$110,000
Irrigation	$350,000	$370,000	$370,000	$360,000	$350,000
Flood Control	$150,000	$150,000	$150,000	$150,000	$150,000
Recreation	$60,000	$70,000	$80,000	$80,000	$90,000
Totals	$600,000	$640,000	$660,000	$660,000	$700,000

a. If an interest rate of 5% is used and there is a B/C ratio of unity, then what capital expenditure can be justified to build the water project now?
b. If the interest rate is changed to 8%, then how does this change the justified capital expenditure?

5.8 The state is considering the elimination of a railroad grade crossing by building an overpass. The new structure, together with the needed land, would cost $1,800,000. The analysis period is assumed to be 30 years on the theory that either the railroad or the highway above it will be relocated by then. Salvage value of the bridge (actually, the net value of the land on either side of the railroad tracks) 30 years hence is estimated to be $100,000. A 6% interest rate is to be used.

At present, approximately 1,000 vehicles per day are delayed as a result of trains at the grade crossing. Trucks represent 40%, and 60% are other vehicles. Time for truck drivers is valued at $18 per hour and for other drivers at $5 per hour. Average time saving per vehicle will be 2 minutes if the overpass is built. No time saving occurs for the railroad.

The installation will save the railroad an annual expense of $48,000 now spent for crossing guards. During the preceding 10-year period, the railroad has paid out $600,000 in settling lawsuits and accident cases related to the grade crossing. The proposed project will entirely eliminate both of these expenses. The state estimates that the new overpass will save it approximately $6,000 per year in expenses attributed directly to the accidents. The overpass, if built, will belong to the state.

Perform a benefit-cost analysis to answer the question of whether the overpass should be built. If the overpass is built, how much should the railroad be asked to contribute to the state as its share of the $1,800,000 construction cost?

5.9 An existing 2-lane highway between two cities is to be converted to a 4-lane divided freeway. The distance between them is 10 miles. The average daily traffic on the new freeway is forecast to average 20,000 vehicles per day over the next 20 years. Trucks represent 5% of the total traffic. Annual maintenance on the existing highway is $1,500 per lane-mile. The existing accident rate is 4.58 per million vehicle miles (MVM). Three alternative plans of improvement are now under consideration.

Plan A: Add 2 lanes adjacent to the existing lanes at a cost of $450,000 per mile. It is estimated that this plan would reduce auto travel time by 2 minutes and truck travel time by 1 minute when compared with the existing highway. The estimated accident rate is 2.50 per MVM, and the annual maintenance is expected to be $1,250 per lane-mile for all 4 lanes.

Plan B: Improve along the existing alignment with grade improvements at a cost of $650,000 per mile, and add 2 lanes. It is estimated that this would reduce auto and truck travel time by 3 minutes each compared with current travel times. The accident rate on the improved road is estimated to be 2.40 per MVM, and annual maintenance is expected to be $1,000 per lane-mile for all 4 lanes.

Plan C: Construct a new 4-lane freeway on new alignment at a cost of $800,000 per mile. It is estimated that this plan would reduce auto travel time by 5 minutes and truck travel time by 4 minutes compared with current conditions. The new freeway would be 0.3 miles longer than the improved counterparts discussed in plans A and B. The estimated accident rate for plan C is 2.30 per MVM, and annual maintenance is expected to be $1,030 per lane-mile for all 4 lanes. If plan C is adopted, then the existing highway will be abandoned with no salvage value.

Useful data:

Incremental operating cost	
– Autos	6 cents/mile
– Trucks	18 cents/mile
Time saving	
– Autos	3 cents/minute
– Trucks	15 cents/minute
Average accident cost =	$1,200

If a 5% interest rate is used, then which of the three proposed plans should be adopted? Base your answer on the individual B/C ratios of each alternative. When calculating these values, consider any annual incremental operating costs due to distance, a user disbenefit rather than a cost.

5.10 A 50-meter tunnel must be constructed as part of a new aqueduct system for a city. Two alternatives are being considered. One is to build a full-capacity tunnel now for $500,000. The other alternative is to build a half-capacity tunnel now for $300,000 and then to build a second parallel half-capacity tunnel 20 years hence for $400,000. The cost of repair of the tunnel lining at the end of every 10 years is estimated to be $20,000 for the full-capacity tunnel and $16,000 for each half-capacity tunnel.

Determine whether the full-capacity tunnel or the half-capacity tunnel should be constructed now. Solve the problem by B/C ratio analysis using a 5% interest rate and a 50-year analysis period. There will be no tunnel lining repair at the end of the 50 years.

5.11 Consider the following typical noise levels in decibels (dBA):

140	threshold of pain
130	
120	four-engine jet aircraft at 500 ft unmuffled motorcycle
110	
100	rock and roll band subway train at 20 ft
90	
	heavy traffic at 25 to 50 ft
80	
	vacuum cleaner
70	dishwasher
60	conversational speech at 3 ft
50	business office
40	home

a. Assume that you are responsible for designing a machine shop. How would you determine an acceptable level of noise? What costs and risks should you weigh?

b. What would your answer be for the design of a commercial aircraft?

5.12 Epidemiological data indicate that only a handful of patients have contracted the AIDS (acquired immune deficiency syndrome) virus from health care workers. Many, though, have called for the periodic testing of all health care workers in an effort to protect or at least reduce the risks to the public. Identify the costs and benefits associated with such a program. Develop an implementation plan for nationwide testing. How would you go about measuring the costs of the plan? What are the costs and risks of not testing?

5.13 As chief industrial engineer in a manufacturing facility, you are contemplating the replacement of the spreadsheet procedures that you are now using for production scheduling and inventory control with a material requirements planning system. A number of options are available. You can do it all at once and throw out the old system; you can phase in the new system over time; you can run both systems simultaneously, and so on. Identify the costs, benefits, and risks with each approach. Construct a decision tree for the problem. Assume that the benefits of any option depend on the future state of the economy which may be "good" or "bad" with probabilities 0.7 and 0.3, respectively.

5.14 The daily demand for a particular type of printed circuit board in an assembly shop can assume one of the following values: 100, 120, or 130 with probabilities 0.2, 0.3, and 0.5. The manager of the shop thus is limiting her alternatives to stocking one of the three levels indicated. If she prepares more boards than are needed in the same day, then she must reprocess those remaining at a cost price of 55 cents/board. Assuming that it costs 60 cents to prepare a board for assembly and that each board produces $1.05 in revenue, find the optimal stocking level by using a decision tree model.

5.15 In Exercise 5.14, suppose that the owner wishes to consider her decision problem over a 2-day period. Her alternatives for the second day are determined as follows. If the demand in day 1 is equal to the amount stocked, then she will continue to order the same quantity on the second day. Otherwise, if the demand exceeds the amount stocked, she will have the options to order higher levels of stock on the second day. Finally, if day 1's demand is less than the amount stocked, then she will have the options to order any of the lower levels of stock for the second day. Express the problem as a decision tree, and find the optimal solution using the cost data given in Exercise 5.14.

5.16 Zingtronics Corp. has completed the design of a new graphic-display unit for computer systems and is about to decide on whether it should produce one of the major components internally or subcontract it to another local firm. The advisability of which action to take depends on how the market will respond to the new product. If demand is high, then it is worthwhile to make the extra investment for special facilities and equipment needed to produce the component internally. For low demand it is preferable to subcontract. The analyst assigned to study the problem has produced the following information on costs (in thousands of dollars) and probability estimates of future demand for the next 5-year period:

	Future demand		
Action	Low	Average	High
Produce	$140	$120	$90
Subcontract	$100	$110	$160
Probability	0.10	0.60	0.30

a. Prepare a decision tree that describes the structure of this problem.
b. Select the best action on the basis of the initial probability estimates for future demand.
c. Determine the expected cost with perfect information (i.e., knowing future demand exactly).

5.17 Refer to Exercise 5.16. The management of Zingtronics is planning to hire Dr. Lalith deSilva, an economist and head of a local consulting firm, to prepare an economic forecast for the computer industry. The reliability of her forecasts based on previous assignments is provided by the following table of conditional probabilities.

	Future demand		
Economic forecast	Low	Average	High
Optimistic	0.1	0.1	0.5
Normal	0.3	0.7	0.4
Pessimistic	0.6	0.2	0.1
	1.0	1.0	1.0

a. Select the best action for Zingtronics if Dr. deSilva submits a pessimistic forecast for the computer industry.
b. Prepare a decision tree diagram for the problem with the use of Dr. deSilva's forecasts.
c. What is the Bayes' strategy for this problem?
d. Determine the maximum fee that should be paid for the use of Dr. deSilva's services.

5.18 Allen Konigsberg is an expert in decision support systems and has been hired by a small software engineering firm to help plan their R&D strategy for the next 6 to 12 months. The company wishes to devote up to 3 person-years, or roughly $200,000, to R&D projects. Show how Konigsberg can use a decision tree to structure his analysis. State all of your assumptions.

5.19 The management of Dream Cruises, Ltd., operating in the Caribbean, has established the need for expanding its fleet capacity and is considering what the best plan for the next 8-year planning period will be. One strategy is to buy a larger 40,000-ton cruise ship now, which would be most profitable if demand is high. Another strategy would be to start with a small 15,000-ton ship now and consider buying another medium 25,000-ton ship 3 years later. The planning department has estimated the probabilities for high and low demand for each period to be 0.6 and 0.4 respectively. If the company buys the large ship, then the annual profit after taxes for the next 8 years is estimated to be $800,000 if demand is high and $100,000 if it is low. If the company buys the small ship, then the annual profits each year will be $300,000 if demand is high and $150,000 if it is low.

After 3 years with the small vessel, a decision for new capacity will be reviewed. At this time, the firm may decide to expand by adding a 25,000-ton ship or by continuing with the small one. The annual profit after expansion will be $700,000 if demand is high and $120,000 if it is low.

a. Prepare a decision tree that shows the actions available, the states of nature, and the annual profits.
b. Calculate the total expected profit for each branch in the decision tree covering 8 years of operation.
c. Determine the optimum fleet-expansion strategy for Dream Cruises, Ltd.

5.20 Referring to Exercise 5.19, determine the optimal fleet-expansion strategy if projected annual profits are discounted at the rate of 12%.

5.21 *Pipeline Construction Model*. This exercise is a variation of the classical "machine setup" problem. The installation of an oil pipeline that runs from an oil field to a refinery requires the welding of 1,000 seams. Two alternatives have been specified for performing the welding: (1) use a team of ordinary and apprentice welders (B-team) only, or (2) use a team of master welders (A-team) who check and rework (as necessary) the welds of the B-team. If the first alternative is chosen, then it is estimated from past experience that 5% of the seams will be defective with probability 0.30, 10% will be defective with probability 0.50, or 20% will be defective with probability 0.20. However, if the B-team is followed by the A-team, then a defective rate of 1% is almost certain.

Material and labor costs are estimated at $400,000 when the B-team is used strictly, whereas these costs rise to $530,000 when the A-team is also brought in. Defective seams result in leaks that must be reworked at a cost of $1,200 per seam, which includes the cost of labor and spilled oil but ignores the cost of environmental damage.

a. Determine the optimal decision and its expected cost. How might environmental damage be taken into account?
b. A worker on the pipeline with a Bayesian inclination (from long years of wagering on the ponies) has proposed that management consider x-ray inspections of five randomly

selected seams *following* the work of the B-team. Such an inspection would identify defective seams, which would provide management with more information for the decision on whether to bring in the A-team. It costs $5,000 to inspect the five seams. Financially, is it worthwhile to carry out the inspection? If so, then what decision should be made for each possible result of the inspection?

5.22 A decision is to be made as to whether to perform a *complete audit* of an accounts receivable file. Substantial errors in the file can result in a loss of revenue to the company. However, conducting a *complete audit* is expensive. It has been estimated that the average cost of auditing one account is $6. However, if a *complete audit* is conducted, resulting in the true but *unknown* proportion p of the accounts in error being reduced, then the loss of revenue may be reduced significantly.

Andrew Garland, the audit manager, has the option of first conducting a *partial audit* before his decision on the *complete audit*. Using the prior probability distribution and payoffs (costs) given in the table below, develop a single auditing plan based on a *partial audit* of three accounts. Work with opportunity losses.

Proportion of accounts in error, p	Prior probability of p, $P(p)$	Conditional cost	
		Do not audit	Complete audit
0.05	0.2	$1,000	$10,000
0.50	0.7	$10,000	$10,000
0.95	0.1	$29,000	$10,000

a. Develop the opportunity loss matrix—the matrix derived from the payoff matrix (state of nature versus cost) by subtracting from each entry the smallest entry in its row.
b. Structure the problem in the form of a decision tree. Specify all actions, sample outcomes, and events. Indicate opportunity losses and probabilities at all points on the tree. Show all calculations.
c. Develop the conditional probability matrix, $P(X)|p)$.
d. Develop the joint probability matrix.
e. Is the single auditing plan better than not conducting a partial audit?
   1. What is the expected opportunity loss with no partial auditing?
   2. What is the expected value of perfect information (EVPI)? Note that EVPI is the difference between the optimal EMV under perfect information and the optimal EMV under the current uncertainty (before collecting more data).
   3. What is the expected value of sample information (EVSI), where EVSI = EVPI − *EMV*? The evaluation of EMV should take into account the results of the partial audit.
   4. State how you would determine the optimal number of partial audits in a sampling plan.

5.23 A trucking company has decided to replace its existing truck fleet. Supplier A will provide the needed trucks at a cost of $700,000. Supplier B will charge $500,000, but its vehicles may require more maintenance and repair than those from supplier A. The trucking company is also considering modernizing its maintenance and repair facility either by renovation or by renovation and expansion. Although expansion is generally more expensive than renovation alone, it enables greater efficiency of repair and therefore reduced annual operating costs of the facility. The estimated costs of renovation alone and of renovation and expansion, as well as the ensuing operating costs, depend on the quality of the trucks that are purchased and the extent of the maintenance that they require. The trucking company therefore has decided on the following strategy: purchase the trucks now; observe their maintenance requirements for 1 year; then make the decision as to whether to renovate or to renovate and expand. During the 1-year observation period, the company will get additional information about expected maintenance requirements during years 2 through 5.

If the trucks are purchased from supplier A, then first-year maintenance costs are expected to be low ($30,000) with a probability of 0.7 or moderate ($40,000) with a probability of 0.3. If they are purchased from supplier B, then maintenance costs will be low ($30,000) with a probability of 0.3, moderate ($40,000) with a probability of 0.6, or high ($50,000) with a probability of 0.1. The costs of renovation, shown here, depend on the first year's maintenance experience.

One-year maintenance requirements	Renovation costs	Renovation and expansion costs
Low	$150,000	$300,000
Moderate	$200,000	$500,000
High	$300,000	$700,000

Expected maintenance costs for years 2 through 5 can best be estimated after observing the maintenance requirements for the first year (Table 5.17). Probabilities of various maintenance levels in years 2 through 5 depend on the types of trucks selected and the maintenance experience during year 1 (Table 5.18).

TABLE 5.17

Supplier	First-year maintenance	Renovate Maintenance years 2–5		Renovate and expand Maintenance years 2–5	
		Low	Moderate	Low	Moderate
A	Low	$100,000	$150,000	$40,000	$60,000
	Moderate	$100,000	$150,000	$40,000	$60,000
		Moderate	High	Moderate	High
B	Low	$150,000	$200,000	$50,000	$90,000
	Moderate	$150,000	$200,000	$50,000	$90,000
	High	$250,000	$300,000	$70,000	$100,000

TABLE 5.18

Supplier	First-year maintenance	Maintenance level, years 2–5		
		Low	Moderate	High
A	Low	0.7	0.3	—
	Moderate	0.4	0.6	—
B	Low	—	0.5	0.5
	Moderate	—	0.4	0.6
	High	—	0.3	0.7

Use decision tree analysis to determine the strategy that minimizes expected costs.

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APPENDIX 5A

Bayes' Theorem for Discrete Outcomes

For a given problem, let there be n mutually exclusive, collectively exhaustive possible outcomes $S_1, \ldots, S_i, \ldots, S_n$ whose prior probabilities $P(S_i)$ have been established. The laws of probability require

$$\sum_{i=1}^{n} P(S_i) = 1, 0 \leq P(S_i) \leq 1, i = 1, \ldots, n$$

If the results of additional study, such as sampling or further investigation, are designated as X, where X is discrete and $P(X) > 0$, Bayes' theorem can be written as

$$P(S_i|X) = \frac{P(X|S_i)}{\sum_{j=1}^{n} P(X|S_j)P(S_j)} \tag{5A.1}$$

The posterior probability $P(S_i|X)$ is the probability of outcome S_i given that additional study resulted in X. The probability of X and S_i occurring, $P(X|S_i)P(S_i)$, is the "joint" probability of X and S_i or $P(X, S_i)$. The sum of all of the joint probabilities is equal to the probability of X. Therefore, Eq. (5A.1) can be written

$$P(S_i|X) = \frac{P(X|S_i)P(S_i)}{P(X)} \tag{5A.2}$$

TABLE 5A.1 Format for Applying Bayes' Theorem

(1) State	(2) Prior probability	(3) Probability of sample outcome, X	(4) = (2) × (3) Joint probability	(5) = (4)/$\sum$(4) Posterior probability $P(S_i \mid X)$
S_1	$P(S_1)$	$P(X \mid S_1)$	$P(X \mid S_1)P(S_1)$	$P(X \mid S_1)P(S_1)/P(X)$
S_2	$P(S_2)$	$P(X \mid S_2)$	$P(X \mid S_2)P(S_2)$	$P(X \mid S_2)P(S_2)/P(X)$
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
S_i	$P(S_i)$	$P(X \mid S_i)$	$P(X \mid S_i)P(S_i)$	$P(X \mid S_i)P(S_i)/P(X)$
.	.	.	.	.
.	.	.	.	.
S_n	$P(S_n)$	$P(X \mid S_n)$	$P(X \mid S_n)P(S_n)$	$P(X \mid S_n)P(S_n)/P(X)$
	$\sum_{i=1}^{n} P(S_i) = 1$		$\sum_{i=1}^{n} P(X \mid S_i)P(S_i) = P(X)$	$\sum_{i=1}^{n} P(S_i \mid X) = 1$

A format for application is presented in Table 5A.1. The columns are as follows.

1. S_i: potential states of nature.
2. $P(S_i)$: estimated prior probability of S_i. (Note: This column sums to one.)
3. $P(X \mid S_i)$: the conditional probability of getting sample or added study results X, given that S_i is the true state (assumed to be known).
4. $P(X \mid S_i)P(S_i)$: joint probability of getting X and S_i; the summation of this column is $P(X)$, which is the probability that the sample or added study results in outcome X.
5. $P(S_i \mid X)$: posterior probability of S_i given that sample outcome resulted in X; numerically, the ith entry is equal to the ith entry of column (4) divided by the sum of the values in column (4). (Note: Column (5) sums to unity.)