# CONSTRUCTION PROJECT SCHEDULING AND CONTROL

3 THIRD EDITION



SALEH MUBARAK

WILEY

# Construction Project Scheduling and Control

## Third Edition

Saleh Mubarak

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# Preface

This is the third edition of *Construction Project Scheduling and Control*. I am very pleased with its continuous success. The book has become popular throughout the world, both in paper and in digital form. I continuously receive correspondence—comments, suggestions, requests for instructional materials (instructor support materials including an instructor manual and PowerPoints can be accessed by visiting http://www.wiley.com/buy/9781118846001 and clicking on the "More Information About this Book" link), and compliments. The most praised traits of the book are its simplicity, comprehensiveness, and practical examples. I was so happy and proud when the language editor (of the first edition) corrected me regarding an activity's *total float* in an example in the book. She had no technical background but had learned the critical path method while linguistically reviewing my book!

During the past nine years, I have been using my book in professional seminars and college classes. I have discussed it with my friends, colleagues, and students. I have always kept a log of all suggestions and corrections. I started thinking about the second edition just after the first edition was published in 2004 and about the third edition just after the second edition was published in 2010. I have modified the definition of the critical path after so many readings and discussions with experts and colleagues. I think I have now the most accurate definition in all of the literature available. Is it possible that I modify the definition in the future? Absolutely!

Although I was very happy and content with the way the book came out and was received, I believe there is no such thing as the perfect human product. Imperfection is part of human nature, but we should think of it positively: there is always room for improvement. I have had to parallel my satisfaction and ambition in completing this third edition with a strong conviction that the fourth edition will be coming out in a few years. In my professional seminars and college courses, even though the course or seminar may be the same, I make updates and adjustments every time I teach it.

I believe in continuous improvement and in the saying, "My today must be better than my yesterday, and my tomorrow must be better than my today."

One experience has added to my knowledge and the book—the overseas jobs that I have held between 2008 and 2014. I could not imagine the pace and amount of construction in such a small place as Qatar. There are more tower cranes than you can count. Professionals come from all over the world, like a huge bouquet of flowers, with their diversity in education, culture, race, and language. Communication has been a challenge, to say the least. Even though English is the official language for doing business in most organizations there, one soon realizes that English is not English! Forget about the difference in pronunciation and accents, forget about the spelling of *labor* versus *labour* and *program* versus *programme;* there are differences in the interpretation of technical terms and in the way business is conducted. To make it interesting, none of these differences is wrong. This situation is the cure for what I call the *background paradigm*, in which everyone believes he or she is right just because he was brought up this way! Then our cultures and ways of doing business clash, and everyone believes the other persons are wrong! In many of these situations, there is no right and wrong; there are just different ways of doing things. However, in a project management team, all must sing together in harmony with one common tune—what a challenge! Keep in mind, our field is an empirical, not an exact, science! Believe it or not, I enjoy every minute of this "clash of cultures." I think of it like this: "one cubic meter of concrete mix: $100; one ton of steel: $600; one workday with 30 different nationalities: priceless!"

This edition contains many additions in almost every chapter and part of the book. One new chapter (Chapter 15) has been added on "Building Information Modeling (BIM) and scheduling." BIM's popularity has been increasing rapidly due to its advantages that new hardware and software technology have made possible. I have also added "Tip boxes" in almost every chapter.

Since the first edition, I have observed more qualitative interest in project scheduling in the professional and academic disciplines. In particular, the Project Management Institute (PMI) has created a certification track in scheduling (Scheduling Professional, PMI-SP) in 2008 (the author served in the committee that prepared the first SP exam), and the AACE International has its own Planning & Scheduling Professional (PSP) certification. Other professional organizations, such as the American Institute of Architecture (AIA), the Construction Management Association of America (CMAA), the Associated General Contractors (AGC), the UK's Chartered Institute of Building (CIOB), and many others inside and outside the United States have also showed increased interest in scheduling and project control issues. This, coupled with the increasing role of project scheduling (using the critical path method) in delay and other claims, has made it an essential part of required knowledge for judges, lawyers, and arbitrators. This is a clear indication of the importance of project scheduling and control for today's bigger and more complicated projects.

It was a grace from God to have been able to finish this work. There are several people to whom I owe a lot of gratitude. I would like to thank Dr. Onur Tokdemir and Ms. Acelya Yildiz for their valuable contribution to the new chapter on BIM.

I also would like to thank attorney Barry Bramble and my colleague Chris Carson for updating Chapters 13 ("Construction Delays and Other Claims") and 14 ("Schedule Risk Management"), which they originally coauthored. Thanks to my colleagues Dr. Gui Ponce de Leon, Dr. Fredrick Plotnick, and Dr. Gunnar Lucko for their contributions to Chapter 11, "Other Scheduling Methods." Thanks also to Al Mazaya Holding Company in Kuwait and its Chief Projects Officer, Dr. Abdulaziz Jarkas, for providing me with wonderful pictures from their projects.

To all my readers—construction and other professionals, educators, and students—I would like to hear from you. If you have a question, suggestion, comment, or correction, please send me an e-mail at CPMXPERT@gmail.com. I promise to make every effort to read and respond to every e-mail that I receive. Such communication will elevate us in the pursuit of perfection.

# Preface to the First Edition

The art of teaching requires two important components: knowledge of the subject and the ability to convey this knowledge to students. Having a love of the subject is a bonus that allows a teacher to take the classroom to an even higher level.

During my career as a structural engineer, as a construction professional, and as a professor, I have had to play many roles and wear many hats. There is no question that the different roles and different positions have provided me with rounded knowledge and a panoramic view of the construction industry. However, no subject has been more interesting and intriguing to me than scheduling and project control. During my teaching career, I acquired many books on this subject. Many of them are good or excellent books, but none has fulfilled my exact need. Some lack the detailed step-by-step approach, some have few examples and exercises, some are written by academicians with little real-world experience, and some deal with the subject of scheduling and project control as if it were still the 1970s or 1980s.

I was searching for a book that does the following:

- Addresses the need of the average student and details all steps clearly and without shortcuts
- Includes many solved and unsolved exercises that cover all the subjects in the book
- Relates to computer software programs used in the construction industry without making them the center of attention or overshadowing the theoretical principles
- Deals with precedence networks as the main and only viable CPM scheduling method, having coverage of arrow networks only as part of the evolution of scheduling

- Focuses on scheduling as part of the overall project management effort (rather than as just one chapter in a project management book)

Not having found such a book and after having taught scheduling for several years using four textbooks, I decided to write my own book. I started writing from scratch in early 2001. I also began living it: in my office, at home, when going to bed, in the shower, while driving the car, almost every waking moment. As ideas would come to mind, I would write them on a piece of paper or record them on my digital tape recorder. I did not want to let any idea escape me. Several experts also reviewed this book and provided me with invaluable critiques, and I made additional changes and improvements every time I read the text. Following is an outline of this textbook.

In Chapter 1, planning, scheduling, and project control are defined, and the steps needed to build a schedule are described. In Chapter 2, bar (Gantt) charts, the most common method used to display and report schedules, are introduced. This topic is revisited in Chapter 9. Networks and the critical path method (CPM) are covered in the next four chapters. Chapter 3 covers arrow and node networks and their history, concepts, and structure. Chapter 4 addresses the CPM and its calculations. Chapter 5 covers precedence networks, an advanced form of node networks with its own calculations and concepts. I realize that this subject can become more complicated than field personnel or students can (or like to) handle. As a result, in this chapter, I offer two approaches: the simplistic approach, which leads to bottom-line results without becoming bogged in the details, and the detailed approach, for those who want to study the subject thoroughly. I further distinguish between continuous and interruptible activities, a subject I have not seen discussed clearly and sufficiently elsewhere in the literature.

Chapter 6 deals with resource allocation and leveling. This concept is explained clearly, more so in English than in mathematical terms. The mathematical model or algorithm for resource leveling is not discussed because it is complicated and unnecessary and because most schedulers never refer to it. Powerful computers and software have made this function feasible and practical.

Scheduling would be worthless without updating and project control, so Chapter 7 covers this important subject. Chapter 8 addresses an interesting topic: schedule compression and time-cost trade-offs. In Chapter 9, I explain some commonsense ideas about reports and presentations, in the context of scheduling. In Chapter 10, I address scheduling as part of the project management effort. This chapter sheds some light on the interrelationships among scheduling, estimating, and other components of construction project management.

Chapter 11 covers a few other scheduling methods, such as the program evaluation and review technique (PERT) and the linear scheduling method (LSM). Chapter 12 provides brief coverage of delay claims, their avoidance, and their resolution. The chapter was written to provide an idea on the subject, and not as an in-depth reference.

Appendix A contains a computer project with multiple assignments that correspond to all subjects discussed in the book. Appendix B contains a few sample reports that the author created using Primavera P3e and SureTrak Project Manager software.

Throughout the book, not only there are illustrated examples for almost every concept, but also end-of-chapter exercises. Such exercises include both numerical type exercises (covering the spectrum of difficulty) and conceptual questions. The latter type contains mostly short, essay-type questions. Multiple-choice questions are not included because students need to know what the terms and definitions of construction scheduling are, rather than what they are not. Also, several exercise projects are provided so that students can use them for a computer project.

My intent was to introduce a scheduling book suitable for the 21st century. I hope that I have succeeded; however, I am sure that readers—construction professionals, educators, and students—will have suggestions and criticisms of this text. I encourage readers to send their corrections and suggestions to the publisher so that I can include any necessary changes in future editions.

In preparing this book, I relied on the help of many friends and associates. To them, I owe my gratitude. I give specific thanks to the reviewers of this text for their helpful comments: Michael J. Cook, University of Florida; Rocky Gerber, University of Washington; Charles R. Glagola, University of Florida; James L. Jenkins, Purdue University; David Leo Lickteig, Georgia Southern University; and James Stein, Eastern Michigan University. Likewise, thanks to Attorney Barry Bramble, who provided me with his invaluable contribution to Chapter 12, Construction Delay Claims.

Chapter 1

# Introduction



Interstate 4 and 17/92 intersection in Sanford, Florida

## PLANNING AND SCHEDULING

*Planning* and *scheduling* are two terms that are often thought of as synonymous. However, they are not. Scheduling is just one part of the planning effort. The term *planning* is used in many ways and different contexts. We commonly hear about *financial planning,* such as retirement planning and college education planning. Although these types of planning may include other aspects (such as what to do after retirement or which college to choose for your child), the main focus is on finance. Government organizations, as well as large corporations, have planning units or teams in almost every department. All plans in the individual units must be aligned with the organization's "*strategic plan,*" which is the long-term plan for the organization itself in terms of operations and growth. At the individual level, a young person may have plans for marriage, a career, and so forth. However, in the context of this book, the term *planning* is restricted to mean project planning, with an emphasis on construction projects.

### What Is a Project?

Before we define project planning, we need to define a project. The Project Management Institute (PMI) defines a **project** as "a temporary endeavor undertaken to create a unique product, service, or result" (PMI, 2013, p. 573). The key words in this definition are *temporary* and *unique*: any project must have a starting point and an ending point, and it must have a deliverable product, service, or result that is unique. As a generic example, a secretary of education saying "we need to improve our students' SAT scores" does not constitute a project. However, saying "we need to improve our students' SAT scores by an average of 15 points in five years" may qualify as a project. Another example: a newlywed couple may decide on saving money to buy a house. This is not a project, but saying "we are planning to save $50,000 in the next five years" may qualify as a project.

**Tip Box 1.1**

Every project must have a start point, a finish point, and a deliverable.

Some government agencies have specific but ongoing work that they call a project, such as maintenance of a certain facility or park compliance with the Americans with Disabilities Act or other regulation. Technically, these are not projects because they have no well-defined deliverable product or service and/or starting and ending points. Each could be called a *program*, instead, with several projects within each program. Basically, we need to distinguish between a program and a project:

- *Program*: A *program* may mean different things to different people, depending on the context. In project management, a program usually is a group of

related projects and/or services intended to meet a common objective and usually managed by one entity. A program can also indicate a large and complex project that is divided into several projects for more effective management. The PMI defines a program as "a group of related projects, subprograms, and program activities managed in coordinated way to obtain benefits not available from managing them individually" (PMI, 2013). Programs may include elements of related work outside the scope of the discrete projects in the program.

Programs may be temporary/one-time or ongoing:

- *Temporary/one-time programs*: For example, the City of Rio de Janeiro (Brazil) may include all of the construction projects for the 2016 Summer Olympics under one program. Once this program culminates with the completion of the projects, by the opening of the 2016 Summer Olympic Games, it will be completed and closed. However, the future maintenance of these facilities is a different matter.
- *Ongoing (usually periodic/annual) programs*: These include projects such as road maintenance and storm water programs for a public works department in many municipalities. Many private and public institutions have maintenance programs for their existing facilities. Such programs usually have an annual budget and cover numerous small projects—as many as the budget allows. The programs usually live as long the facility does.

One important note: in the United Kingdom, as well as in some other countries that use British terminology, the schedule (timeline) of the project is called *program* (spelled *programme*). This is *not* the same type of program that we are discussing.

- *Portfolio*: This is a group of projects, not necessarily related or dependent, that is, usually under one project manager or department. The PMI defines it as "projects, programs, subportfolios, and operations managed as a group to achieve strategic objectives" (PMI, 2013).
- *Project*: Defined earlier.
- *Subprojects*: These are segments of the original project that are divided according to specialty, responsibility, phase, area, or other criteria. To the person in charge of a subproject, the subproject is a project, except that the person has to consider not only the internal relationships among the activities but the external relationships as well (with activities in other subprojects in the same project). For example, in a residential or commercial development project, building the infrastructure may be regarded as a subproject. In fact, building the sewer system in the development can be a subproject (to the entire development project) or even a sub-subproject (to the infrastructure subproject).

  *Figure* 1.1 *demonstrates the structure of programs, portfolios, projects; and the relationships among them.*

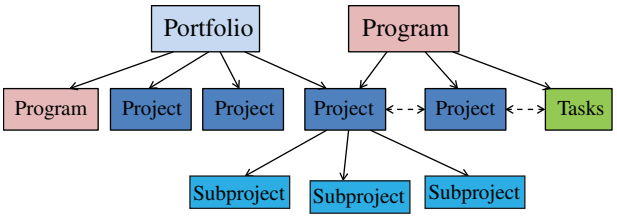



**Figure 1.1 Programs, Portfolios, and Projects**

### Are Projects Unique?

Some people may think of two construction projects as being identical just because they have the same design. In project management, we may have similar projects, but every project is unique. Differences may occur because of location (soil type, weather conditions, labor market, building codes, unforeseen conditions, etc.), labor skill level, management type and experience, or for other circumstances (and how much Murphy's Law was involved).

> **Tip Box 1.2**
>
> Just because two projects have exactly the same design and perhaps were built by the same contractor doesn't make them *identical*. They are similar but differences can come from site, location (building code, weather, etc.), workforce, execution conditions, and so on.

**Project planning** has been defined as "the process of choosing the one method and order of work to be adopted for a project from all the various ways and sequences in which it could be done" (Antill and Woodhead, 1990, p. 8; Callahan, Quackenbush, and Rowings, 1992, p. 2). The PMI defines the Planning Process Group as "those processes required to establish the scope of the project, refine the objectives, and define the course of action required to attain the objectives that the project was undertaken to achieve" (PMI, 2013). Project planning serves as a foundation for several related functions, such as cost estimating, scheduling, project control, quality control, safety management, and others.

**Scheduling** is the determination of the *timing* and *sequence* of operations in the project and their assembly to give the overall completion time. As mentioned previously, scheduling focuses on one part of the planning effort.

Project planning answers the questions: *What* is going to be done? *How*? *How much*? *Where*? By *whom*? *When?* (in general terms, the project's start and end). Scheduling deals with *when* on a detailed level. Figure 1.2 graphically demonstrates this concept. (See Figure 1.2.)

In fact, scholars have generally separated planning from scheduling: "CPM separates planning and scheduling, and once project information is collected and expressed

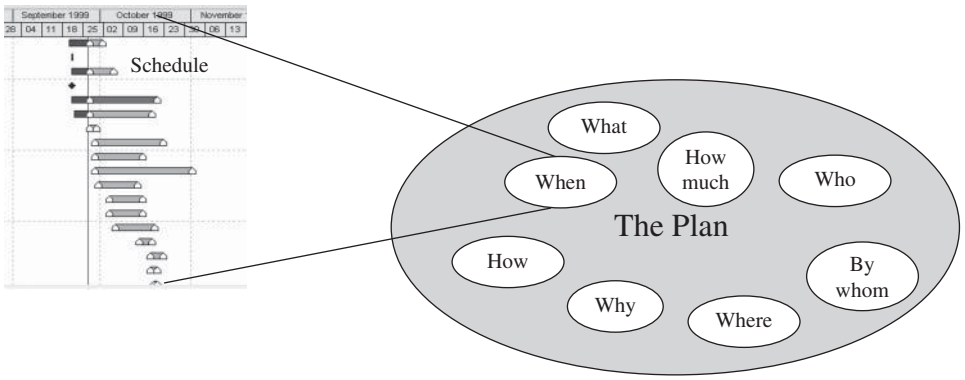



**Figure 1.2 Planning and scheduling**

as a network plan and activity time estimates assigned, CPM calculations can be made. Planning ceases and scheduling starts when the first computation is performed that shows a project duration. The project duration is then compared with the desired schedule and scheduling begins" (O'Brien and Plotnick, 2009, p. 417).

To get an idea about the relationship between project planning and scheduling, assume that you are planning a family vacation "project" for next summer. Your *plan* may include considerations such as the following:

- Who will go on the trip?
- Which places do you want to visit? (You would like to visit many places, but your time and monetary resources are limited.)
- What is the time frame for the vacation (just the starting and ending dates)?
- What is the total budget for the "project" (including the contingency you did not tell other family members about)?
- What types of activities do you want to participate in during the trip? (Are there sharp differences among the family members?)
- What means of transportation do you plan to use (your car, a rental car, air, train, bus, RV, etc.)?
- What other issues, such as accommodations, food, and clothing, need to be addressed?

The project *schedule* is simply the itinerary, such as the following:

- Leave home in Tampa, Florida, on June 8, 2015.
- Arrive in Panama City, Florida, on June 8, 2015.
- Leave Panama City on June 15, 2015.
- Arrive in Atlanta, Georgia, on June 15, 2015.

- Leave Atlanta on June 22, 2015.
- Arrive in Gatlinburg, Tennessee, on June 22, 2015.
- Return home to Tampa on July 7, 2015.

Note that not only are the plan and the schedule related, but also many of the activities and elements of the plan are interrelated. For example, most of the choices in the plan (length of stay, type of accommodations, type of activities, means of transportation, food, etc.) affect the budget. Since different means of transportation have longer time durations than others, they may affect not only the cost but also the schedule. Clearly, a lack of clarity of scope before the project starts may lead to heated arguments and dissatisfaction among team members later on. In real projects, it may lead to huge budget overruns, schedule delays, different parties' dissatisfaction, and a potential loss of business. Therefore, it is important to have a clear understanding of the project's scope, its constraints and requirements, and the decision-making process.[1] Many issues are at stake in this example, but demonstrating the concept of planning and scheduling is the objective.

It has been proven that good planning results in a high "rate of return" in terms of saving time, money, effort, change orders, claims and disputes, and headaches. In fact, there are many construction professionals who assert that there is an inverse relationship between the time of planning and the time of execution. Many owners rush the design and construction process because "they don't have time for planning." In fact, this is, in most cases, self-defeating and causes additional delays, costs, and headaches. An old carpenters' saying, "Measure twice and cut once," embodies this concept well.

**Tip Box 1.3**

Plan first: Measure twice and cut once!

**Project Management Plan:**

In the context of construction projects, a typical plan for an office building project may include the following:

- A *scope definition*, such as a five-story building for commercial use (offices) with a total area of about 30,000 square feet. The location is also part of the planning, although, in some cases, the exact location may be selected later or a few sites may be mentioned as candidates.
- A *schematic* or *conceptual design*. This is not a must but will help in visualizing the project. Also, deciding on the level of finish (economy, average, or luxury)

[1] There is more discussion on this issue in Chapter 10.

will help in making financial arrangements. The final design may later differ significantly.

- A *budget number* (e.g., $6 million). The planner must be aware of all project-related expenses, such as the cost of land, permits, design fees, construction, and so forth.
- A *time frame* (i.e., when the project is expected to start and end).
- *Other pertinent information* that may be used to justify the project or clarify some of its aspects. If an investor is doing the planning, a **pro forma** helps predict the rate of return and helps in making the decision as to whether or not to build the project.

PMI (PMI, 2013) defines a **project management plan** as "the document that describes how the project will be executed, monitored, and controlled." It may be summary or detailed and may be composed of one or more subsidiary management plans and other planning documents. The objective of a project management plan is to define the approach to be used by the project team to deliver the intended project management scope of the project.[2] It captures the entire project, covering all project phases, from initiation through planning, execution, and closure.

The level of details of the project management plan depends on several factors: the purpose of the plan, the timing of the plan, and the detailed information available (which is, in part, a function of the timing).

The project manager creates the project management plan following input from the project team and key stakeholders. The plan should be agreed on and approved by at least the project team and key stakeholders. It is a good practice, used by professional project management and consulting firms, to have a formal project management plan approved in the early stages of the project and applied throughout the project. Many owners (clients) require the contractor to submit a project management plan and have it approved as part of the contract documents.

Many professional organizations have an office dedicated to the project management planning and effort, called a *project management office (PMO)*, which is defined by the PMI as "an organizational structure that standardizes the project-related governance processes and facilitates the sharing of resources, methodologies, tools, and techniques" (PMI, 2013).

**Tip Box 1.4**

Have you ever thought of applying project management principles to your own life?

[2] This paragraph was taken from the PMI *PMBOK Guide,* 5th edition, 2013.

## PROJECT CONTROL

Once a project starts, certain aspects can easily deviate or go astray. This deviation can be overspending, a schedule slippage, a departure from the objective/scope, or something else. It is of the utmost importance to know at all times where you stand in comparison with where you planned to be (the baseline) at this time. If you find any variance, you must know the amount and causes of the variance and then take corrective action to get back on track or, at the very least, to minimize the variance. If the variance is positive (i.e., the project is ahead of schedule or under budget), actual performance was probably better than that expected in the baseline plan. This process exemplifies **project control**. Although the concept of project control may cover all aspects of the plan (budget, schedule, quality, etc.), our main focus in this book is on schedule and budget control, which are related. (Extensive coverage of project control is provided in Chapter 7.)

## WHY SCHEDULE PROJECTS?

There are several parties involved in any project (stakeholders). They all need and use project schedules but from different perspectives. Following is a group of reasons why project schedules are needed, from two different perspectives: contractors and owners.

Contractors need project scheduling to:

1. *Calculate the project completion date*: In most construction projects, the general contractor (GC), including subcontractors and other team members, is obligated to finish the project by a certain date that is specified in the contract. The contractor has to make sure that the schedule meets this date or otherwise has to accelerate the project. Some contracts contain clauses for penalties for finishing the project later than contractually required and/or incentives (financial or other) for finishing earlier. Also, the schedule may show the stage of **substantial completion**, when the owner may start occupying and using the facility, while the contractor is still doing some final touches.
2. *Calculate the start or end of a specific activity*: Specific activities may require special attention, such as ordering and delivering materials or equipment. For instance, the project manager may need special and expensive equipment to be delivered just in time for installation. Long-lead items may have to be ordered several months in advance. Delivery of very large items may need coordination or a special permit from the city so that the delivery does not disrupt traffic during rush hour. The schedule must show such important dates.
3. *Coordinate among trades and subcontractors, and expose and adjust conflicts*: In today's construction, the GC's role is mostly to coordinate different subcontractors. The responsibility of the GC may be to allocate the time of use of a tower crane among subcontractors or just to ensure that adequate work space is provided to all workers and personnel on-site. These tasks are in addition

to coordinating logical relationships, such as when a subcontractor's activity depends on the completion of another subcontractor's activity. For example, the drywall contractor cannot start until the framing has been done; once the drywall is installed, the painter can start painting; and so on.

4. *Predict and calculate the cash flow*: The timing of an activity has an impact on the cash flow, which may be an important factor for the contractor (or the owner) to consider. The contractor (or the owner) must know his or her total spending in any month or time period. He or she may delay the start of certain activities within the available *float* (this term is explained subsequently) to make sure that the cash flow does not exceed a certain cap.
5. *Improve work efficiency*: By properly distributing workers and equipment and having efficient materials management (which is explained in Chapter 6), the GC can save time and money.
6. *Serve as an effective project control tool*: Project control must have a solid and sound baseline with which current performance can be compared. Project control is achieved by comparing the actual schedule and budget with the baseline (as planned) schedule and budget (this subject is explained in Chapter 7).
7. *Evaluate the effect of changes*: **Change orders (CO)**[3] are usually inevitable, but well-planned projects may have few or minor ones. Change orders may come in the form of a directive, that is, an order to the contractor to make a change, or a request for evaluation before authorization. This change may be an addition, a deletion, or a substitution. Change orders may have an impact on the budget, schedule, or both. Cost estimators estimate the cost of change orders (including the impact on the overhead cost as a result of the schedule change), but schedulers calculate the impact of the change on the project schedule. It is the contractor's responsibility to inform the owner of such an impact on the budget or schedule and obtain the owner's approval.
8. *Prove delay claims*: Construction **delay claims** are common. Contractors must be able to accurately prove their claims against owners (or other parties) using project schedules. In most cases, only a **critical path method (CPM)** schedule can prove or disprove a delay claim, which can be a multimillion dollar one.

Project owners and developers need project scheduling to:

1. *Get an idea of a project's expected finish date*: Before an owner demands that the GC complete the project by a certain date, the owner needs to make sure that it is a feasible and reasonable date. This date is calculated by a CPM schedule, prepared by the owner or the designer, or a consultant hired by the owner. This date is also important to the owner, even before selecting a contractor, to conduct feasibility studies and financial planning.

[3] Also called *variation orders* in other countries, such as the United Kingdom.

2. *Ensure contractor's proper planning for timely finish*: Owners may demand a project schedule from the prospective or bidding contractor; however, it is very important for the owner to review such a schedule and make sure that it is reasonably accurate and realistic. The owner's approval of the contractor's prepared schedule may imply a liability on the owner's side.
3. *Predict and calculate the cash flow*: The owner is obligated to make timely progress payments to the contractor and other parties during the life of the project. Failure to do so not only may delay the project and/or incur additional cost but also may—at a certain point—be deemed a breach of contract.
4. *Serve as an effective project monitoring tool*: Both the owner and the contractor must monitor the progress of the work and compare the actual progress (schedule and cost) with the baseline (as-planned) schedule and budget. The contractor uses this process to detect and correct any deviations and also to prepare progress payments. The owner uses this process to verify the actual work progress and the contractor's payment requests.
5. *Evaluate the effect of changes*: Owners may desire or require change orders. In many instances, owners don't expect or fully appreciate the impact these change orders may have on the schedule and/or budget. It is wise for an owner to determine this impact before making a decision regarding a change order. It is also recommended that owners analyze the contractor's assessment of the change order to make sure that it is fair and reasonable.
6. *Verify delay claims*: Owners use CPM schedules to analyze, verify, and/or dispute contractors' delay claims. Although most delay claims are initiated by contractors against owners, it is possible to have an owner's claim initiated against the contractor and/or have other parties involved. In either case, a CPM schedule is vital for the owner to prove his or her case.

Other parties involved in the project may also need a CPM schedule, such as the designer, project management consultant, and financial (lending) institution.

The need for a CPM schedule varies with several factors. In general, it increases with the increase in size and complexity of the project. For example, a home builder who has built tens or hundreds of almost identical homes may not have a need for a CPM schedule as much as a high-rise building contractor does. Project control is still needed for all projects but may be conducted through simpler methods by the home builder.

## THE SCHEDULER

Is the scheduler a civil engineer, an architect, a computer whiz, a mathematician, a project manager, an artist, or a communicator? In reality, the answer is a combination of all of these! Using computer software and other high-tech tools has been an increasing trend in all industries. Software packages include generic types, such as word

processors and spreadsheets, that everyone uses, as well as specialized types that require knowledge in both the software and the specific technical discipline. Scheduling is no exception to this rule.

Let us distinguish among three types of knowledge that a scheduler must have:

1. Knowledge of computer software (and perhaps hardware as well) in project scheduling specifically but also project management and other related (e.g., cost estimating) software
2. Knowledge of the principles and concepts of project scheduling and control (as part of project management)
3. Knowledge of the specific technical field, such as commercial building, industrial, transportation, and so forth

To efficiently operate a scheduling and control program, such as Oracle Primavera Project Manager (P6) (Oracle Primavera Systems, Inc., Bala Cynwyd, Pennsylvania), the scheduler must have the first two types of knowledge. The third type is a big plus. Just because an individual knows computers and can do "computer stuff" does not mean that he or she can operate a scheduling and project control program. Even if the individual can operate it, he or she may not understand its language and may have problems relating to and interpreting the technical information.

Currently, many high-tech innovations such as PCs/laptops, tablets, cell/mobile phones, digital cameras, and the Internet are available. They have become useful tools and an essential part of our daily life. Nevertheless, the human factor should never be underestimated. The combination of good tools and an educated and experienced operator is the only path to success in project management.

### Certification

Several organizations now have a process and examination that lead to certification in project scheduling. The most prominent ones are:

- The AACE International's Planning & Scheduling Professional (PSP)
- The PMI's Scheduling Professional (PMI-SP)

Usually, an applicant for certification in project scheduling has to fulfill certain conditions:

1. Achieve minimum education requirements
2. Achieve minimum experience requirements
3. Pass the certification examination
4. Submit application and pay fees

Such certification is important in showing the qualifications of the scheduler, particularly to a potential employer. A certification from a reputable organization,

however, cannot alone guarantee good results. It just provides a minimum level of confidence in the qualifications of the person (usually the job applicant).

Unfortunately, the author knew people who carried the title "scheduler" but lacked the fundamental requirements for the position. In one incident, the author met a "scheduler" from a construction company who had no education or experience that was relevant to his job. He was chosen for that position because of his computer skills!

#### The Tripod of a Good Scheduling System

1. *The human factor*: A proficient scheduler or scheduling team that understands the concepts, definitions, and applications of project scheduling and control
2. *Technology*: A good scheduling computer system (software and hardware), along with capable IT support
3. *Management*: A dynamic, responsive, and supportive management team that believes in the use of scheduling as part of the management effort

If anyone of these three "legs" of the tripod is missing, the system will fail.

## SCHEDULING AND PROJECT MANAGEMENT

Planning, scheduling, and project control are extremely important components of project management. However, project management includes other components, such as cost estimating and management, procurement, project/contract administration, quality management, safety management, HSE (health, safety, and the environment) management, among others. These components are all interrelated in different ways. The group of people representing all these disciplines is called the **project management team**. It is usually headed by the **project manager (PM)**. In Chapter 10, we discuss the relationships between scheduling and other project management components.

## CHAPTER 1 EXERCISES

1. Define *project planning* and *scheduling*. Differentiate between the two terms.
2. Define *project*. What makes planning and scheduling construction projects different from general planning? (*Hint*: Think of the key words in the definition of *project*.)
3. Are the following projects? If no, make modifications that would qualify them as projects:
   a. Repair of a broken diesel generator
   b. Raising my two kids to be the best
   c. Cooking daily for my family
   d. Preparing for my son's wedding
   e. Investing in the stock market

f. Periodically backing up the data on my hard drive

g. Converting my garage to a play room

4. Define *portfolio* and *program* in the context of project management. Give examples of each.
5. What is a *project management plan*? Give an example.
6. What is *project control*? Why is it important?
7. Think of a construction project in which you participated or that you observed. Write down the steps involved in its planning and the steps involved in its scheduling (without much specificity).
8. List the benefits of CPM scheduling in construction projects from the contractor's perspective.
9. List the benefits of CPM scheduling in construction projects from the owner's perspective.
10. Do all construction projects have the same need for CPM scheduling? Why or why not? Give examples.
11. What characteristics must a scheduler of a building project have? Can the same person be a scheduler for an industrial project? Why or why not?
12. Meet with a project manager for a construction project. Ask whether he or she uses CPM scheduling. If so, discuss the benefits obtained from such scheduling. If not, politely ask why CPM scheduling is not being used.
13. Search for an article on a CPM scheduling topic (*ENR*, *Civil Engineering*, *PM Network,* and *Cost Engineering* are magazines that are good sources; avoid scholarly journals). Summarize and discuss the article.

Chapter **2**

# Bar (Gantt) Charts



Wadi Dayqah Main and Saddle Dams, Oman

## DEFINITION AND INTRODUCTION

A bar chart is a graphical representation of project activities that are shown in time-scaled bar lines with no links shown between the bars (activities) (Popescu and Charoenngam, 1995, p. 96). PMI (PMI, 2013) defines it as "a graphic display of schedule-related information. In the typical bar chart, schedule activities or work breakdown structure components are listed down the left side of the chart, dates are shown across the top, and activity durations are shown as date-placed horizontal bars."

The bar chart was originally developed by Henry L. Gantt, an American mechanical engineer, in 1917 and is alternatively called a **Gantt chart**.[1] It quickly became popular—especially in the construction industry—because of its ability to graphically represent a project's activities in a clear, simple, and time-scaled manner.

Before a bar chart can be constructed for a project, the project must be broken into smaller, usually homogeneous components, each of which is called an **activity** or a **task**. None of the methods is a uniquely "correct" way to break down a project into activities, nor can we describe other ways as incorrect. However, the scheduler should take a balanced approach and break the project down into a reasonable number of activities that are easily measured and controlled without being overly detailed. (Project breakdown is discussed further in Chapter 4.)

An activity, or a task, may be as large as laying the foundation of a building, as small as erecting the formwork of one footing, or anywhere in between. The duration of each activity must be estimated. Bars are then drawn to show each activity: the duration and the starting and ending points. As mentioned previously, links between activities are not usually shown.

On a bar chart, the bar may not indicate continuous work from the start of the activity until its end. For example, the activity Getting a Building Permit may be represented by a 2-month-long bar. However, most of this time is a waiting period. Likewise, a Concrete Foundation summary activity may include several days of waiting for the concrete to cure. Noncontinuous (dashed) bars are sometimes used to distinguish between real work (solid lines) and inactive periods (gaps between solid lines) (Callahan, Quackenbush, and Rowings, 1992).

Bar charts have become a vehicle for representing many pieces of a project's information. Many variations of bar charts have evolved; some simply show the start and the end of each activity (Figures 2.1 and 2.2), some are loaded with resource or budget numbers (Figures 2.3 and 2.4), and others compare the **as-planned schedule** with

[1] The notion that bar charts and Gantt charts are two different types of charts is baseless. There is a variety of bar chart types, and any of them can be called Gantt chart. Even though the PMI when defining bar charts says "also known as Gantt charts," it defines a Gantt chart as "a bar chart of schedule information where activities are listed on the vertical axis, dates are shown on the horizontal axis, and activity durations are shown as horizontal bars placed according to start and finish dates." This is not much different from the bar chart definition given previously.

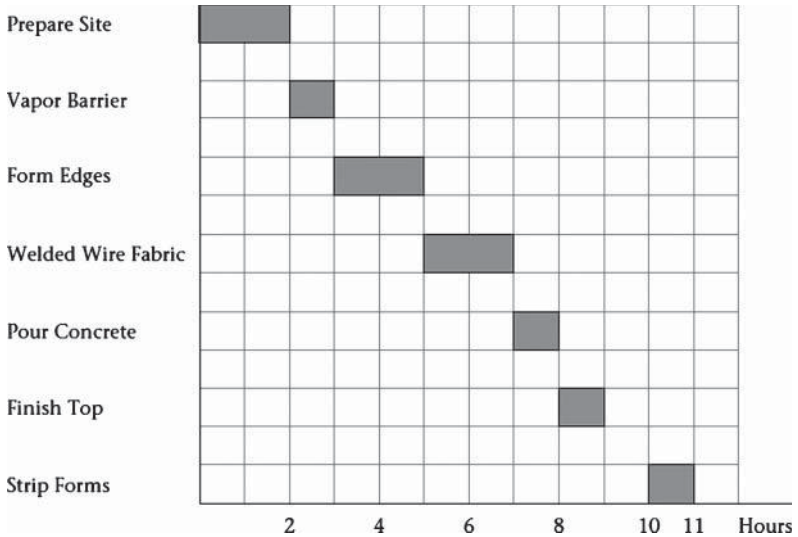



**Figure 2.1 Bar chart for placing a simple slab on a grade**

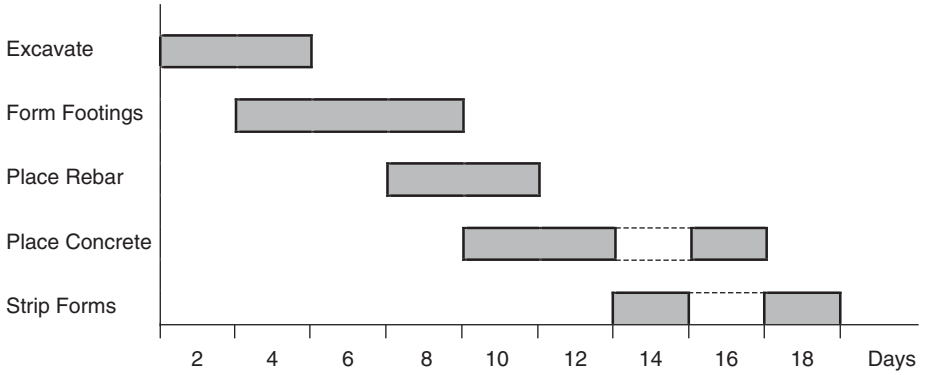



**Figure 2.2 Alternative bar chart for placing a simple slab on a grade placed in two parts**

the **as-built schedule** (Figure 2.5). Using Oracle Primavera Project Manager (P6) software, we can show activities with interruptions as continuous bars or as "necked" bars (Figure 2.3).

Since bar charts basically use the *x*-axis only (to depict time), the *y*-axis is used (in addition to showing individual activities) to represent a variable across time, such as man-hours (Figure 2.4), budget (Figure 2.5), percent complete (Figure 2.6), and so forth. This variable is usually shown as a curve superimposed on the bar chart. In Figure 2.5, **S curves** (also called *lazy-S curves*) represent the percent on extrapolation from the as-built curve.

| Activity ID | Activity Description | Orig Dur |
|---|---|---|
| 1000 | Excavate | 4 |
| 1010 | Form Footings | 6 |
| 1020 | Place Rebar | 4 |
| 1030 | Place Concrete | 6 |
| 1040 | Strip Forms | 4 |

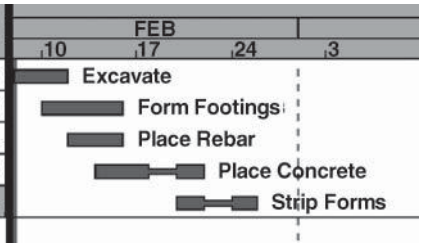



**Figure 2.3 Bar chart for placing a simple slab on a grade, with activities "necked" during nonwork periods**

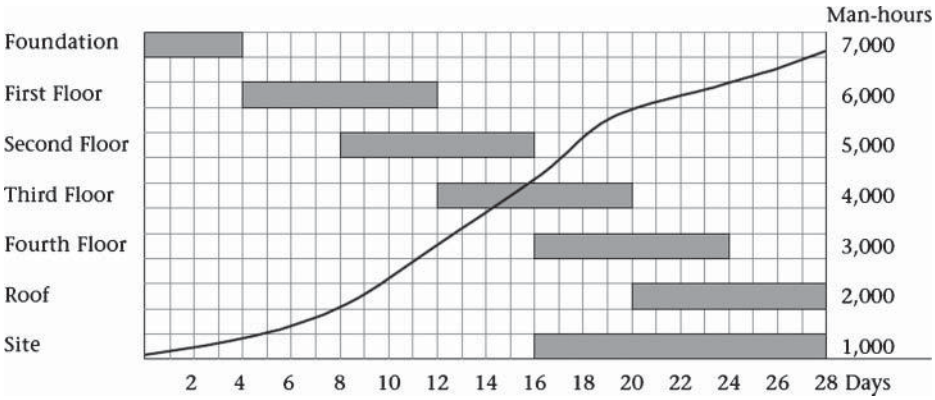



**Figure 2.4 Bar chart—loaded with man-hours—for construction of a two-story building**

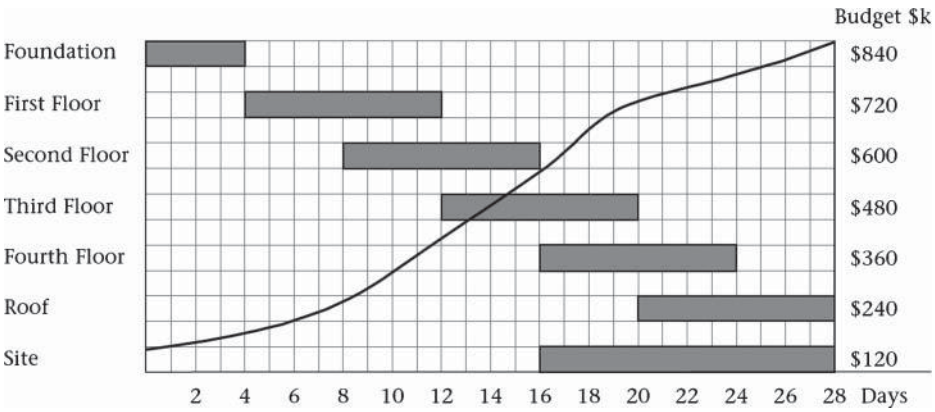



**Figure 2.5 Bar chart—loaded with the budget—for construction of a two-story building**

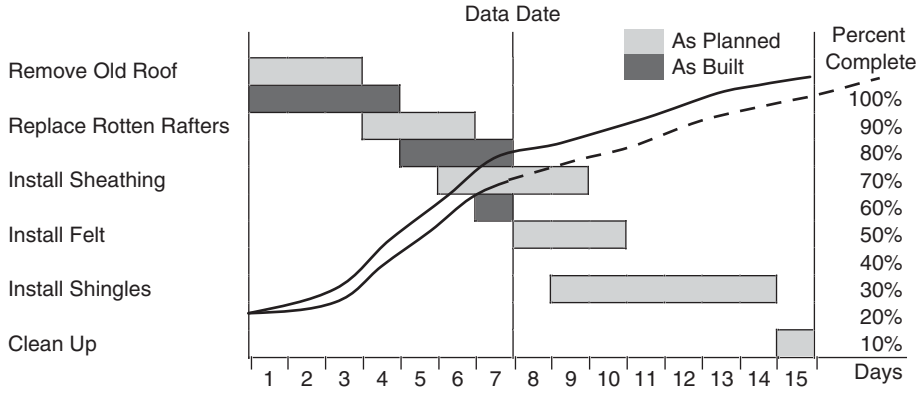



**Figure 2.6 Bar chart for replacement of an old roof, showing a comparison between the percent complete of the planned (as-planned) activities (thin line) and that of the actual (as-built) activities (thick line). The dashed line is an extrapolation of the actual curve.**

## ADVANTAGES OF BAR CHARTS

Bar charts have gained wide acceptance and popularity, mainly because of their simplicity and ease of preparation and understanding. No "theory" or complicated calculations are involved. Anyone can understand them. They can be prepared anywhere with just a pencil and paper. So, although bar charts can carry—or be loaded with—other information, the user must be careful not to overload them and, thus, lose their main advantage: simplicity.

Unlike networks, bar charts are time-scaled; that is, the length of a bar representing a certain activity is proportional to the duration of that activity. Just by looking at the chart, you can get an idea of the duration of each activity and the entire project.

Another advantage of bar charts is that they particularly appeal to persons who do not have a technical background. For example, some clients and upper-level managers may better understand the plan for carrying out a construction project by looking at a bar chart than by looking at a schematic of a logic network.

A final advantage of bar charts is the ability to roll up or roll down a schedule, on the basis of either a specific activity code (e.g., area, phase, responsibility, or floor) or the project's work breakdown structure (WBS) (explained in Chapter 4). For example, if the schedule on the detailed level (say level 5) has 2,130 activities, the bar chart can be rolled up to 342 activities (level 4) or to only 55 activities (level 3). Another example is that in a schedule for a high-rise building, you can show the bars summarized by floor, where all of the work on a floor is shown in one bar so that you can show the 3,000+ activities in only 30–40 bars. This is a major reporting advantage, because you can show the schedule in detail to the technical teams but "roll it up" to a small number of major (summary) activities for executive management. Although this roll-up/roll-down feature exists in logic networks, it is much clearer and simpler in bar charts.

With the advent of logic networks and the critical path method (CPM) and the evolution of powerful computers and software, bar charts have not perished or lost importance. Instead, they have evolved from a scheduling technique to a reporting tool, which that has made them more valuable and popular. This is explained in Chapters 3 and 4.

**Tip Box 2.1**

The most important advantage of bar charts is their simplicity. Whatever you do, don't lose this advantage.

## DISADVANTAGES OF BAR CHARTS

The main disadvantage of bar charts is their lack of logical representation (relationships); for example, why an activity started on a certain date (bar charts don't reveal the answer). The reason can be a logical relationship, a resource constraint, or a subjective decision by the project manager. Although some software programmers try to depict logical relationships on bar charts, the result is not always clear. The logic lines get tangled, and unlike networks, bar charts do not allow the length of the bars to be subjectively changed or the bars to be moved around to make the chart look or read better.

Another limitation, rather than a disadvantage, of bar charts is the size and complexity of projects. Bar charts may not be practical for projects with a large number of activities, *unless* you use them in two ways:

1. You show a subset of the work activities to maintain the simplicity of the chart. For example, the general contractor can produce bar charts for activities to be performed during only a certain period (two weeks, for example), for **critical activities** (activities that cannot be delayed or the entire project would be delayed; a full definition and discussion follows in Chapter 4) only, for activities in a certain section of the project, or for activities under a certain subcontractor.
2. You show summary/rolled up bars (each bar represents a group of activities combined on the basis of a certain criterion, such as department, major component, or responsibility). This can be done during the early planning phase, when details are not available (see, for example, Figure 2.7) and when you are reporting the information to high-level management.

New technology (computers, software, printers, plotters, etc.) has minimized or even eliminated some of the disadvantages of bar charts by enabling the user to organize, filter, roll up, summarize, or do almost anything to customize bar charts. We will discuss reporting and presentation further in Chapter 10.

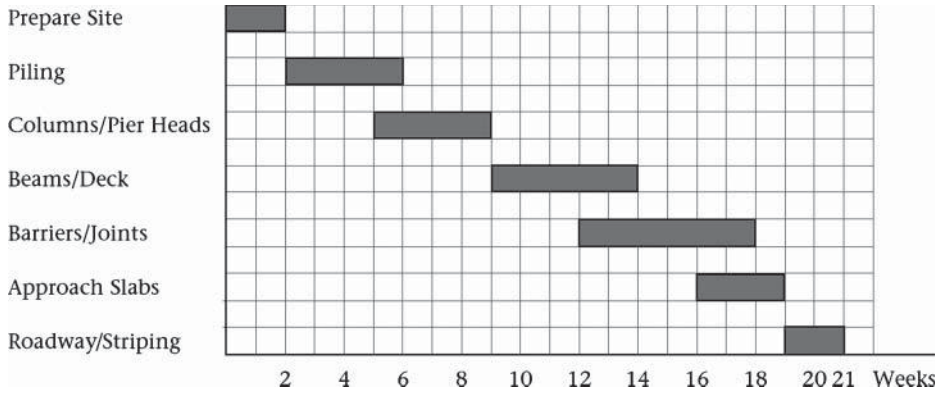



**Figure 2.7 Bar chart representing the summary activities for constructing a bridge**

## CHAPTER 2 EXERCISES

1. What is a *bar chart*? What other term is synonymous with bar chart? How did the other term originate?
2. What are the main advantages of bar charts that have made them so popular? What are their main disadvantages?

   In the following exercises, draw a bar chart that shows the time scale on the *x*-axis. Use engineering paper or draw light vertical lines at certain intervals (e.g., every 5 days) to help you read the start and end dates of any activity. Make simplifying assumptions whenever necessary. Be sure to mention these assumptions.
3. You are running out of space in your house, so you have decided to transform your two-car garage into a family room. In addition, you will build a simple carport in your driveway. Make a bar chart for this project, breaking your project into 10–15 work activities.
4. Think about obtaining a bachelor degree from a college as a project. You are advising a friend, a senior in high school who plans to attend college next year. Prepare a bar chart for him, depicting all of the courses that he must take from the start of college until graduation. Obtain the program course list. Make sure you do not overlook any prerequisite requirements. Make the following simplifying assumptions:

   a. Your friend is smart. He will not fail any course.
   b. All courses are available during every fall and spring semester.
   c. No summer semesters are included. Your friend will work during the summer.
   d. Your friend's total load every semester should be no less than 15 credit hours and no more than 18. You can let him take as many as 20 credit hours in one semester only, but only during the last year.
   e. Your friend must graduate in eight semesters.

After finishing the bar chart, show it to your adviser and get his or her approval on your sequence of courses. Note that several correct solutions to this problem may be possible (which is often the case with construction projects).

5. Draw a bar chart for building a detached shed in your backyard. Break your project into 10–15 work activities.
6. You are given the task of replacing the worn-out carpet in your office. Draw a bar chart showing all activities involved for this task (including removing and reinstalling baseboards; removing and disposing of the old carpet and the pad; selecting, purchasing, and delivering the new carpet and a new pad; cleaning up before and after installing the new carpet; and any other relevant activity).
7. Prepare a bar chart for building an in-ground swimming pool. If you do not know the steps involved, ask a friend or a local contractor.
8. Prepare a bar chart for making a cake (from scratch; don't use a ready mix). Choose the appropriate time unit (minutes, or 5- or 10-minute intervals).
9. Contact a contractor and ask the contractor whether he or she uses bar charts (they may be called *Gantt charts*). Ask about the main types of bar chart reports. Which groups of activities are included? Ask if the bar charts are prepared as bar charts or as an output for a CPM schedule.
10. To demonstrate the concept of summary bars, draw bar charts for building a new home. Use a few summary activities, such as laying the foundation, putting a slab on a grade, framing, electrical work, plumbing, HVAC (heating, ventilation, and air-conditioning), putting on the roof, installing doors and windows, and doing the finishing. You may need to show some of these activities (e.g., the electrical work or the plumbing) as discontinuous bars because you will start the activity (do a rough-in), stop, and then return and finish it. Take the chart to a specialized contractor and expand one of the bars. Expanding a summary bar means breaking it down into a number of activities that make up the summary activity. For example, you can expand Framing to Installing First-Floor Bottom Plates, Installing First-Floor Studs, Installing First-Floor Blocking, Installing First-Floor Top Plates, Installing Second-Floor Joists, and so forth. Note that the total duration of the summary activity must equal the total duration (not necessarily the algebraic summation) of the detailed activities within the summary activity.

Chapter 3

# Basic Networks



Sunny Isles Condominiums, Sunny Isles, Florida

## DEFINITION AND INTRODUCTION

A **network** is a logical and chronological, graphic representation of the activities (and events) composing a project. Network diagrams are basically of two types: arrow networks and node networks. Arrow networks were more popular in the 1960s and 1970s, and then precedence diagrams (an advanced form of node diagrams) became the choice for network scheduling.

Network scheduling has revolutionized the management of construction projects. It has provided management with a more objective and scientific methodology than simply relying completely on the project manager's experience and personal skills.

## ARROW NETWORKS

Arrow networks are also called the **arrow diagramming method (ADM)**, **activity on arrow (AOA) network**, or the **I-J method** (because activities are defined by the *from node*, I, and the *to node*, J). In this book, we use the term *arrow networks*. Throughout this chapter, you will find seven examples of arrow networks.

### Example 3.1

Draw the arrow network for the project given next.

| Activity | IPA[a] |
|---|---|
| A | – |
| B | A |
| C | A |
| D | B |
| E | C, D |

[a]Immediately preceding activity.

### Solution

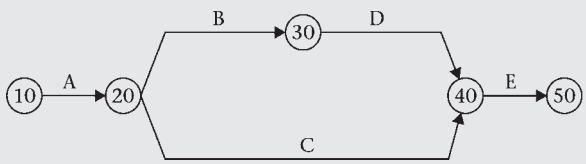



**Figure 3.1 Solution for example 3.1: a simple arrow network**

### Brief Explanation

In example 3.1, the project has only five activities, each represented by an arrow, as shown in Figure 3.1. Each arrow connects two nodes (depicted by circles with numbers in them): the *from node* and the *to node*. These nodes represent events: an **event** is a point in time when an activity starts or ends. In computer software, events with significance can be created as **milestones**, and they are either *start milestones,* such as Notice to Proceed, or *finish milestones,* such as Substantial Completion.

### The Logic

In example 3.1, activity A starts the project. Activities B and C follow, but independently. In reality, depending on the availability of resources and other factors, activities B and C may occur concurrently, overlap, or occur consecutively. However, both B and C cannot start until A is complete. Activity D must wait until activity B is complete. Once both C and D are complete, activity E can start. The end of activity E means the project is completed. Activity A is considered a **predecessor activity** to activities B and C.[1] Similarly, activity B is a predecessor to activity D. Conversely, we can say that activities B and C are **successor activities** to activity A, activity D is a successor to activity B, and so on. Activity A has successors but no predecessors. Activity E has predecessors but no successors. All other activities have both successors and predecessors.

As mentioned previously, a node in an arrow network represents an event or a point in time. This event is the starting or ending point of an activity (or activities). Node 10 represents the start of activity A (and hence the start of the project). Node 20 represents the end of activity A and the start of activities B and C. Node 30 represents the end of activity B and the start of activity D. Node 40 represents the end of activities C and D, and the start of activity E. Node 50 represents the end of activity E and the project.

### Notation

The arrow diagram is also called the *I–J method* because each activity is identified by the two nodes that define its start and end. For example, activity A is also known as 10–20, B as 20–30, C as 20–40, and so on.

### Dummy Activities

Let us consider a simple project.

[1] If you think of the activity as a college course, the predecessor(s) is similar to the prerequisite course(s).

### Example 3.2

Draw the arrow network for the project given next.

| Activity | IPA |
|---|---|
| A | – |
| B | A |
| C | A |
| D | B, C |

### Solution A

The main problem in this case, as shown in Figure 3.2, is that both activities B and C start from node 20 and finish at node 30. Hence, both are identified as 20–30.

This situation will create an identity problem. To solve this problem, we introduce a fictitious activity and an additional node. This fictitious activity is called a **dummy activity**, d. It is treated in the critical path method (CPM) calculations (discussed in Chapter 4) and in computer programs as a real activity even though it is not.

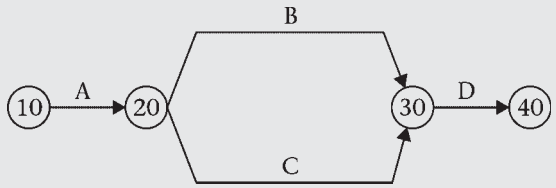



**Figure 3.2a Improper solution for example 3.2**

### Solution B

In this case, activity B is identified as 20–30, whereas activity C is 20–40, as shown in Figure 3.3. Note that the dummy can be inserted in different positions, as shown next. They all serve the same purpose.

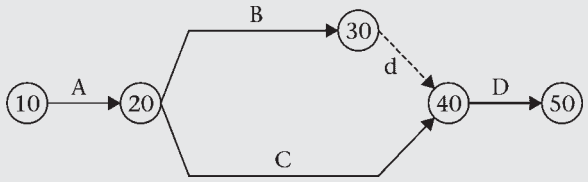



**Figure 3.2b Proper solution for example 3.2**

### Other Solutions

The position of the dummy is not unique in this example, it can be inserted in different positions, as shown in Figure 3.2c.

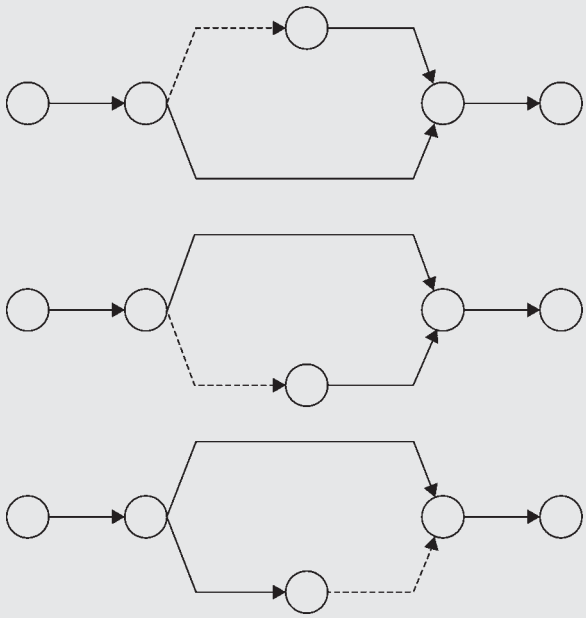


**Figure 3.2c Other proper solutions for example 3.2**

Let us now consider another example.

### Example 3.3

Draw the arrow network for the project given next.

| Activity | IPA |
|---|---|
| A | – |
| B | A |
| C | A |
| D | B |
| E | B, C |

The problem in this example is how to draw the preceding logic correctly. We need to show that activity E depends on both activities B and C, whereas activity D depends only on activity B. The solution can only be achieved by using a dummy activity, as shown next. Figures 3.3a and 3.3b are examples of improper logic. Figure 3.3c shows the proper logic.

### Solutions

We can complicate example 3.3 just a little with one change.

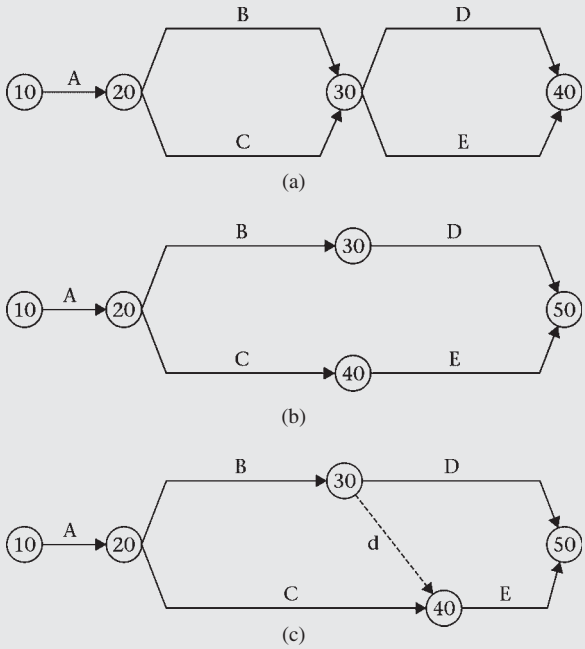



**Figure 3.3 (a) Improper solution, (b) another improper solution, and (c) proper solution for example 3.3**

### Example 3.4

Draw the arrow network for the project given next.

| Activity | IPA |
|---|---|
| A | – |
| B | A |
| C | A |
| D | B |
| E | B, C |
| F | C |

### Solution

The solution requires two dummy activities (or simply *dummies*) (Figure 3.4).

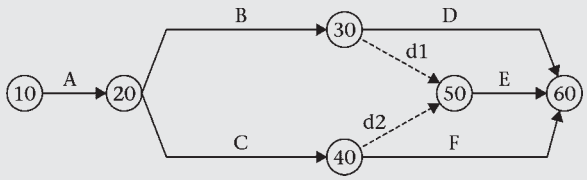



**Figure 3.4 Solution for example 3.4**

From the previous examples, we can define a dummy activity as a fictitious activity inserted in an arrow network to maintain proper logic or to distinguish the activities' identities. Two more examples demonstrate the need for dummy activities to straighten up the logic.

### Example 3.5

Draw the arrow network for the project given next.

| Activity | IPA |
|---|---|
| A | – |
| B | – |
| C | – |
| D | A, B |
| E | B, C |

### Solution

The solution also requires two dummies, *see* Figure 3.5.

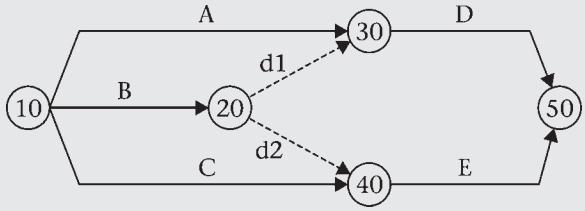



**Figure 3.5 Solution for example 3.5**

### Example 3.6

Draw the arrow network for the project given next.

| Activity | IPA |
|---|---|
| A | – |
| B | – |
| C | – |
| D | A |
| E | A, B |
| F | A, B, C |

### Solution

Again, the solution also requires two dummies as in Figure 3.6.

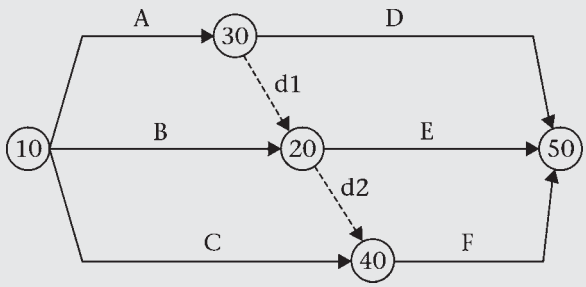



**Figure 3.6 Solution for example 3.6**

In larger projects, dummy activities may not only increase the number of activities but also complicate the schedule. This fact is one of the main disadvantages of arrow networks. The following example demonstrates this disadvantage.

### Example 3.7

Draw the arrow network for the project given next.

| Activity | IPA | Activity | IPA |
|---|---|---|---|
| A | – | H | C, D |
| B | A | I | D |
| C | A | J | E, F, G |
| D | A | K | F, G, H |
| E | B | L | H, I |
| F | B, C | M | K, L |
| G | C | | |

### Solution

This example is more complicated than the previous ones, requiring eight dummies, as shown in Figure 3.7. However, real projects with hundreds or thousands of activities, are far more complicated.

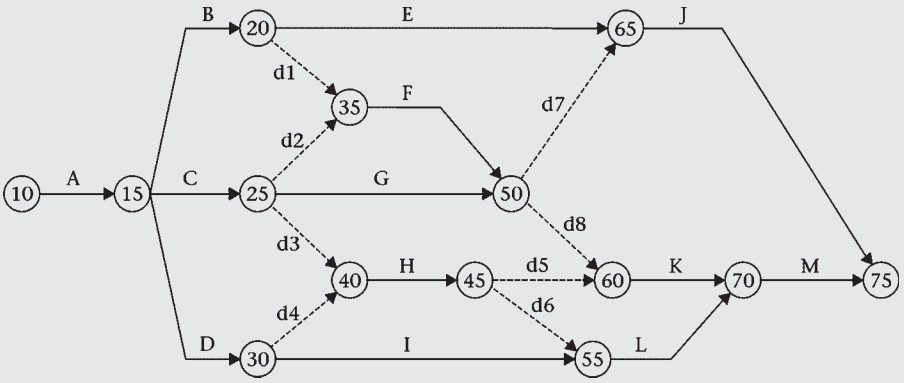



**Figure 3.7 Solution for example 3.7**

#### Redundancies

It is interesting to note that when you are building an arrow network, you can have not only a logically improper network but also a proper one with redundant dummy activities. This fact is especially true for complicated networks. Redundant dummy

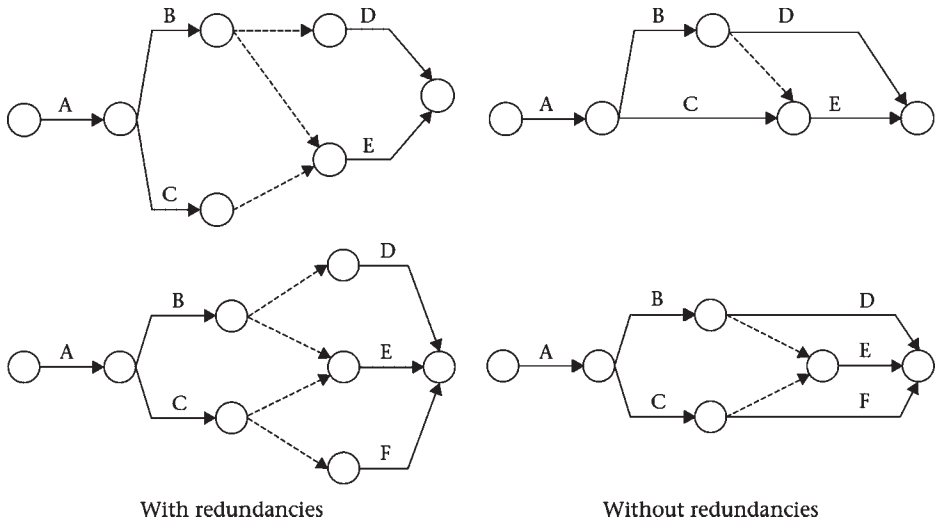



**Figure 3.8 Redundant versus needed dummy activities**

activities are not logically improper; they are simply redundant (see Figure 3.8). (*Note*: Students may lose points on exams for having redundant dummies.)

## NODE NETWORKS

Node networks are also called **activity on node (AON) networks**. In node networks, we use a different notation for representation: a node represents an activity. Nodes (activities) are connected with arrows (or lines) that represent logical relationships. For example, let us redo Examples 3.1 and 3.2 as node diagrams (see Figures 3.9 and 3.10). There is no need in the node diagram for dummy activities. A scheduling novice can draw a node diagram much easier than an arrow diagram.

For aesthetic reasons only, we like to start any network with one node (whether this node represents an event or an activity) and end it with one node. Doing so may require one or two fictitious activities in node diagrams that start or end with more than one activity. We call these activities *PS (project start)* and *PF (project finish)*, displayed as diamond-shaped nodes. For example, let us redo Examples 3.3

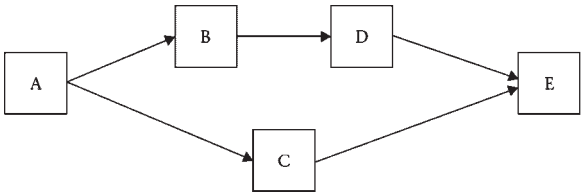



**Figure 3.9 Solution for example 3.1 as a node network**

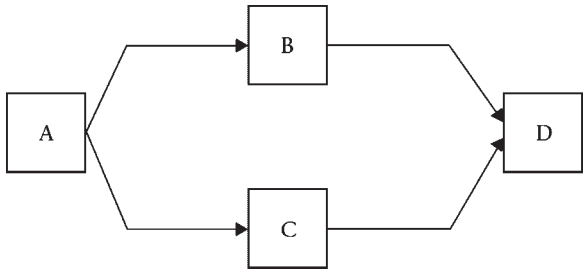



**Figure 3.10 Solution for example 3.2 as a node network**

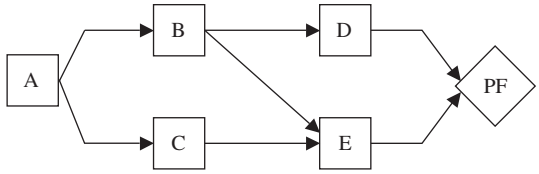



**Figure 3.11 Solution for example 3.3 as a node network**

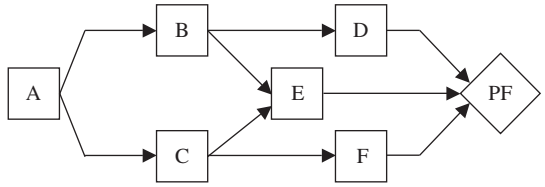



**Figure 3.12 Solution for example 3.4 as a node network**

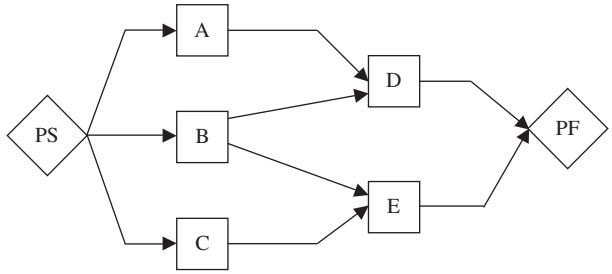



**Figure 3.13 Solution for example 3.5 as a node network**

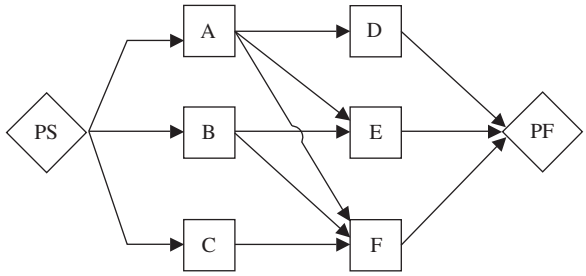



**Figure 3.14 Solution for example 3.6 as a node network**

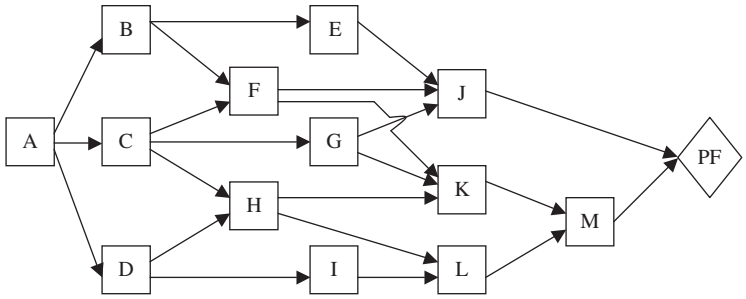



**Figure 3.15 Solution for example 3.7 as a node network**

through 3.7 as node diagrams. Figures 3.11 through 3.15 show the results. As shown in Figure 3.15, by using a node diagram, we can solve Example 3.7 without using the annoying eight dummy activities.

### Lags and Leads

In some situations, an activity cannot start until a certain time after the end of its predecessor. A typical example is concrete operations. Let us imagine this sequence:

1. Form the concrete column.
2. Install the steel reinforcement (commonly known as *rebar*).
3. Place the concrete.
4. Wait for the concrete to set (attain sufficient strength).
5. Strip the forms.

Note that the fourth step is not a "real" activity to which we must allocate resources and a budget. It is merely a waiting period, commonly known as a **lag**. A node network can accommodate such a lag if we simply put the lag on the relationship line between Place Concrete and Strip Forms, as shown in Figure 3.16a. This 3-day lag means a minimum waiting period of 3 days. Waiting less than 3 days violates the preceding logic, whereas waiting more than 3 days does not violate the logic. In some networks, the lag number is put inside a little box for better visibility.

Thus, a *lag* is defined as a minimum waiting period between the finish (or start) of an activity and the start (or finish) of its successor. Arrow networks cannot accommodate lags. The only solution in such networks is to treat it as a real activity with a real duration, no resources, and a $0 budget (Figure 3.16b).

With arrow networks, an activity is defined as "a unique unit of the project which can be described within prescribed limits of time" (Harris, 1978, p. 18) or "a time-consuming task" (Callahan, Quackenbush, and Rowings 1992, p. 29). Note

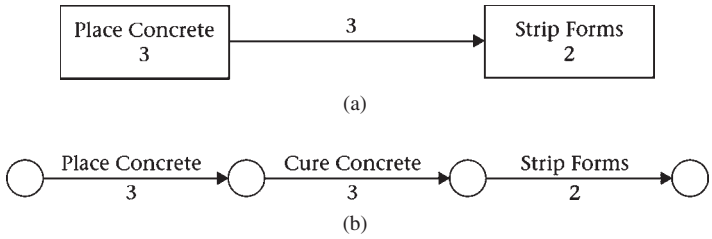



**Figure 3.16 (a) A lag in a node network; (b) a lag in an arrow network**

that these definitions include "waiting activities" that have no real work or assigned resources. With the current popularity of node (precedence) networks, the author of this book suggests changing the definition to "a resource-consuming task," since waiting periods are treated as lags rather than as real activities.

The term **lead** simply means a negative lag. It is seldom used in construction. In simple language, a positive time gap (lag) means "after" and a negative time gap (lead) means "before."

Lags and leads are covered in Chapter 4, where we discuss CPM calculations.

### Recommendations for Proper Node Diagram Drawing

1. Since nodes in arrow diagrams (events) are always drawn as circles, we like to draw nodes in node diagrams (activities) as squares (rectangles). Doing so not only eliminates confusion between an arrow network and a node network but also, more importantly, defines the "start side" and the "end side" of an activity. This distinction is important in precedence networks, which are discussed in Chapter 5. Milestones are usually drawn as diamonds to emphasize the fact that they have no duration; thus, nodes have no "sides." See Figure 3.17.
2. Do not connect nodes (in node diagrams) from the top or bottom (see Figure 3.18). Connect only the sides. The left side represents the start side, and the right side represents the end (finish) side, as shown in Figure 3.17.
3. Although networks are not time-scaled, in general, they should be designed from left to right in an almost chronological order. Relationship lines (arrows)

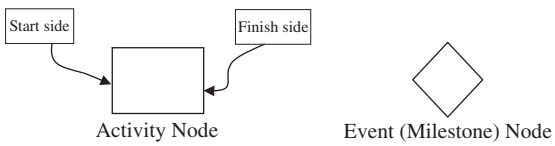



**Figure 3.17 Nodes and milestones in node networks**

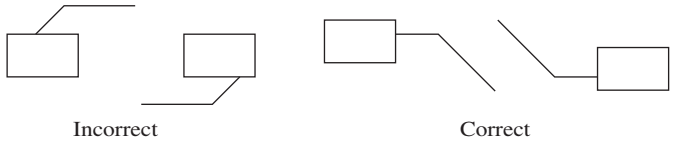



**Figure 3.18 Node connection in node networks**

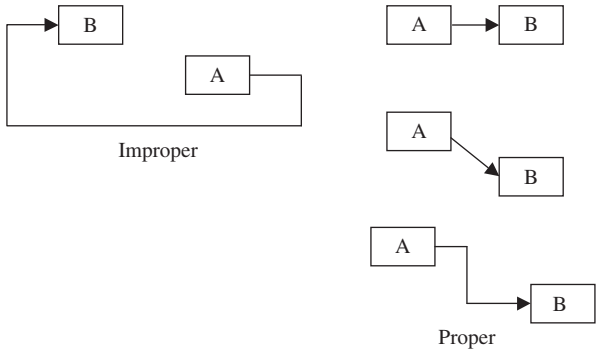



**Figure 3.19 Node order in node networks**

can be horizontal, inclined, or broken; however, they should be positioned, in general, from left to right. Try to avoid the situation shown in Figure 3.19.

4. Do not combine relationship lines (see Figure 3.20). These relationships are independent from their start to their end. Besides, one of them may carry a lag while the other one may not (or may carry a different lag).
5. Try to minimize line crossings (see Figure 3.21). When two lines (relationships) must intersect, make a "jump" on one of them to indicate that they do not intersect or meet.
6. Start the network with one node and finish it with one node. If the network starts with only one activity (such as those in Figures 3.11 and 3.12), then there is no need for an additional node. If it does not start with only one activity (such as those in Figures 3.13), then insert a PS (Project Start) milestone node at the start and tie it to those activities that start the network, as shown in

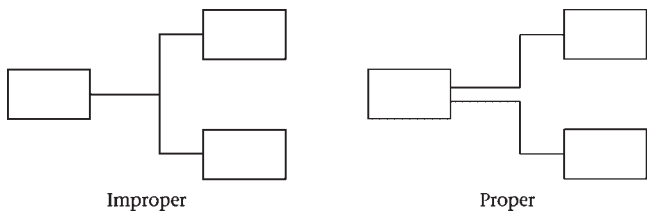



**Figure 3.20 Relationship lines in node networks**

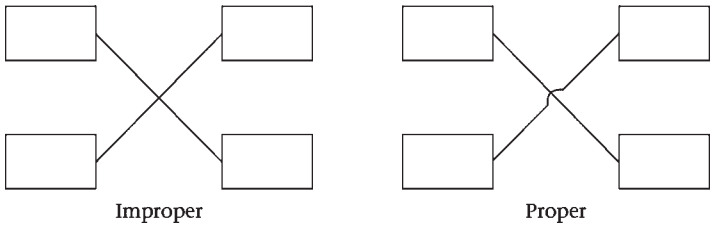
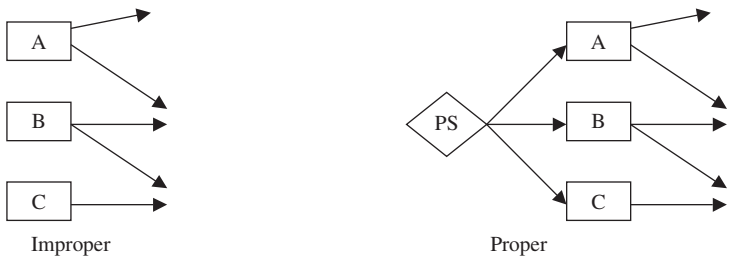



**Figure 3.21 Intersecting relationship lines in node networks**

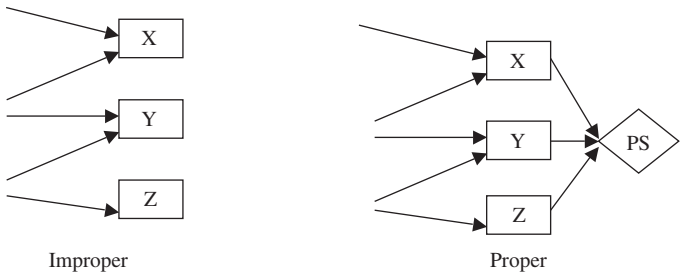
Figure 3.22a. The same concept applies to the end of the network: if it ends with one activity, then there is no need for an additional node. If not (such as those in Figures 3.11 to 3.15), then insert a PF (Project Finish) milestone node at the end and tie those activities that end the network to it, as shown in Figure 3.22b.

**Tip Box 3.1**

Every network must start with only one node and must finish with only one node.




(a) Do not start a network with more than one node




(b) Do not end a network with more than one node

**Figure 3.22 Converging the start and finish of node networks**

7. In many cases of hand drawing, you will need to redraw the network after your first attempt. Although your first attempt may be logically correct, it may look awkward and confusing. Redraw it to minimize lines crossing and relocate activities to be as near as possible to their predecessors and successors.

In most of the preceding points, the word *improper* may not mean "incorrect." However, following the preceding guidelines will result in a better and clearer drawing.

## COMPARISON OF ARROW AND NODE NETWORKS

From our discussion of arrow and node diagrams, we find that node networks have the following four advantages over arrow networks:

1. Node networks are easier to draw.
2. Node networks do not require dummy activities to fix the activity identity problem or to straighten out the logic.
3. Node networks can accommodate lags between activities without the addition of more activities.
4. In addition to the preceding advantages, node diagrams can be taken to an advanced stage in which they represent not just the traditional finish-to-start relationship but also three other relationships (start to start, finish to finish, and start to finish). This subject is discussed in detail in Chapter 5. However, we mention it here as one more advantage of node networks. Arrow networks can represent only the traditional finish-to-start relationship.

In fairness to arrow networks, they have one important advantage over node networks: they depict activities as well as events. Node networks do not contain provisions for events. This point is circumvented in node diagrams by creating milestone "activities" (such as in computer programs) with a zero duration to represent an important event such as the substantial completion of a facility. Generally, milestones in node networks work better than event nodes in arrow networks. Milestones are tied to the start or end of the specific activity or activities that we are considering. An event node in arrow networks may be tied to several events that represent the end and/or start of several activities when we are focusing on just one of these events. To understand this point, consider the event of the completion of activity K in example 3.7. This event is shown in the arrow network of Figure 3.7 as node 70. However, node 70 also represents the completion of activity L and the start of activity M. These three events may not—and usually do not—happen at the same time. Thus, the calculated event time for node 70 may not represent what we are looking for. In node networks, we create a milestone activity and tie it directly to the end of activity K. In this case, it will reflect the event of completion of activity K only. In addition, contrary to arrow networks that have a large number of event nodes, a user of node networks can decide to create only a few milestone activities (events, in actuality), which give them better visibility and more focus.

## NETWORKS VERSUS BAR CHARTS

When comparing bar charts with networks, we find that networks have three advantages over bar charts:

1. Networks show logic (i.e., the relationships among activities). Bar charts do not.
2. Networks can better represent large and complicated projects.
3. Networks can estimate, or predict, the completion date of a project, or other dates, on the basis of mathematical calculations of the CPM.

Bar charts predict the completion of the project, or other dates, on the basis of the user's skills. In contrast to networks, bar charts have five advantages:

1. Bar charts are time-scaled (i.e., the length of the activity bar represents the time duration of the activity). Both nodes, in the node networks, and arrows, in the arrow networks, are not time-scaled.
2. Bar charts are simple to prepare.
3. Bar charts are easy to understand.
4. Bar charts are more acceptable for presentations, especially for field people and people who are unfamiliar with the CPM.
5. Bar charts can be loaded with more information, such as cash-flow diagrams and man-hours. This advantage is partially a by-product of being time-scaled.

**Tip Box 3.2**

Bar charts did not vanish with the introduction of logic networks and the Critical Path Method (CPM). It just turned from a scheduling method to a display method for project schedules.

### Effective Use of Bar Charts with CPM

Bar charts have an effective weapon that CPM networks do not have: simplicity and power of presentation. As mentioned in item 4 in the preceding list, bar charts can be used effectively for mainly two types of presentations:

1. *Presentations to field people*: The project manager produces customized reports that include only a small group of the project activities (e.g., subcontractors' bar charts or "look-ahead" bar charts for work activities in the next 2 weeks). The project manager can also filter a group of activities that are to be done at a specific area of the project or only critical activities. With the use of activity codes and the power of computer software, there is no limit for such uses.

2. *Presentations to high-level staff*: CEOs and senior managers are usually not concerned with the progress at the individual activity level. They prefer to have an overall picture of the project and its main components. Roll-up or summary bar charts have become a popular option in computer software. The project activities are grouped (rolled up or summarized) based on a certain attribute, such as area, responsibility, phase, or the company's *work breakdown structure* Instead of looking at hundreds or thousands of activities, a top-level executive will look at a few bars that provide an overall picture of the progress of the project.

## TIME-SCALED LOGIC DIAGRAMS

Some scheduling software vendors tried to take the advantage of networks (logic, or relationships) and impose that advantage on bar charts in what some people called **time-scaled logic diagrams** (Figure 3.23). The result was more like spaghetti. Depicting all relationships not only complicated bar charts (which eliminates their main

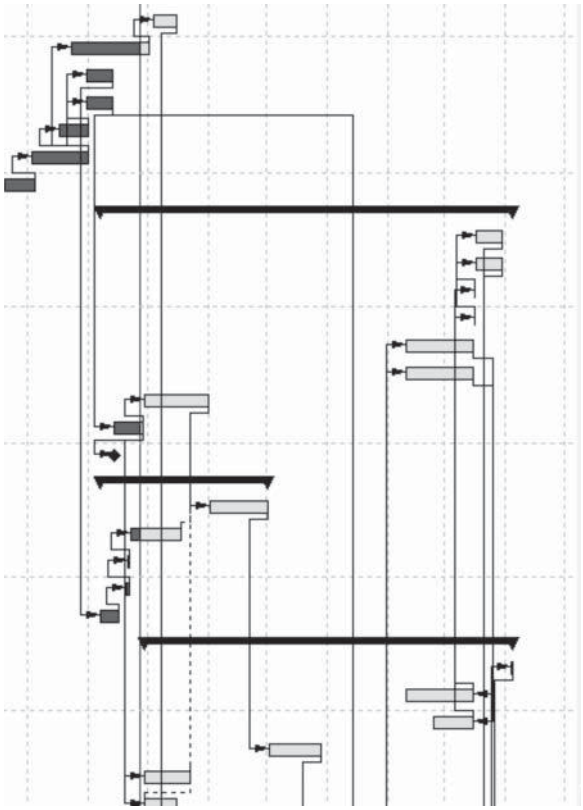


**Figure 3.23 Time-scaled logic diagram or bar chart with logic links**

advantage) but also did not make the logic as clear as it was in networks. This experiment was followed, in the software industry, by adding enhanced options such as "show only critical relationships" or "show only driving relationships." In some simple cases, this approach might work as a good and acceptable solution.

## CHAPTER 3 EXERCISES

1. What does a node mean in an arrow diagram?
2. What does an arrow mean in an arrow diagram?
3. What does a node mean in a node diagram?
4. What does a line mean in a node diagram?
5. What are the main differences between bar charts and networks?
6. What are the differences between arrow and node networks?
7. Arrow networks have another name; what is it? What is the reason for this name?
8. What are the main advantages of node networks over arrow networks?
9. What is the main advantage of arrow networks over node networks? How was it overcome?
10. What are *time-scaled logic diagrams*? Discuss their practicality.
11. What are the main advantages of networks over bar charts? How did bar charts manage to stay popular despite the advantages of networks?
12. Did logic networks and the critical path method replace bar charts as a scheduling technique? Explain your answer.
13. Draw both the arrow network and the node network for the following project:

| Activity | IPA |
|---|---|
| A | – |
| B | A |
| C | A |
| D | B |
| E | B, C |

14. Draw both the arrow network and the node network for the following project:

| Activity | IPA |
|---|---|
| A | – |
| B | – |
| C | A |
| D | A, B |
| E | C, D |

15. Draw both the arrow network and the node network for the following project:

| Activity | IPA |
|---|---|
| A | – |
| B | A |
| C | A |
| D | A |
| E | B |
| F | B, C |
| G | D, E, F |

16. Draw both the arrow network and the node network for the following project:

| Activity | IPA | Activity | IPA |
|---|---|---|---|
| A | – | F | D |
| B | – | G | D, E |
| C | – | H | C, F, G |
| D | A, B | I | C, G |
| E | B | J | H, I |

17. Draw both the arrow network and the node network for the following project:

| Activity | IPA | Activity | IPA |
|---|---|---|---|
| A | – | H | C, D |
| B | A | I | D |
| C | A | J | E, F, G |
| D | A | K | F, G, H |
| E | B | L | H, I |
| F | B, C | M | K, L |
| G | C | | |

18. Draw both the arrow network and the node network for the following project:

| Activity | IPA | Activity | IPA |
|---|---|---|---|
| A | – | H | D, E |
| B | – | I | D, E, F |
| C | A | J | F |
| D | A, B | K | C, H, I |
| E | A, B | L | I, J |
| F | B | M | I |
| G | C | N | G, K |

19. Draw both the arrow network and the node network for the following project:

| Activity | IPA | Activity | IPA |
|---|---|---|---|
| A | – | L | E, G |
| B | A | M | F, G, H |
| C | A | N | F, G, H, I |
| D | A | O | H, I |
| E | A | P | M, N, O |
| F | B | Q | K, L |
| G | B, C | R | L, M |
| H | B, C, D | S | J, P |
| I | C, D | T | Q |
| J | E | U | Q, R |
| K | F | V | T, U, S |

20. Convert the following arrow network into a node network.
21. Find and correct the errors and redundancies in the following arrow network.
22. Convert the following node network into an arrow network.

Chapter 4

# The Critical Path Method (CPM)



Expansion Nadd Al Hamar/Beirut Roads Tunnel, Dubai,
United Arab Emirates

## INTRODUCTION

Suppose that you meet two friends and decide to go on a hunting trip. One friend will get the food, the other will get the hunting gear, and you will prepare your Jeep for the trip. After each person finishes his or her assignment, you will drive together to the hunting location. Also suppose that the first activity (getting the food) requires 2 hours, the second activity (getting the hunting gear) requires 3 hours, and the third activity (getting the Jeep ready) requires 4 hours. If all three activities start at 8:00 A.M. (when each of you leave to perform his or her task), the following activity (driving to the hunting location) cannot start until all three of you return (i.e., when all three activities are completed). If everything works according to plan, the first person will return with the food at 10:00 A.M.; the second, with the hunting gear, at 11:00 A.M.; and you, with the Jeep ready, at 12:00 P.M. (see Figure 4.1).

Now, ask yourself the following question: "Which activity 'drives' or controls, the schedule?" The answer is the third activity (preparing the Jeep). Any delay in your return will delay the trip past 12:00 P.M. In contrast, your first friend will have 2 extra hours to "play with," and your second friend will have 1 extra hour. They can choose to use the extra time however they like. For instance, they can do the following:

- Get an early start, finish early, and then take a break
- Get a late start (10:00 A.M. for the first person and 9:00 A.M. for the second person) and finish at 12:00 P.M.
- Take breaks between work periods

We call this extra time **float.** Your friends will have to watch their time carefully so that they do not "waste" more time than the float they have: 2 hours for the first person and 1 hour for the second person. Any delay past these float times will result in a delay in the entire schedule. You, however, have no float. You are running on a tight schedule. Your activity is *critical.* This scenario provides a simplified example of the critical path method (CPM).

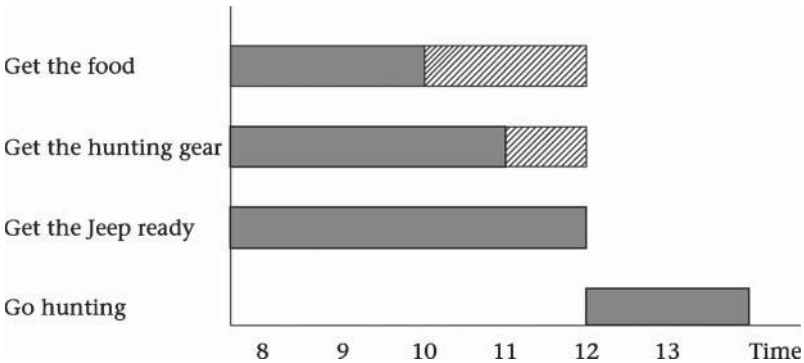



**Figure 4.1 Bar chart for introductory hunting trip example**

## STEPS REQUIRED TO SCHEDULE A PROJECT

For the planning, execution, and completion of a project, many steps are required that may not be part of scheduling. In this chapter, we discuss the role of the scheduler, given that the project has been defined (and designed in most cases). Some schedules (especially those for **fast-track projects**, in which construction starts before design finishes) may include design and design review activities as part of the schedule. In general, the preparation of a CPM schedule includes the following four steps:

#### *1. Break down the project into work activities*

Any project, no matter how large or small, must be divided into smaller entities, called *activities*, or *tasks*.[1] An activity is a unique, definable element of work. In this step, there is no absolutely correct or incorrect way to break down the project into work activities. You may give the same project to 10 schedulers, and they may devise 10 different breakdowns, with some breakdowns being significantly different. In this regard, there are two schools of thought:

a. *Restrict the number of activities for the simplicity of the project schedule*: In this case, activities become "major" components. However, there is a practical—and sometimes contractual—limit on how large an activity can be. For instance, it is impractical to have Concrete Operations as one activity with 300 days' duration. In addition, in many contracts, a maximum limit is set on the duration of any activity, usually about 14 to 30 days.
b. *Break the project down into smaller activities*: This approach will result in a large number of activities. The main advantage of this approach is better control of the schedule during execution. You can easily tell the status (percent complete) of a minor activity, such as Place Concrete for Spread Footings No. 23, better and more objectively than you can for a major activity, such as Building Foundation. The main disadvantage of having too many activities is the additional administrative work involved. However, this disadvantage may not be as important with the use of computers. Furthermore, you can roll up a group of activities into a major activity, as discussed in Chapter 3.

Factors that should be considered in breaking down the project into individual activities for better control are the following:

1. *Nature of the work/homogeneity*: If the work involves two different materials and/or is measured by different units, it must be divided into two different activities. For example, wall construction involves framing, drywall, and paintingas basic different activities.

[1] In reality, the two terms are synonymous. Some software packages use the term *task,* while others use *activity*, sometimes with the term *task* to indicate a subactivity.

2. *Location/floor/segment*: Activities occurring in different locations must be separated.
3. *Size/duration*: For large activities or those with large quantity, it is better to divide the activities into smaller portions. For example, excavation activities can bes divided into smaller activities by grid or depth. For linear excavation, this can be divided by stations or 100-foot segments. This helps in measuring the work's progress during execution. As mentioned earlier, this can be a contractual requirement.
4. *Timing/chronology*: Sometimes a portion of the work may be delayed purposely by the contractor. For example, a portion of the slab on grade (SOG) for a building may be delayed until the end of the project because the area is being used as storage. Such a portion must be considered as an activity by itself.
5. *Responsibility/trade*: Schedulers must break down portions of work that are done by different parties (e.g., subcontractors, crews). In case of a schedule variance, it is important to indicate who is responsible for the variance.
6. *Phase*: This can be a division made by the designer based on certain criteria, such as timing, location, or other aspects.
7. *Contractual restrictions*: In many contracts, especially government contracts, there is an upper limit to the duration of an activity, which, in turn, limits the size of that activity. Such a limit usually ranges from 14 to 30 days.
8. *Level of confidence in the duration*: The scheduler should use the "divide and rule" principle: whenever the scheduler's confidence in the duration of a certain activity is not high enough, the activity must be broken down into smaller activities so that the confidence level increases.

**Tip Box 4.1**

Never combine two activities if they are measured differently, performed at different locations, performed during different time periods, or performed by different crews.

The preceding eight factors underscore the difference between the cost estimator's and the scheduler's mentality in breaking down the project into activities. For example, to the estimator a slab on grade in the project is a slab on grade, no matter where or at what time it was placed. To the scheduler, it does matter.

The level of the details in breaking down the project into activities depends also on whether the schedule is a preliminary or a final, detailed schedule. In a typical preliminary schedule, it is normal to see a small number of major activities; each one represents a work package, assembly, or some activities that are grouped based on a particular criterion. Later on, when the design is completed, these major activities are broken down into minor activities, so a schedule with 50–70 activities can explode into one with 800–1,500 activities.

Each activity must be given a unique identity (ID). In this book, we deal mostly with examples of small projects. We use letters of the alphabet (A, B, C, etc.) as an ID for activities. Real-life projects may comprise hundreds—perhaps thousands—of activities. The ID must be chosen to follow a certain pattern that consistently uses alphanumeric characters. In many cases, the breakdown must be coded according to the company's policy, in which the code reflects the name of the project, the location, the type of activity, and so forth. The activity must have a title (description). Computer software programs require unique IDs but not unique titles, so it is possible for a scheduler to use the same title for a number of activities in the same project. The author strongly recommends making the titles unique as well by having the title describe two things: what (type of work) and where (location of the activity). For example in a multistory building, there will be many Suspended Concrete Slab activities, but it is better to give them titles such as Suspended Concrete Slab, 2nd floor, Suspended Concrete Slab, 3rd floor, and so on.

**Tip Box 4.2**

The title of each activity must indicate the work type (what) and the location (where).

One way to break down a project is by using the **work breakdown structure (WBS)**. The WBS is defined as a task-oriented, detailed breakdown of activities that organizes, defines, and graphically displays all of the work to be accomplished in order to achieve the final objectives of a project. The WBS breaks the project down into progressively more detailed levels. Each descending level represents an increasingly detailed definition of a project component. An example of the WBS can be seen in Figure 4.2. In construction scheduling, the components at the lowest WBS level are used as activities to build the project schedule. As mentioned previously, activities may be rolled up for summarization purposes.

Using principle 8 from our earlier discussion (level of confidence) means that not all activities will necessarily have the same level of detail. Two activities, for example, can be at WBS level 4. However, due to our low confidence in the duration of one of the activities, it has been broken down (detailed) to level 5, while the other activity stays at level 4 (Figure 4.3).

**Tip Box 4.3**

Defining activities: are you confident enough in the duration? If not, break it down.

Schedulers and estimators can use the standard breakdown of the CSI (Construction Specifications Institute) MasterFormat, which started in 1995 with 16 divisions

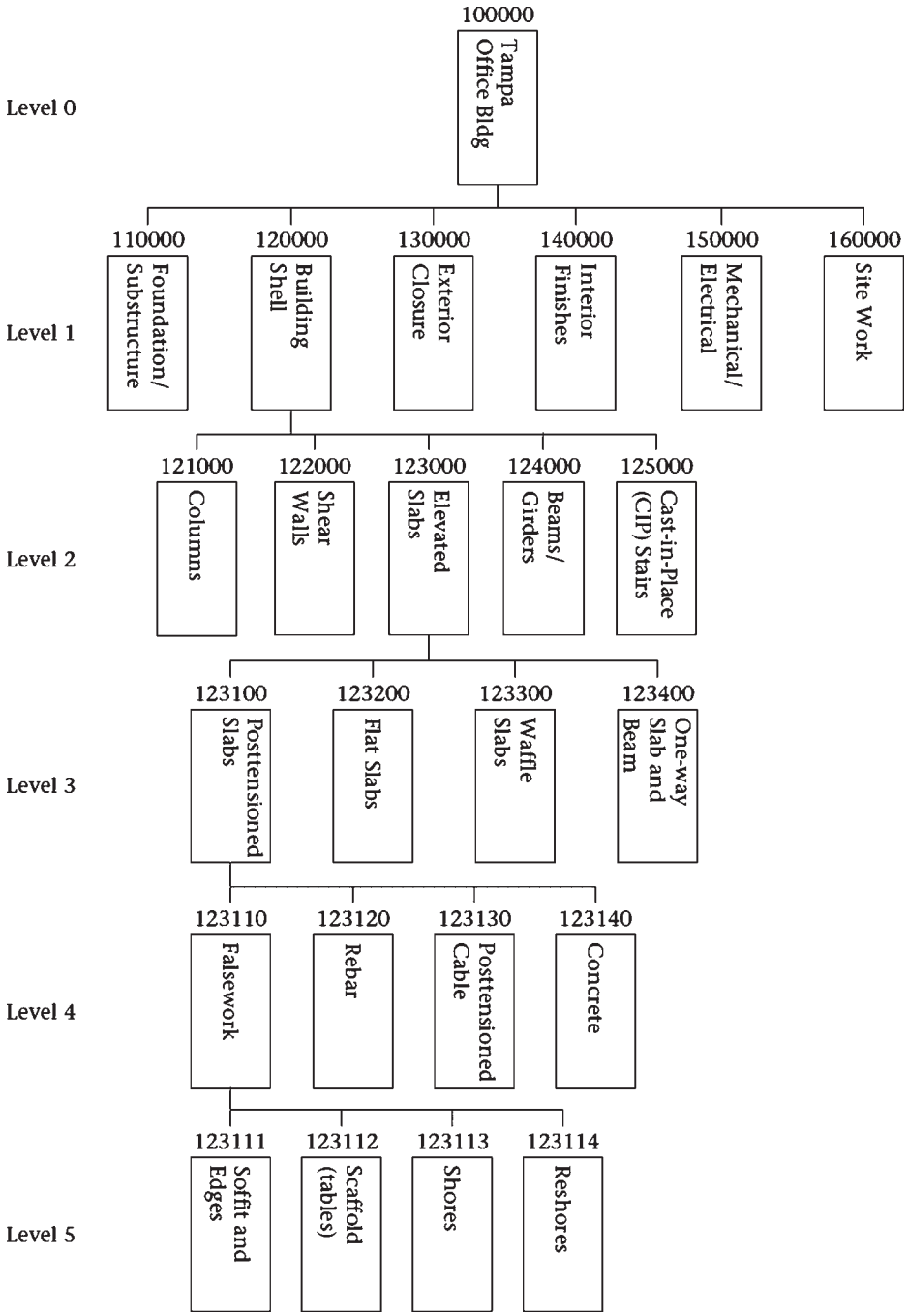



**Figure 4.2 Sample work breakdown structure (WBS)**

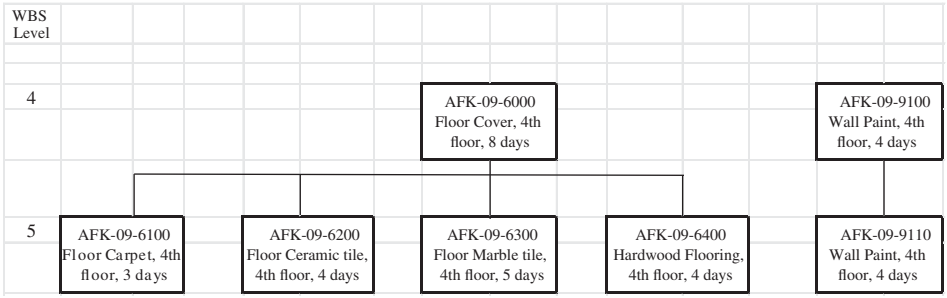



**Figure 4.3 Level of confidence forces the breakdown of one activity while another activity at the same level stays without being broken down further**

and then was expanded in 2004 to 50 divisions[2] and was later updated in 2010–2014, and will keep getting periodic updates.

#### *2. Determine activities' durations*

Techniques for estimating **activity duration** vary from one situation to another, depending on the type of work, the estimator, and other factors. Most activity durations can be estimated as follows.

For example, for 10,000 CY (cubic yards) of excavation and a crew that averages 800 CY per day, the following is true:

$$\text{Duration} = 10,000 \text{ CY} / 800 \text{ CY per day} = 12.5 \text{ days} \approx 13 \text{ days}$$

This information could come from the project team (project manager, project superintendent), who receives feedback from field crew leaders; from the estimating department; or from other sources (e.g., subcontractors). It is given to the scheduler with the project manager's approval. Durations are by no means carved in stone. They are based on previous experiences, with adjustments made for current job conditions, such as weather conditions, design complexity, soil type, and so forth. Durations are also subject to the crew size and the number of crews, if there is more than one crew. The durations of some activities are totally subjective and left to the project manager and the technical team, such as the mechanical or electrical repair team, to "guesstimate." Depending on the nature of the work and the work environment, it is a good idea for the scheduler to be moderately conservative in estimating durations. Remember that such estimates of durations, even when they have a scientific basis, are future predictions—and Murphy's Law always exists!

[2] Fifteen of the 50 divisions in the CSI MasterFormat 2014 are currently blank and labeled as "Reserved for future use." Some construction professionals refer to the count of the CSI MasterFormat 2004 and later versions as 49 divisions, because they forget to count division 00, Procurement and Contracting Requirements.

In most construction projects, durations are calculated in **workdays**, which usually, but not always, follow a 5-day workweek. In some cases, the project, or only certain crews, follow a 6- or 7-day workweek. In some other countries, a 6-day workweek may be the norm. In others, such as those in the Middle East, a workweek starts on Sunday not Monday. The scheduler must be aware of such **calendars.**

The scheduler must also account for **nonworkdays**, such as holidays, rain (weather) days, shutdowns, and the like. The contract usually specifies official holidays and the allowed number of **rain days**. Rain days represent the number of days (per month) during which work on the project is expected to be suspended because of weather delays. This prediction is usually calculated on the basis of past meteorological data for the location. It does not include unusual weather and disasters. (Delays due to unusual weather or disasters are discussed in Chapter 13.) The distribution of this time allowance is discussed in Chapter 10.

**Tip Box 4.4**

The scheduler should never unilaterally assign durations to activities without consultation with and getting an approval from the project manager and the technical teams' leaders.

Although the workday is the most often used **calendar unit** in construction projects, other units of time, such as hour, week, or month, are not unthinkable. Industrial and process (oil/gas) projects may have to be scheduled by the hour, especially with multiple-shift schedules. The scheduler, along with the management team leaders, must decide on the unit of time before preparing the schedule because changing the unit of time after the project starts is extremely difficult and confusing and can lead to unnoticeable errors. When choosing a time unit for duration, you can roll up the timeline in reporting, but you cannot roll it down. For example, if the time unit is "week," you can report in weeks, months, quarters, or years, but you cannot report in days.

**Tip Box 4.5**

If the activity has a planned nonwork (pause) period, it may be better to split it so that the resulting activities don't have any nonwork "gaps."

#### *3. Determine logical relationships*

Again, this step is a technical matter. The scheduler should obtain this information from the project managers and technical team leaders. Logical relationships should not be confused with **constraints.**

a. **A logical relationship** exists between two activities when the start of one activity (or finish, as is explained in Chapter 5) depends *physically* on the finish (or

start) of another activity. For example, you cannot place the concrete until the formwork and reinforcement are erected. You cannot hang the drywall until framing is done.

b. A resource constraint (or restriction) is when you can theoretically do two tasks at the same time but you schedule one as a predecessor of the other because of resource (labor, equipment) limitations.

   Some practitioners refer to the preceding two types of relationships as *hard logic* and *soft logic*, respectively. This terminology is scientifically suitable because hard logic cannot be relaxed under any circumstances, whereas soft logic can be relaxed if more resources are acquired.

c. There is another type of constraint: when an activity is under a subjective restriction such as approval of an owner or a government agency, funding availability, or even workspace availability. In most cases, such a constraint can be transformed into one of the two types previously discussed. Typically, a good project schedule may only have a few constraints of this type, at most.

**Tip Box 4.6**

Have you included all activities, including those to be performed by "external parties?"

#### *4. Draw the logic network, and perform the CPM calculations*

If you are using a computer program, it will perform these functions for you, provided that you have input the correct data. In this step, you will obtain the calculated finish date of the project, the critical path, and the available float for all noncritical activities. It is important to check the input and the output and not to rely totally on the computer.

In most construction projects, subcontractors are involved, and their input regarding the schedule is important. The **schedule** is typically one topic discussed in preconstruction meetings with the owner, the general contractor (GC), and major subcontractors. Often, the GC provides an opportunity for the major subcontractors to supply him or her with schedules for work so that he or she can incorporate them into the master schedule. Alternatively, the GC may create the overall schedule based on feedback from subcontractors and other involved parties. (The GC then has to communicate the schedule to all participants and get their approval or acceptance of their roles. This topic is discussed further in Chapter 10.)

**Tip Box 4.7**

Subcontractors' schedules must be compatible with the master schedule so they can be integrated smoothly.

## SUPPLEMENTAL STEPS

The preceding four steps make up the "backbone" of the CPM. Following are four additional steps that are essential for creating an effective, accurate, and successful schedule.

#### *5. Review and analyze the schedule*

First, review the logic and make sure that every activity has the correct predecessors and no redundant relationships. Common errors are as follows:

a. *Wrong relationship*: A wrong relationship occurs when the relationship is connected to the wrong activity or to the appropriate activity but at the wrong end (e.g., you connect the end of an activity when the relationship is start to start).
b. *Missing relationship*: A missing relationship occurs when a predecessor of an activity is simply not shown. If an activity does not have a predecessor or a successor, it is called a **dangling activity**. This is why we like to start the project with only one activity and finish it with only one activity. Computer programs such as Oracle Primavera P6 list all activities with either no predecessors or no successors. We typically like to see only one of each. Project managers and schedulers look at excessive float (explained later) as a red flag. Such excessive float usually—but not always—indicates a dangling activity. Even with practice, there is still a possibility of missing relationships, particularly external ones, that is, those that tie activities under one party to other activities under other parties.
c. *Redundant relationship*: When, for example, C requires B and B requires A, if we draw A and B as predecessors of C, A is a redundant predecessor of C (Figure 4.4a). Redundant relationships are not errors. They are just a nuisance and complication to the network.
d. *Logic loop*: A **logic loop** occurs when you leave a point on the network and then return to it later (e.g., A requires B, but B requires A) (Figure 4.4b). This

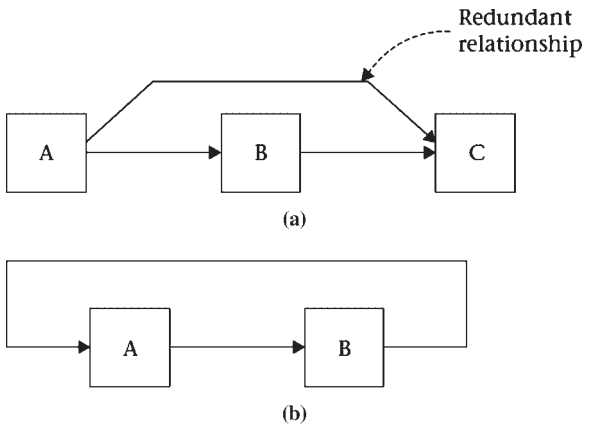



**Figure 4.4 Common scheduling errors: (a) redundant relationship; (b) logic loop**

error terminates the calculations in any CPM computer program. This author strongly recommends that when drawing (or inputting) the relationships, you do so from one side only. This means looking at either predecessors or successors, not both at the same time. This author personally prefers dealing with predecessors. When reviewing the logic, you can look at both ends of an activity to determine the accuracy of the logic.

#### *6. Implement the schedule*

Implementing the schedule means taking the scheduling from paper to execution. This step is important for fulfillment of the schedule. Most importantly, the scheduler (under directions from the project manager) must choose start and finish dates within the range of the calculated dates (early and late). When an activity has a range of dates (e.g., can start as early as 13 June 2011 and as late as 11 July 2011), it is *not* a good idea to give the choice of date selection to the field crew or even to the subcontractor. Computer software programs choose the early dates by default, unless there is a constraint forcing other dates.

Every participating party must receive correct information at the appropriate time. Too little or too much information may be counterproductive. Four important points should be noted: First, the schedule must be realistic, fairly accurate, and accepted by all parties. Second, the upper managers must take it seriously. Third, communication channels must remain open and clear among all project participants throughout the project duration. All parties must be informed of any change that may occur to the schedule. Fourth, such implementation and commitment must continue throughout the project.

#### *7. Monitor and control the schedule*

As defined in Chapter 1, *project control* means comparing the **baseline** (what was planned or what was supposed to have been done) with what actually has been done, analyzing any deviation (variance) from the baseline, and taking corrective action whenever and wherever needed. The main difference between the two terms (*monitor* and *control*) is in the corrective action taken. *Monitoring* includes observing and reporting, and perhaps analyzing. *Control* adds corrective action to this definition. The schedule may be monitored by the owner or the project management consultant (PMC). These two parties have no power to take direct corrective action during execution of the project. Only the party who is executing the work (usually the GC and subcontractors) can take direct corrective action. As in the last step, keeping open communication channels among all involved parties and disseminating appropriate and timely information are extremely important.

An important part of the control effort is *forecasting* Forecasting is done mostly by extrapolating the actual performance for the remaining portion of the project. When actual performance is below the baseline, forecasting is used more as a warning. For example, the project manager may say, “We are 20% complete for the project and we are $10,000 over budget. If we don’t make an adjustment, we’ll finish the project

$50,000 in the red." The scheduler can also experiment with different future scenarios and even use simulation to predict possibilities and their outcomes.

#### *8. Revise the database and record feedback*

This process is continuous and iterative. All cost and time estimates for activities are based on past experience. This past experience must be documented in a well-organized, easy-to-retrieve fashion. Every new cycle should be more accurate than the previous one. Suppose that you are estimating your new job on the basis of the past three jobs. After finishing this job and inputting the new results, your database now has four jobs, and the next job will be based on the four previous jobs, and so on.

In addition to documenting and organizing, you must record any unusual events and explain any adjustments that you make, because your record may be used for future estimates. For example, your productivity level for a certain activity happens to be significantly below normal because of extreme weather, sticky soil, hard rock, equipment failure, low morale as a result of an accident, or some other reason. Your productivity level may be above average because of an unusually favorable (or lucky[3]) work environment. Work stoppage also needs to be explained and justified. If the job being estimated is expected to be completed under unusual circumstances, the estimate must be adjusted accordingly.

## RESOURCE ALLOCATION AND LEVELING

In addition to the eight steps just discussed, two other optional steps may be implemented for a comprehensive approach to scheduling as part of project management:

#### *9. Cost/resource allocation (or loading)*

**Resources** in this context include labor, equipment, and materials. *Cost loading* means assigning the appropriate cost (or budget) to each activity. When the cost of all activities is added up, it should equal the project's budget. *Resource allocation* simply means assigning the right amount of resources to each activity at the right time. The objective of this step is to load each activity with the amount of resources it requires and, hence, calculate its budget. This can help link scheduling with estimating and accounting. At any point in the project, you should be able to tell the original (baseline) budget, actual cost, **estimate to complete (ETC)**, **estimate at completion (EAC)**, and other financial data for each activity and for the entire project. You can also link them to cost accounting for procurement, invoicing, and other functions.

[3] We teach that good results and smooth, flawless work are no accident or coincidence. However, the term *lucky* is used in this instance to emphasize the reality of estimation.

**Resource loading**, along with the "Resource Dictionary,"[4] will result in cost loading to each activity but in a smarter way than just assigning cost figures. Let's compare the cost of an Excavation activity with 12 days' duration, assigned in two different ways:

a. A cost number of $19,152
b. One Equipment Operator, one Laborer, and one Hydraulic Excavator

From the Resource Dictionary we find the unit cost for these resources:

Equipment Operator @ $45/hour
Laborer @ $32/hour
Hydraulic Excavator @ $980/day

So, the total cost for Excavation = 12 days $*$ [8 hours/day $*$ (45 + 32) + 980] = $19,152.

Assigning a budget by assigning resources to activities (method "b") has many advantages, such as:

- Ease of changing/updating the cost of an activity and the project when the unit price of a resource changes, especially when multiple activities use that resource
- Ability to integrate with accounting and procurement
- Ability to estimate and store (in a database) productivities and man-hours and to do a cost analysis
- Ability to do resource leveling and to set upper limits on resource consumption
- Ability to use "resource-driven" activities (i.e., allow the computer program to assign the maximum available resource amount to an activity, thus controlling its duration and timing within its float)

#### *10. Resource leveling*

This topic is discussed in detail in Chapter 6. **Resource leveling** is simply the attempt to maintain the uniform daily use of a resource (or resources) for the entire life cycle of the project or for the longest continuous segment of it. The objective of this step is to improve the efficiency of resource utilization (particularly labor and equipment) during the life cycle of the project.

[4] Resource Dictionary in Oracle Primavera P3 or P6 is a small database, at the level of the project, containing information on all resources such as cost and availability. It can—and usually is—exported from one (existing) project to another (new) one.

## BEGINNING-OF-DAY OR END-OF-DAY CONVENTION

In this book, for mathematical computations and for the sake of simplicity, we follow the **end-of-day convention:** any date mentioned for an activity means the end of that day. In this convention, projects usually start at the beginning of day 1, which becomes the end of day 0. Almost all authors use this convention. Computer software programs, however, are more sophisticated: the start date follows the **beginning-of-day convention**, and the finish date follows the end-of-day convention. These conventions are explained further in the following examples.

## THE CPM EXPLAINED THROUGH EXAMPLES

### Example 4.1: Logic Networks and the CPM

**Example 4.1**

Draw the logic network and perform the CPM calculations for the schedule shown next.

| Activity | IPA[a] | Duration[b] |
|---|---|---|
| A | – | 5 |
| B | A | 8 |
| C | A | 6 |
| D | B | 9 |
| E | B, C | 6 |
| F | C | 3 |
| G | D, E, F | 1 |

[a]Immediately preceding activity.
[b]In days.

**Solution: The Forward Pass**

The project starts with activity A, which starts at the beginning of day 1 (end of day 0). It takes 5 days to finish activity A; it finishes on day 5 (end of the day). At this point, activities B and C can start. Activity B takes 8 days; it can start on day 5 (directly after activity A finishes), so it can finish as early as day 13. Similarly, activity C can finish on day 11 (5 + 6). Activity D follows activity B. It can start on day 13 (end of B) and end on day 22. Activity E must wait until *both* activities B and C are finished. Activity C finishes on day 11, but activity B does not finish until day 13. Thus, activity E cannot start until day 13. With 6 days' duration, activity E can then finish on day 19. Activity F depends on activity C only. Thus, it can start on day 11 and finish on day 14. The last activity, G, cannot start until activities D, E, and F are finished. Through simple observation, we can see that activity G cannot start until day 22 (when the

last activity of D, E, and F finishes). Activity G takes 1 day, so it can finish on day 23. Figure 4.5 shows the completed logic network.

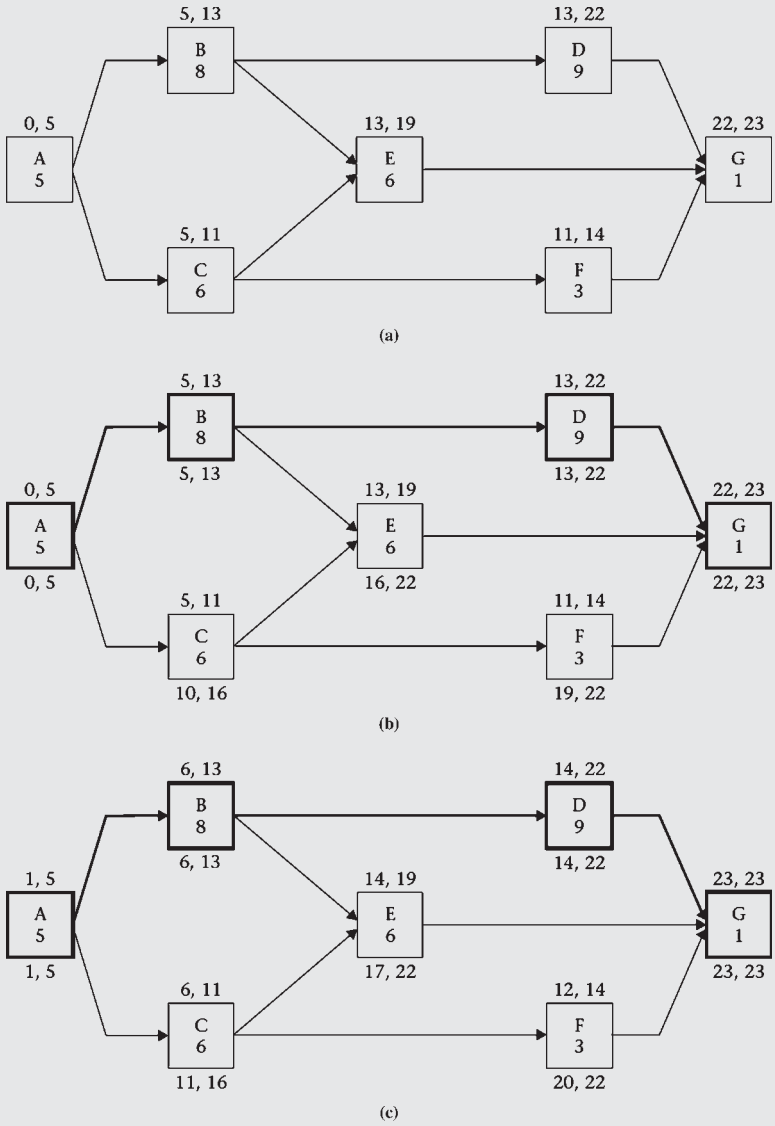



**Figure 4.5 Completed logic network: (a) forward pass; (b) forward and backward passes; (c) computer generated**

For this example, we have calculated two types of dates:

1. The expected completion date of the project: day 23
2. The earliest date when each activity can start and finish

These dates are called the **early start (ES)** and the **early finish (EF)** dates for each activity. As you will soon learn, an activity cannot start earlier than its ES date and cannot finish earlier than its EF date, but it *may* start or finish *later* than these dates.

In mathematical terms, the ES time for activity $j$ ($ES_j$) is as follows:

$$ES_j = \max(EF_i) \tag{4.1}$$

where ($EF_i$) represents the EF times for all immediately preceding activities.

Likewise, the EF time for activity $j$ ($EF_j$) is as follows:

$$EF_j = ES_j + Dur_j \tag{4.2}$$

where $Dur_j$ is the duration of activity $j$.

The **forward pass** is defined as the process of navigating through a network from start to finish and calculating the **early dates** for each activity and the completion date of the project. See Figure 4.5.

### Solution: The Backward Pass

Now let us start from the end of the project and work our way back to the start. We already know the end-of-project date[5]: day 23. Activity G must finish by day 23. Its duration is only 1 day, so it must start no later than day 22 (23 – 1) so that it does not delay the project. Similarly, activities D, E, and F must finish no later than day 22 so that they will not delay activity G. Through simple computations, we can find their late start dates: activity F: 22 – 3 = 19; activity E: 22 – 6 = 16; and activity D: 22 – 9 = 13. Activity C must finish before activities E and F can start. Their late start dates are 16 and 19, respectively. Clearly, activity C must finish by the earlier of the two dates, day 16, so that it will not delay the start of activity E. Thus, its late start date is day 10 (16 – 6). Similarly, activity B must finish by the earlier of its successors' late start dates: day 13 for D and day 16 for E. Therefore, the late finish date for activity B is day 13, and its late start date is day 5 (13 – 8). The last activity (from the start) is A: It must finish by the earlier of the late start dates for activities B and C, which are day 5 for B and day 10 for C. Consequently, the late finish date for activity A is day 5, and its late start date is day 0 (5 – 5).

[5] For now, we'll start the *backward pass* with the project's completion date, as calculated in the *forward pass*. Later on in this chapter, we will discuss other cases when an *imposed finish date* is implemented.

In mathematical terms, the **late finish (LF)** time for activity $j$ ($LF_j$) is as follows:

$$LF_j = \min(LS_k) \tag{4.3}$$

where ($LS_k$) represents the late start times for all succeeding activities.

Likewise, the **late start (LS)** time for activity $j$ ($LS_j$) is as follows:

$$LS_j = LF_j - Dur_j \tag{4.4}$$

The **backward pass** is defined as the process of navigating through a network from finish to start and calculating the **late dates** for all activities. This pass, along with the forward-pass calculations, helps identify the critical path and the float for all activities.

If you refer to Figure 4.5b, you can see that for some activities (light lines), the late dates (shown under the boxes) are later than their early dates (shown above the boxes). For other activities (thick lines), late and early dates are the same. For the second group, we can tell that these activities have strict start and finish dates. Any delay in them will result in a delay in the entire project. We call these activities *critical activities*. We call the continuous chain of critical activities from the start to the end of the project the **critical path**.

Other activities have some leeway. For example, activity C can start on day 5, 6, 7, 8, 9, or 10 without delaying the entire project. As mentioned previously, we call this *leeway float*.

There are several types of float. The simplest and most important type of float is **total float (TF)**:

$$TF = LS - ES \text{ or } TF = LF - EF \text{ or } TF = LF - Dur - ES \tag{4.5}$$

We tabulate the results in the following table (boldface activities are critical):

| Activity | Duration | ES | EF | LS | LF | TF |
|---|---|---|---|---|---|---|
| A | 5 | 0 | 5 | 0 | 5 | 0 |
| B | 8 | 5 | 13 | 5 | 13 | 0 |
| C | 6 | 5 | 11 | 10 | 16 | 5 |
| D | 9 | 13 | 22 | 13 | 22 | 0 |
| E | 6 | 13 | 19 | 16 | 22 | 3 |
| F | 3 | 11 | 14 | 19 | 22 | 8 |
| G | 1 | 22 | 23 | 22 | 23 | 0 |

With the completion of the backward pass, we have calculated the late dates for all activities. With both passes completed, the critical path is now defined and the amount of float for each activity is calculated.

### The CPM with Computer Software Programs

If we plot the previous CPM network by using one of the commercially available computer software programs, such as Oracle Primavera P6 or Microsoft (MS) Project, Figure 4.5c will be the result. The only difference between the network shown in Figure 4.5b and that shown in Figure 4.5c is the start dates because, as mentioned previously, these computer programs use the start of the day when calculating start dates and the end of the day when calculating finish dates. This approach affects the forward-pass and backward-pass calculations. Equations 4.1 through 4.4 are, thus, rewritten as follows:

$$ES_j = \max(EF_i) + 1 \qquad (4.1)'$$

$$EF_j = ES_j + Dur_j - 1 \qquad (4.2)'$$

$$LF_j = \min(LS_k) - 1 \qquad (4.3)'$$

and

$$LS_j = LF_j - Dur_j + 1 \qquad (4.4)'$$

### The Critical Path

If we think about the situation in the project we have just scheduled, we will notice that activities A, B, D, and G are "driving" the schedule. These activities are critical because any delay in their start or finish will delay the entire project. For example, if activity B takes 9 days instead of 8 days, it will finish on day 14. Activity D can then start and will finish on day 23. Finally, activity G can start on day 23 and will finish on day 24, which is 1 day past the originally scheduled date. This delay in the project completion date may not occur with a delay (within certain limits) in other activities, such as C, E, or F. Project managers usually focus on the critical path because of its criticality and direct impact on the project finish date. Knowing not only which activities are critical and which are not but also the impact of the delay of one activity on other activities and on the entire project is the crux of understanding scheduling.

Following are five observations about the critical path:

1. In every network, there must exist at least one critical path.
2. More than one critical path may exist. Multiple paths may share some activities.
3. Any critical path must be continuous from the start of the project until its end. There is one exception: when a constraint is imposed (which is discussed later), a path may become critical as a result of the constraint, from the start until the constrained activity, or from the constrained activity until the end. In general, the entire path must be either critical or noncritical.

4. If all paths in a network must go through one particular activity, this activity must be critical (e.g., activities A and G in example 4.1).
5. Some people like to define *critical path* as the path with zero float. This definition is correct only if no **imposed finish date** is used in the backward-pass calculations (again, this point is discussed later). However, our definition—the longest path in a network, from start to finish—is more appropriate because it is always true. We can also say that the critical path is the path with least float.[6]

**Tip Box 4.8**

Near-critical activities may be as important as critical activities.

**Driving and Nondriving Relationships:** Activity E in example 4.1 has two predecessors: B and C. We observe that the relationship coming from activity B is the one that controls the start of activity E. The relationship coming from activity C has no bearing on the starting of activity E. In this case, we call the relationship from activity B to activity E a *driving relationship*. Conversely, we call the relationship from activity C to activity E a *nondriving relationship*. Similarly with activity G, the relationship from activity D is driving, while the relationships from activities E and F are nondriving.

**Tip Box 4.9**

Contractors: Don't accept unrealistic durations demanded by owners. Don't overpromise; otherwise, you will underdeliver!

#### Definitions

**Activity, or task:** A basic unit of work as part of the total project that is easily measured and controlled. It is time- and resource-consuming.

**Backward pass:** The process of navigating through a network from end to start and calculating the late dates for each activity. The late dates, along with the early dates, determine the critical activities, the critical path, and the amount of float that each activity has.

[6] Think algebraically; TF = −8 is less than TF = 0.

**Critical activity:** An activity on the critical path. Any delay in the timely completion of a critical activity will result in a delay in the entire project.

**Critical path:** The longest continuous path in a network from start to finish. It represents the summation of the durations of activities and lags along that path, taking into consideration calendars, constraints, resources, and other impacting factors.

**Driving relationship:** A relationship from a predecessor activity that controls the start or finish of a successor activity. For any activity with predecessors, there must be at least one driving relationship.

**Early dates:** The early start date and early finish date of an activity.

**Early finish (EF):** The earliest date on which an activity can finish within project constraints.

**Early start (ES):** The earliest date on which an activity can start within project constraints.

**Event:** A point in time marking the start or end of an activity. In contrast to an activity, an event does not consume time or resources. In computer software, events with significance can be created as milestones, and they are either **start milestones**, such as Notice to Proceed, or **finish milestones**, such as Substantial Completion.

**Forward pass:** The process of navigating through a network from start to end and calculating the completion date for the project and the early dates for each activity.

**Late dates:** The late start date and late finish date of an activity.

**Late finish (LF):** The latest date on which an activity can finish without extending the project's duration.

**Late start (LS):** The latest date on which an activity can start without extending the project's duration.

**Total float (TF)**: The maximum amount of time an activity can be delayed from its early start without delaying the entire project or violating a schedule constraint.

**Tip Box 4.10**

A project manager needs to decide on a single set of dates within the range of early/late dates. Never give your subordinates two start dates and two finish dates.

## Examples 4.2 and 4.3: Node Diagrams and the CPM

### Example 4.2

Draw the node diagram and perform the CPM computations for the schedule shown next.

| Activity | IPA | Duration |
|---|---|---|
| A | – | 2 |
| B | A | 6 |
| C | A | 10 |
| D | A | 4 |
| E | B | 7 |
| F | B, C | 5 |
| G | C, D | 3 |
| H | E, F | 5 |
| I | G, H | 2 |

### Solutions

Performing forward and backward passes yields the solution shown in Figure 4.6. The critical path is A, C, F, H, I. Activities B, D, E, and G have total floats equal to 2, 13, 2, and 7, respectively.

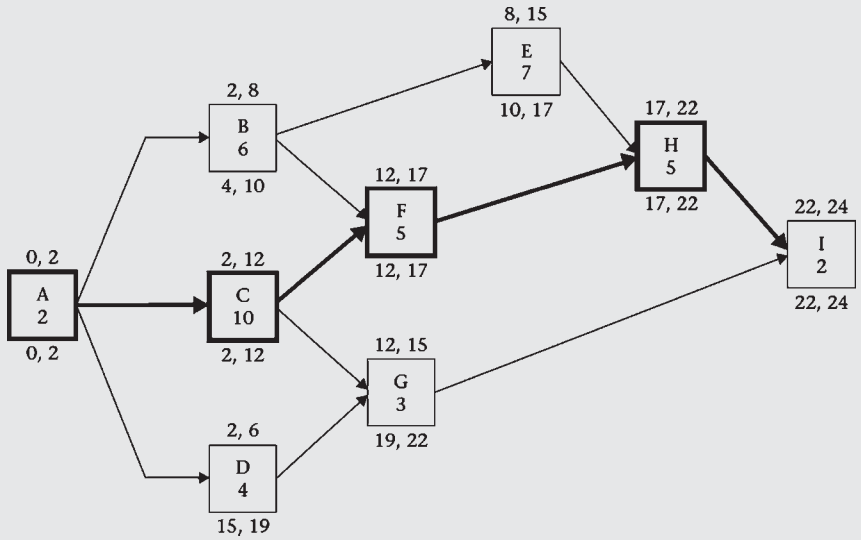



**Figure 4.6 Node diagram for example 4.2**

### Free Float

Let us examine the impact that one activity may have on other activities when it consumes its total float or part of it. In example 4.2, if activity B is delayed by only 1 day and starts on day 3 (which is well within its available float), it will finish on day 9. (*Remember*: We always mean the end of the day.) Activity E, then, cannot start on its early start date (i.e., day 8). The earliest date E can start is day 9. If we delay activity B by 2 days, activity E cannot start until day 10 and, thus, becomes critical. This 1- or 2-day delay in the start of activity B will not affect the project completion date. However, if we delay activity B by more than 2 days, it will finish past day 10, which will affect the start of the critical activity H and, thus, delay the entire project. This discussion illustrates the concept of *total float*, which was defined previously as the maximum amount of time an activity can be delayed without delaying the entire project. Note, though, that this delay—within the total float—may (and did in this case) or may not delay the early start of the following (succeeding) activities.

Now let us apply the same discussion to activity G. It has 7 days of total float. Delaying it by as many as 7 days will not impact the succeeding activity, I. The same argument applies to activity E, only with 2 days of total float.

Next, we discuss yet another case of total float. Consider activity D, which has 13 days of total float. When we delay it by 1 or 2 days, for example, we notice that this delay does not impact the early start of the following activity, G, since G is waiting for the completion of activity C as well. However, when the delay of activity D exceeds 6 days, the situation changes. If we consider delaying activity D by 7 days, it finishes on day 13. Activity G, then, cannot start until day 13. It should finish on day 16, which will not delay activity I or the entire project. This 7-day delay in activity D delays the early start of its successor (activity G), yet it does not delay the entire project. We can increase this delay to 13 days (which is the total float for activity D) without affecting the completion date of the entire project, but it does impact the succeeding activity, G.

We can divide activity D's 13-day total float into two portions: the first 6 days will not delay its successor. This is called *free float (FF)*. The other 7 days will cause a delay to its successor even though they will not delay the entire project. This is called **interfering float (Int. F)**. We can look at the situation this way: activities D and G share the 7-day interfering float. If the first activity uses it, it will be taken away from the next activity. Similarly, we can determine that activity B has no free float (total float is all interfering float). The free float of activity G equals its total float (no interfering float). To calculate free float for an activity, we need to compare its early finish date with its successor's early start date. When there is only one successor activity (Figure 4.7a), the calculation is simple:

Activity G's free float, $FF = 22 - 15 = 7$ days. When the activity has more than one successor (Figure 4.7b), you must pick the earliest early start date among the successors: activity B's free float, $FF = \min(12,\ 8) - 8 = 0$ days. In general, free float is calculated by using the following equation:

$$FF_i = \min(ES_{i+1}) - EF \tag{4.6}$$

where $\min(ES_{i+1})$ means the least (i.e., earliest) of the early start dates of succeeding activities.

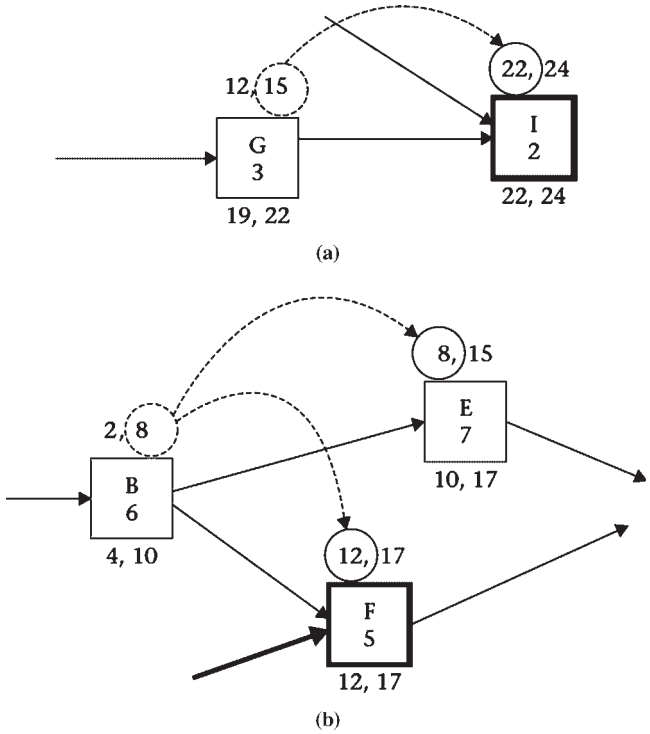



**Figure 4.7 Free float with (a) one successor activity and (b) more than one successor activity**

### Example 4.3

Draw the node diagram and perform the CPM computations for the schedule shown next.

| Activity | IPA | Duration | Activity | IPA | Duration |
|---|---|---|---|---|---|
| A | – | 2 | H | D | 9 |
| B | A | 7 | I | F, G | 12 |
| C | A | 10 | J | F | 5 |
| D | A | 4 | K | E, J | 5 |
| E | B | 6 | L | G, H | 6 |
| F | B, C | 5 | M | F, H | 4 |
| G | C, D | 8 | N | I, K, L, M | 3 |

### Solution

Performing forward and backward passes yields the solution shown in Figure 4.8.

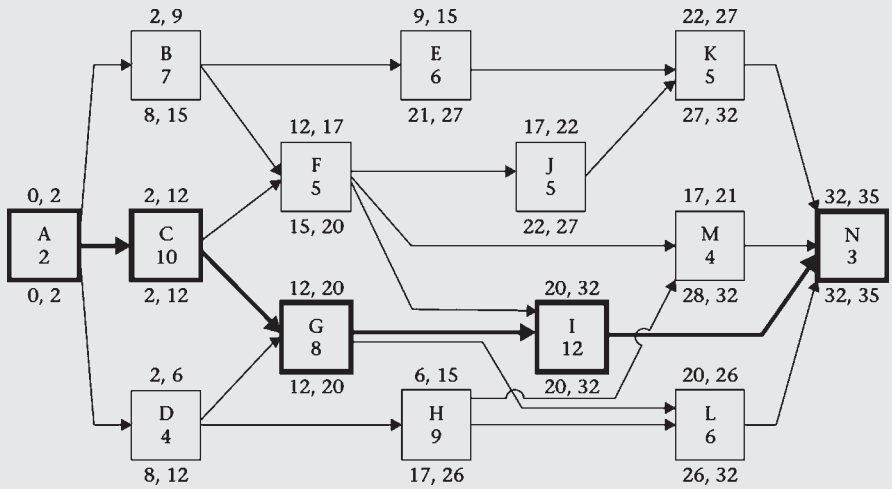



**Figure 4.8 Node diagram for example 4.3**

Performing the CPM calculations, we find the early dates, late dates, total float (TF), and free float (FF) for all activities, as shown in the following table.

| Activity | Duration | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|
| A | 2 | 0 | 2 | 0 | 2 | 0 | 0 |
| B | 7 | 2 | 9 | 8 | 15 | 6 | 0 |
| C | 10 | 2 | 12 | 2 | 12 | 0 | 0 |
| D | 4 | 2 | 6 | 8 | 12 | 6 | 0 |
| E | 6 | 9 | 15 | 21 | 27 | 12 | 7 |
| F | 5 | 12 | 17 | 15 | 20 | 3 | 0 |
| G | 8 | 12 | 20 | 12 | 20 | 0 | 0 |
| H | 9 | 6 | 15 | 17 | 26 | 11 | 2 |
| I | 12 | 20 | 32 | 20 | 32 | 0 | 0 |
| J | 5 | 17 | 22 | 22 | 27 | 5 | 0 |
| K | 5 | 22 | 27 | 27 | 32 | 5 | 5 |
| L | 6 | 20 | 26 | 26 | 32 | 6 | 6 |
| M | 4 | 17 | 21 | 28 | 32 | 11 | 11 |
| N | 3 | 32 | 35 | 32 | 35 | 0 | 0 |

### More Definitions

**Free float** can be defined as the maximum amount of time an activity can be delayed without delaying the early start of the succeeding activities. Some authors add "and without delaying the entire project." This statement is not incorrect, but it is

redundant. The first condition, "without delaying the early start of the succeeding activities," is more stringent than "without delaying the entire project."

We must always realize that $FF \leq TF$. In fact, free float is the part of total float that will not affect the early start of the following activities.[7] The other part, interfering float, may be defined as the maximum amount of time an activity can be delayed without delaying the entire project but causing delay to the succeeding activities. It represents the part of the total float that remains after free float is deducted:

$$\text{TF} = \text{FF} + \text{Int.F} \quad \text{or} \quad \text{Int.F} = \text{TF-FF}$$

In some scheduling software programs, we may assign a start or a finish constraint to a certain activity. Total float may then be calculated as the maximum amount of time we can delay the activity from its early start without delaying the entire project or the constraint (whichever is more stringent). In example 4.3, let us assign a finish constraint on activity E: Finish No Later Than (also called *Finish on or Before*) day 18. In this case, TF = 18 − 15 = 3 days. The computer program may still calculate the free float on the basis of the early start of the succeeding activities, $FF = 7$ days, without regard to the constraint. In such a situation, you may wonder how free float could be greater than total float. It is not! The software program is calculating the two variables (*TF* and *FF*), in this case, using different criteria. Nevertheless, our earlier rule, $FF \leq TF$, still stands in all cases.

If we look further into free float, we find that it is calculated so that it does not affect the succeeding activities, but it may be affected by the preceding activities. For example, in example 4.3, if activity B is delayed (within its total float), this amount will be taken away from the total float and the free float of activity E. Let B start on day 8 and finish on day 15 (using its entire total float). Activity E will then start on day 15 and finish on day 21. This leaves activity E with only 6 days of total float, one of which is free float.

This brings us to the definition of **independent float (Ind. F)** of an activity, which is not shared or affected by any other activity. We may define it as the maximum amount of time an activity can be delayed from its early start without delaying the early start of the succeeding activities and without being affected by the allowable delay of the preceding activities. Independent float is calculated as follows:

$$Ind.F_i = \min(ES_{i+1}) - \max(LF_{i-1}) - Dur_i$$

For activity E in the previous example, $Ind.F = 22 - 15 - 6 = 1$ day. This equation may result in negative numbers, which should be interpreted as zero independent float. Independent float is part of free float, so make sure that $Ind.F \leq FF \leq TF$. Independent float is the only float that can be considered truly an activity float, that is, not shared with any other activity, predecessor, or successor.

[7] The author calls *free float* the "unselfish" portion of the total float.

Interfering float and independent float are not used in construction scheduling or even calculated by commercially available software-scheduling programs. They are sometimes used, although rarely, in delay-claims resolution.

### Float Check

When you are calculating float, of any type, it is important to apply educated common sense to the results, since some computer software programs use their own concepts and/or assumptions. For example:

- If you are calculating the total float of an activity and find it to be 10 days, try to delay this activity by that amount and see if the project completion date will be impacted. If not, increase the delay by 1 day and recheck the project completion date. It must show a delay of 1 day.
- If you are calculating the free float of an activity and find it to be 5 days, for example, try to delay this activity by that amount and see if the early start (ES) of the successor(s) has been impacted. If not, add 1 more day and make sure the ES of any successor is affected.
- If you are calculating the independent float of an activity and find it to be 3 days, apply the previous argument (for free float) to make sure using this amount of float won't impact the ES of any successor and then delay its predecessors by the maximum total float they have. This delay should not decrease the amount of the independent float this activity has.

Remember always that TF ≥ FF ≥ Ind. F.

**Tip Box 4.11**

The most important question is: "Who owns the float?" Start with reading the scheduling-related clauses in the contract.

### Node Format

Since each activity has several data items, schedulers have been creative in depicting these data items inside the activity node. In the examples in this book, the author follows a simple node format in which the box contains the activity ID and original duration. The early dates are placed above the box, and the late dates are placed below the box. Whether we are drawing the CPM network manually or by using a computer, we can use one of many node formats or devise our own format. This is a matter of personal preference; there is no correct or incorrect format. Oracle Primavera P6 and MS Project provide ways to customize nodes. Two examples of node formats are shown in Figure 4.9.

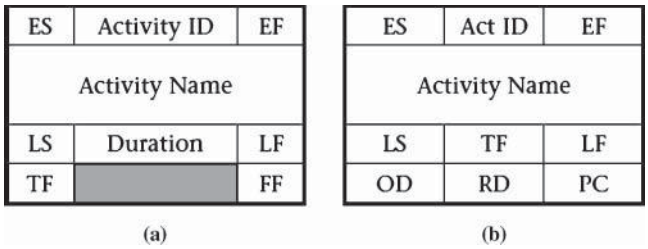



**Figure 4.9 Node formats: (a) activity ID and name, duration, early start (ES), early finish (EF), late start (LS), late finish (LF), total float (TF), and free float (FF); (b) activity ID and name, ES, EF, LS, LF, TF, original duration (OD), remaining duration (RD), and percent complete (PC). If early dates are followed by the letter *A*, they are actual dates, and late dates are not used**

It is not uncommon to include information such as activity codes (responsibility, area, phase, etc.) or cost in the activity box. The challenge becomes balancing the amount of information inside the box, the legibility and clarity of the information, and the size of the chart.

### Lags and Leads into CPM Networks

As defined in Chapter 3, a *lag* is a minimum mandatory waiting period between the completion (or start) of an activity and the start (or completion) of its successor.

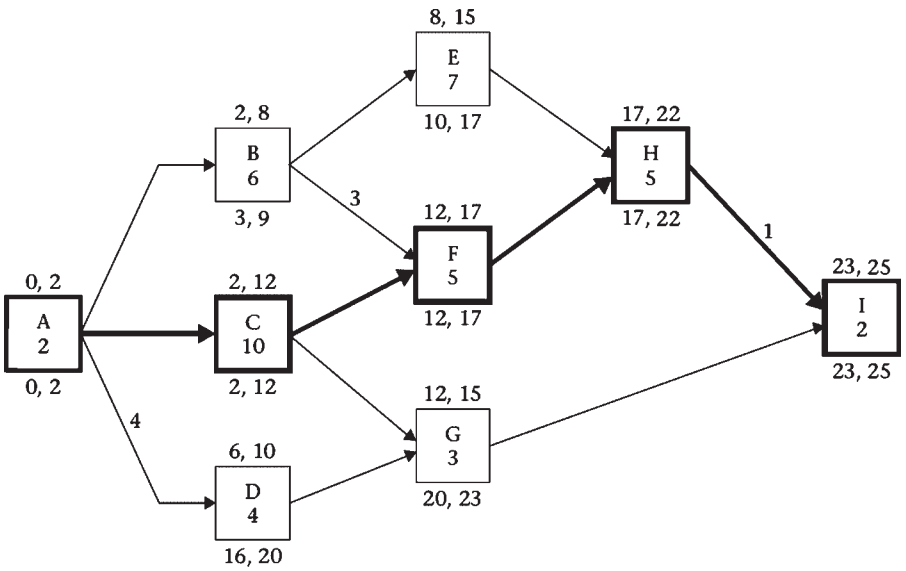



**Figure 4.10 Lags in a CPM network**

*Lead* is a negative lag. Thus, a lag means "after" and a lead means "before." Although lags are not real activities, they consume time and must be incorporated into the CPM calculations. They are shown as numbers above the lines of arrows: these numbers may be boxed (as in Figure 4.12) or not boxed (as in Figure 4.10).

You can think of a lag, if this simplifies calculations, as a real activity, in which duration equals the lag. This works well for positive lags but not for leads (negative lags).

### Example 4.4

Redo example 4.2 with some lags added as shown next.

| Activity | IPA | Duration | Lag |
|---|---|---|---|
| A | – | 2 | |
| B | A | 6 | |
| C | A | 10 | |
| D | A | 4 | 4 |
| E | B | 7 | |
| F | B | 5 | 3 |
| | C | | |
| G | C, D | 3 | |
| H | E, F | 5 | |
| I | G | 2 | |
| | H | | 1 |

### Solution

Performing forward and backward passes yields the solution shown in Figure 4.10. The 4-day lag between activities A and D means that activity D cannot start until at least 4 days after the completion of activity A. The same principle applies to the lags between activities B and F and between activities H and I.

In this example, the critical path does not change, but it may change in other cases. The 1-day lag between activities H and I adds 1 day to the project. In fact, if we look at the definition of *critical path* (the longest path in the project network from start to finish), we need to include the lags as part of the path. In this example, the critical path is A, C, F, H, I. Its length (i.e., the duration of the entire project) is $2 + 10 + 5 + 5 + (1) + 2 = 25$ days (the lag is in parentheses).

Other lags in this example contribute to changes in the forward-pass and backward-pass calculations, causing total float and free float to change in some cases. Notice that in the CPM calculations, the lags must be added in the forward pass and subtracted in the backward pass.

### Example 4.5

Draw the node diagram and perform the CPM computations for the schedule shown next.

| Activity | IPA | Lag | Duration | Activity | IPA | Lag | Duration |
|---|---|---|---|---|---|---|---|
| A | – | | 2 | G | C | | 5 |
| B | A | 2 | 5 | H | D, E | | 10 |
| C | A | | 6 | | F | 2 | |
| D | B | | 6 | I | E, F, G | | 8 |
| E | B | 3 | 7 | J | D | | 7 |
| F | B, C | | 4 | K | H, J | | 1 |
| | | | | | I | 1 | |

### Solution

Performing forward and backward passes yields the solution shown in Figure 4.11. The critical path in this example is A, B, E, H, K. Its length is $2 + (2) + 5 + (3) + 7 + 10 + 1 = 30$ days. The solution to example 4.5 is summarized in the following table.

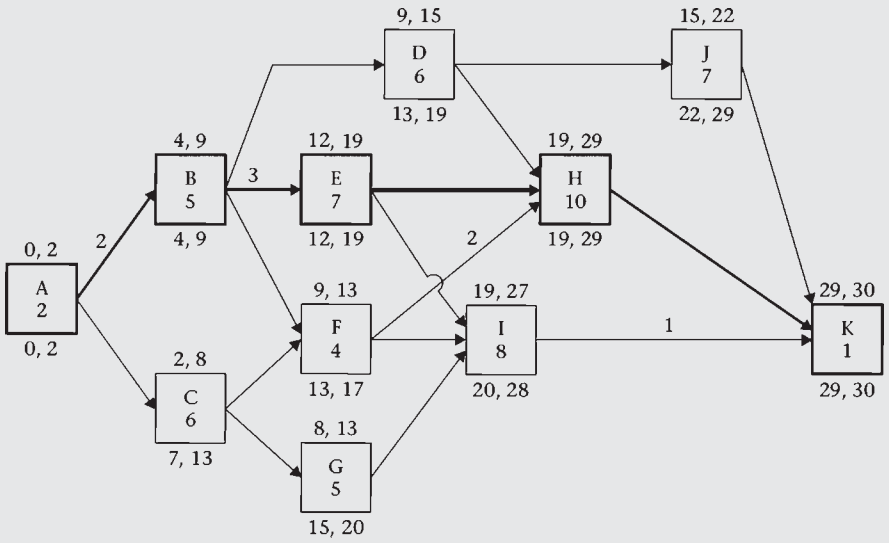



**Figure 4.11 Lags in scheduling software**

| Activity | Duration | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|
| A | 2 | 0 | 2 | 0 | 2 | 0 | 0 |
| B | 5 | 4 | 9 | 4 | 9 | 0 | 0 |
| C | 6 | 2 | 8 | 7 | 13 | 5 | 0 |
| D | 6 | 9 | 15 | 13 | 19 | 4 | 0 |
| E | 7 | 12 | 19 | 12 | 19 | 0 | 0 |
| F | 4 | 9 | 13 | 13 | 17 | 4 | 4 |
| G | 5 | 8 | 13 | 15 | 20 | 7 | 6 |
| H | 10 | 19 | 29 | 19 | 29 | 0 | 0 |
| I | 8 | 19 | 27 | 20 | 28 | 1 | 1 |
| J | 7 | 15 | 22 | 22 | 29 | 7 | 7 |
| K | 1 | 29 | 30 | 29 | 30 | 0 | 0 |

### Lags and Leads in Computer Software

In software scheduling programs, you may assign different calendars to different activities. For example, activity A follows a 5-day calendar, but activity B follows a 7-day calendar. Which calendar does the lag follow? Theoretically, it could follow A's calendar, B's calendar, or its own. Some software packages do not give the user the choice, and some do. You need to know which calendar the lag follows and whether you have any choices.

One interesting scenario (Figure 4.12) may lead to a pitfall: there is a 2-day lag, but the scheduler has timed activity A to finish on a Friday without inserting a lag. The next activity, B, will start on the next business day (i.e., Monday). This leaves a "natural lag" of 2 days: Saturday and Sunday. A good example of this is concrete placement. Let us assume activity A to be FRP (Formwork-Rebar-Concrete) Columns. Activity B is Strip Forms, Columns. The schedule works well unless a delay forces activity A to finish 1 or 2 days later. Activity B will then start the next day without any lag. Ideally, a 2-day lag must be entered. If there is a choice for the lag calendar, we should choose the 7-day calendar. If not, we can create a 2-day activity (Wait for Concrete to Set) in lieu of the lag and assign the 7-day calendar to it. Such an activity will have no resources or cost assignment.

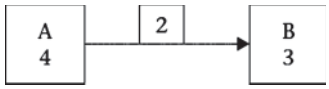



**Figure 4.12 Two-day lag**

### Further Discussion of Float

From practical observation, we can deduce the following five points about float:

1. In construction project scheduling, total float (TF) is the most frequently used type of float. Free float (FF) comes in a distant second. Interfering float and independent float are almost unheard of, except in some delay-claim resolution cases. In fact, most commercially available computer software programs do not calculate these two types of float or even mention them.
2. The project manager should be responsible for distributing the total float and should understand that total float, in most cases, is shared among several activities. If the first activity consumes it, the remaining activities will be affected and may be left without float and hence become critical.
3. Total float may be used for resource leveling, which is explained in Chapter 6. The project manager may choose a certain day on which to start an activity (between the early start and the late start) to satisfy certain resource or other needs. For example, an activity that includes the installation of expensive equipment may have 60 days of float. The owner may elect to delay the installation as late as possible in order to defer the cost.
4. The question of float ownership is a broad and complicated subject. It is not only a technical subject but also a legal one. Some contracts spell out whether the contractor has granted the owner float ownership. If not, the float could be distributed in different ways. Some regulations give the right of "first come, first served." Others suggest distributing it in proportion to the duration, budget, "priority code," or other criteria of the activities that share it. There are many publications on this subject, such as those by Pasiphol and Popescu (1994) and Ponce de Leon (1986).
5. The project manager may choose to hide or reduce the total float. Scheduling software provides several tricks for doing so, such as imposing a constraint on the activity to finish by a certain date. In computer programs such as Oracle Primavera P6, you can do the following:
   - Reduce or eliminate the total float by imposing a finish constraint. For example, activity H in example 4.3 has an early finish date of day 15 and a late finish date of day 26, which gives it 11 days of float. If we impose the constraint Finish No Later Than Day 19, day 19 will replace the late finish date in the calculation of total float. Thus, $TF = 19 - 15 = 4$ days. Of course, if we impose the constraint Finish No Later Than Day 15, the total float will be zero and activity H will be critical. Different software packages provide different types of constraints: some can override the logic and some cannot. For example, if we impose the constraint Finish No Later

Than Day 13 (which is earlier than its early start date), will it then be forced to start on day 4 (before activity D is finished) and finish on day 13? You must check the definitions of constraints in the software.

- Restrict the activity to its early dates and totally eliminate its total float. In MS Project, the constraint is called *ASAP* (*As Soon As Possible*). Note that the difference between this constraint and the one discussed previously is that this constraint is dynamic and the previous one is static. For example, if a delay in activity D causes it to finish on day 8, the ASAP constraint will force activity H to finish on its *new* early finish date (i.e., day 17). The Finish No Later Than constraint will not adjust because of the change in the calculated dates.
- Delay the activity to its latest dates. Doing so may—and usually does—affect the float of the succeeding activities.
- Delay the activity as much as possible without affecting the succeeding activities. Both Oracle Primavera P6 and MS Project have such a constraint called *As Late As Possible* (it used to be called *zero free float*). For example, if we add an *As Late As Possible* constraint to activity E in example 4.3, it will be delayed by 7 days to start on day 16 and finish on day 22. It will still have 5 days of total float left (compared with 12 without the constraint). This type of constraint is particularly useful in procurement activities. When you have an equipment procurement activity with a large float, you may not want the equipment to be delivered too early or the contractor and the owner may have problems (the possibility of theft or vandalism, lack of storage space, tying up the cash, etc.).

### Effect of Choice of Dates on Cash Flow

The effect of different dates on cash flow is shown in Figure 4.13. Early dates and late dates provide a time frame within which the project manager can choose his or

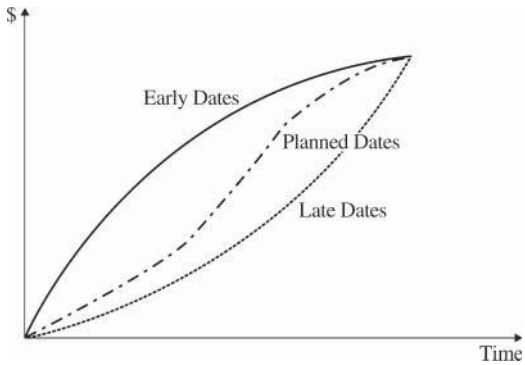



**Figure 4.13 Effect of choice of dates on cash flow**

her planned dates. Conservative thinking leans more toward early dates (especially for the contractor). The owner's financial considerations may lean toward late dates. The contractor may have other considerations for choosing planned dates, such as resource availability and cost, resource leveling (explained in Chapter 6), other ongoing or potential projects, and so forth.

### Project Schedule "Health Check"

Some software programs, authors, and user agencies use certain metrics to check the integrity and validity of the project schedule. The title "Health Check" is relatively common for such check. Some of these metrics are:

a. Missing predecessors
b. Missing successors
c. Redundant relationships
d. Inaccurate lags
e. Dangling activities
f. Number of constraints
g. Missing status
h. Out of sequence activities
i. Excessive float

The most famous check is the "DCMA 14," which is a check developed by the U.S. Defense Contract Management Agency (DCMA), which is responsible for overseeing federal acquisition programs. It contains a 14-point assessment check protocol to be used for CPM schedule reviews made by their department. DCMA 14-Point Schedule Assessment.[8] This check has been adopted by several organizations and software programs. In general, it is a good idea to develop or have a list of checks for the validity and integrity of the CPM schedule.

### Event Times in Arrow Networks

Event times in arrow networks are calculated in the following manner:

- The early event time, $T_E$, is the largest (latest) date obtained to reach an event (going from start to finish).
- The late event time, $T_L$, is the smallest (earliest) date obtained to reach an event (going from finish to start).

[8] See http://www.ronwinterconsulting.com/DCMA_14-Point_Assessment.pdf

The preceding logic is similar to that of the forward and backward passes: when you are going forward, pick the largest number; when you are going backward, pick the smallest number.

### Example 4.6

Perform the CPM calculations, including the event times, for the arrow network shown in Figure 4.14a.

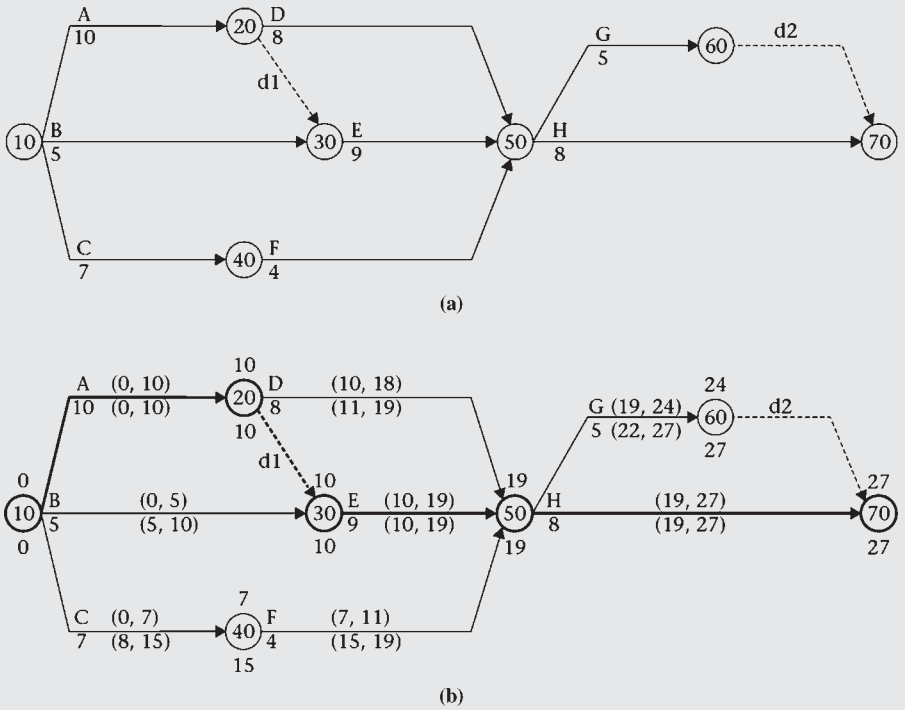



**Figure 4.14 (a) Arrow network for example 4.6; (b) event times in arrow network**

### Solution

*Early Times,* $T_E$. We start the project at node 10 with an early event time of $T_E = 0$ (Figure 4.14b). Event (node) 20 is reached when activity A is complete, which is on day 10. However, event 30 requires both A and B to be completed. In this case, we take the larger of $(0 + 10 = 10)$ and $(0 + 5 = 5)$, which is 10, for the early time. The early time for event 40 is $0 + 7 = 7$. Event 50 needs activities D, E, and F to be finished. We take the largest date of 18, 19, and 11 for the early time. The answer is 19. Similarly, early events 60 and 70 have early times of 24 and 27, respectively. *Late times,* $T_L$, starting

at event 70, the late time, $T_L$, is 27. Since all dummies have zero duration, event 60 has $T_L = 27$. For event 50, we must pick the earlier of the following: $T_L$ of event 60 − Duration of G (27 − 5 = 22) and $T_L$ of event 70 − Duration of H (27 − 8 = 19). So, $T_L$ for event 50 = 19. For event 40, $T_L = 19 - 4 = 15$. For event 30, $T_L = 19 - 9 = 10$. For event 20, pick the earlier of (19 − 8 = 11) and (10 − 0 = 10). Hence, $T_L = 10 - 0 = 10$. For event 10, pick the earliest of (10 − 10 = 0), (10 − 5 = 5), and (15 − 7 = 8). Clearly, $T_L = 0$.

*Event float* We easily find that events 40 and 60 have floats of 8 and 3 days, respectively. All other events are critical.

### Effect of the Imposed Finish Date on the Schedule

So far, all calculations have been based on the duration estimate for each activity, along with the logic between these activities. The result is a **calculated finish date**. In many cases, the calculated finish date is different from that stipulated by the owner. As a result, the contractor may have to adjust the schedule to meet the owner's imposed finish date. This possibly means accelerating the schedule, a subject covered in Chapter 8. In this section, we just study the effect that such an imposed date may have on the schedule.

The concept is simple. Do the CPM forward pass as usual: find the project's calculated finish date, based on the assumptions of durations and logic. Then, on the backward pass, start with the imposed finish date and use this date for your backward-pass calculations. The imposed finish date may be earlier or later than the calculated finish date:

- If the imposed finish date is earlier than the calculated finish date, the activities on the critical path will have a negative float equal to the difference between the imposed finish date and the calculated finish date. Other activities may also develop a negative float but greater (or less, in absolute value) than the total float of the critical path. The contractor must accelerate the project (i.e., reduce its duration) by an amount of time equal to the negative float of the critical path. This acceleration, say 8 days, may be taken from several activities (e.g., 1 day from one activity, 2 days from another, and so on), with a total reduction in duration that is equal to 8 days.
- If the imposed finish date is later than the calculated finish date, the contractor is in good shape (at this point). The difference between the two dates may be regarded as a **time contingency**, and the contractor may keep the calculated finish date as a target date. In such a situation, inserting the imposed finish date into the computer program will result in the "disappearance" of the critical path. This occurs because we gave each activity a "bonus float" equal to the difference between the imposed finish date and the calculated finish date. Since, by default, most computer programs define *critical activities* as those with zero or less float, no critical activities will be found. For this reason, the scheduler should not enter the imposed finish date until the calculated finish date is determined.

### Example 4.7

The owner of the project discussed in example 4.3 needs to have the project finished in 30 days. Use the imposed finish date to determine the effect on the entire schedule and on individual activities. See Figure 4.15.

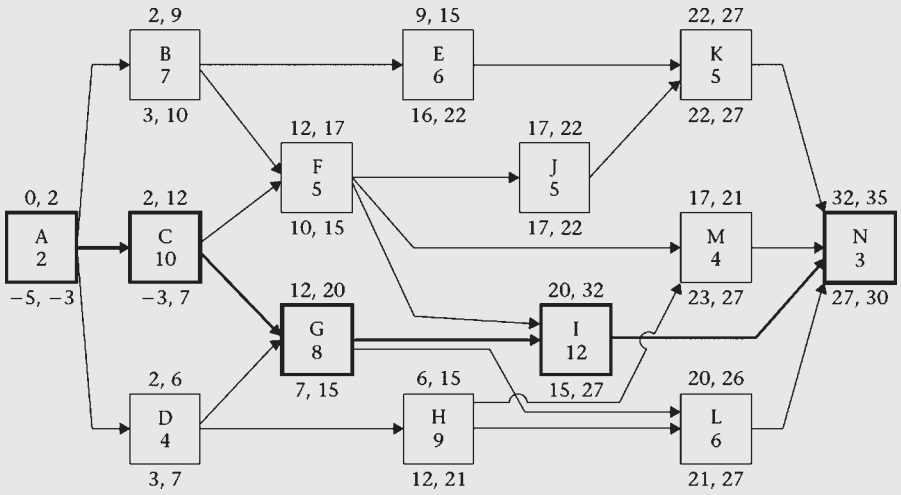



**Figure 4.15 Effect of imposed finish date on the schedule**

### Solution

The results of example 4.7 can be tabulated as follows.

| Activity | Duration | ES | EF | LS | LF | TF |
|---|---|---|---|---|---|---|
| A | 2 | 0 | 2 | −5 | −3 | −5 |
| B | 7 | 2 | 9 | 3 | 10 | 1 |
| C | 10 | 2 | 12 | −3 | 7 | −5 |
| D | 4 | 2 | 6 | 3 | 7 | 1 |
| E | 6 | 9 | 15 | 16 | 22 | 7 |
| F | 5 | 12 | 17 | 10 | 15 | −2 |
| G | 8 | 12 | 20 | 7 | 15 | −5 |
| H | 9 | 6 | 15 | 12 | 21 | 6 |
| I | 12 | 20 | 32 | 15 | 27 | −5 |
| J | 5 | 17 | 22 | 17 | 22 | 0 |
| K | 5 | 22 | 27 | 22 | 27 | 0 |
| L | 6 | 20 | 26 | 21 | 27 | 1 |
| M | 4 | 17 | 21 | 23 | 27 | 6 |
| N | 3 | 32 | 35 | 27 | 30 | −5 |

**Discussion of Example 4.7**

We will discuss the details of project compression in Chapter 8, but we note that in cases such as example 4.7, when the project needs to be accelerated, not all activities need to be shortened. This often overlooked point may result in a lot of wasted money in construction projects. Shortening activities B, D, E, and so forth does not help. At the same time, we observe that activity F, which is not on the critical path, needs to be accelerated by 2 days. However, this may not be exactly true. If we accelerate any activity on the critical path, other than G, by at least 2 days, activity F will not need to be accelerated. Following is a numerical illustration of this point:

1. The critical path (A, C, G, I, N) is 35 days long.
2. The path (A, C, F, I, N) is 32 days long.
3. We need to shorten any path that exceeds 30 days.
4. Shortening a path is achieved by shortening the duration of an activity or a combination of activities by the desired amount of days—5 in this case.
5. Since the two paths share all activities except F and G, any reduction in the duration of any shared activity (A, C, I, or N) will result in a reduction in both paths.

This subject is discussed further in Chapter 8.

**Tip Box 4.12**

Don't insert the contract/owner's "imposed finish date" in the schedule until you have calculated your own finish date (based on your durations and logic).

## LOGIC AND CONSTRAINTS

A trend among many schedulers and project managers is to "fix" the dates of activities rather than allowing the software to calculate them using the CPM concepts. For example, the project manager might ask the scheduler to make Door Installation start on 28 APR 2015. The scheduler assigns a constraint to this activity so that it will start on that particular date. This practice strips the schedule of its most important advantage: logic. The difference is simple: logic is dynamic; constraints are not. This author—when put in the shoes of the scheduler—would ask the project manager, "Why do you want to start that activity on 28 Apr 2015?" The project manager would give an answer such as, "That's when the drywall will be finished" or "That's when doors will be delivered." The scheduler can then tie Door Installation to Finish Drywall and/or Doors Delivery. To appreciate the advantage of logic over constraints, assume that the predecessor, Finish Drywall, is delayed. With the absence of logic,

we need to go to Door Installation and manually move it. With logic, all we have to do is recalculate the schedule.

It is also possible to combine logic and constraints. Assume that an activity may be completed as early as 08 June 2015, but the project manager wants to delay it until 15 July 2015 for a reason that may have nothing to do with logic, such as cash-flow requirements. The scheduler may add a constraint (without taking out the logic) that will not allow it to start before 15 July 2015, assuming this date is ≤ LF.

The author believes that the overwhelming reason for using constraints in lieu of logical relationships is a lack of understanding of the concept of the CPM. Some contractors, especially those who work on small projects, used to make bar chart "schedules" by using a spreadsheet program or even by drawing a bar chart manually without any CPM calculations. In such schedules, the contractor would choose the start and finish dates for every activity rather than calculating them. Such a bar chart is subjective and not based on CPM. Furthermore, it may not have much value in the court of the law. Consequently, using such schedules is strongly discouraged.

Nevertheless, constraints may be extremely useful. The owner may have, in addition to the project completion date, other deadlines, such as Substantial Completion, which means reaching the stage when the facility can be used for the main purpose for which it was intended. Even though the deadline for Substantial Completion may be in the contract, the contractor must show it as a milestone in the schedule. The owner bears the responsibility of noting the absence of such milestones in the schedule before accepting it.

**Tip Box 4.13**

If you have too many constraints (more than you can count on your fingers), review them. You may have used constraints in lieu of logic.

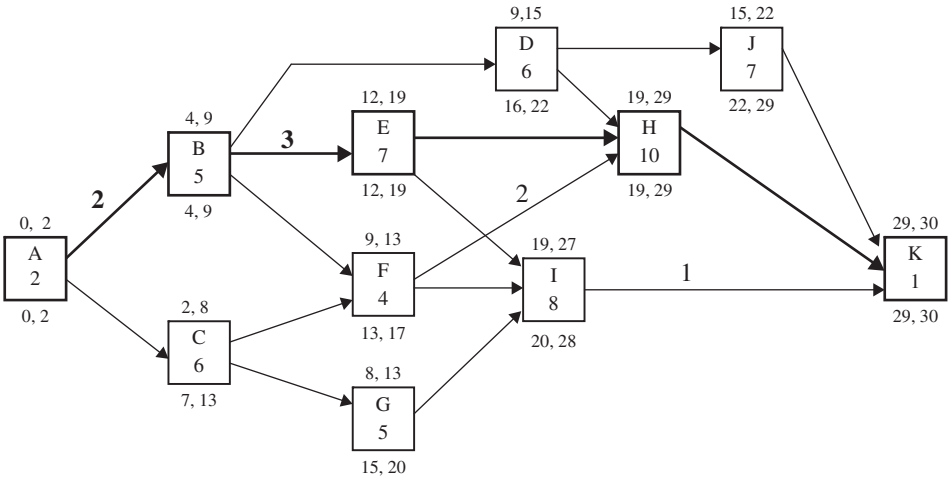
#### The "Hub" Concept

Airlines use the term **hub** to describe a central airport where the airline has the most flights: arriving as well as departing. This concept applies to activities or milestones in logic networks with la arge number of predecessors and/or successors. An example of this is Building Dry-in, Substantial Completion, Walk Through, or Punch List. Each of these activities/milestones has many predecessors. An activity such as Materials Delivery, when it means the arrival of a delivery truck carrying materials for several activities, could be a predecessor to many activities. There is a high likelihood for hub activities to be critical. In fact, special attention must be given to hub activities, as a delay in one of them can be a cause of serious delays in the schedule.

#### The Definition of Critical Path, Revisited

We defined *critical path* earlier as "the longest continuous path in a network from start to finish. It represents the summation of the durations of activities and lags along that

path, taking into consideration calendars, constraints, resources, and other impacting factors." The part that it represents, the "summation of the durations of activities and lags along that path," is well understood. However, we need to explain the part, "taking into consideration calendars, constraints, resources, and other impacting factors." In the solution of example 4.5 (Figure 4.11), there are nine paths:




1. A-B-D-J-K 23
2. A-B-D-H-K 26
3. A-B-E-H-K 30
4. A-B-E-I-K 29
5. A-B-F-H-K 26
6. A-B-F-I-K 23
7. A-C-F-H-K 25
8. A-C-F-I-K 22
9. A-C-G-I-K 23

Path 3 fulfills the portion of the Critical Path definition, "the summation of the durations of activities and lags along that path," with 30 days (25 days of activities' durations and 5 days of lags). However, let's imagine these possible scenarios in what pertains to the other portion of the definition, "taking into consideration calendars, constraints, resources, and other impacting factors:"

- *Scenario 1*: All activities on path 3 are on a 5-workday/week calendar. Activity I is on a 6-workday/week calendar. This will likely make path 4 longer than path 3, considering calendar days (since the length of the project is usually specified in contracts in calendar days).
- *Scenario 2*: Assume a constraint, "Start on Day 18," is assigned to activity G; thus, it won't finish until day 23. Activities I and K will follow, with dates

(23, 31) and (32, 33), respectively. This makes A-C-G-I-K the critical path, even though its "length" is only 23 days, without taking the constraint in consideration.

- *Scenario 3*: Assume the crew for activity I is unavailable until day 22 (a delay of 3 days). This delays the completion of that activity until day 30 and the completion of the project until day 32, making A-B-E-I-K the critical path.

From the preceding discussion, we conclude that the critical path in a network is the longest continuous path from start to finish, taking into consideration all time-consuming and time-impacting factors. This definition will take another twist in Chapter 11 with the introduction of program evaluation and review technique (PERT), which considers a range of durations of each activity. PERT considers not only the length of the path but also the uncertainty (variance/standard deviation), which measures the confidence in finishing the project by a certain date.

**Tip Box 4.14**

Make sure that you show "submittal review cycle," taking into consideration the possibility of rejection. Also show procurement activities.

## CHAPTER 4 EXERCISES

1. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 3 | – | | | | | | |
| B | 7 | A | | | | | | |
| C | 4 | A | | | | | | |
| D | 5 | B | | | | | | |
| E | 8 | B, C | | | | | | |

2. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | LS | EF | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 7 | – | | | | | | |
| B | 10 | – | | | | | | |
| C | 15 | A | | | | | | |
| D | 8 | A, B | | | | | | |
| E | 4 | C, D | | | | | | |

3. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 2 | – | | | | | | |
| B | 4 | A | | | | | | |
| C | 6 | A | | | | | | |
| D | 9 | A | | | | | | |
| E | 5 | B | | | | | | |
| F | 7 | B, C | | | | | | |
| G | 3 | D, E, F | | | | | | |

4. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 6 | – | | | | | | |
| B | 2 | – | | | | | | |
| C | 8 | A | | | | | | |
| D | 5 | A, B | | | | | | |
| E | 3 | B | | | | | | |
| F | 6 | D, E | | | | | | |
| G | 5 | C, D | | | | | | |
| H | 2 | F, G | | | | | | |

5. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 6 | – | | | | | | |
| B | 2 | – | | | | | | |
| C | 9 | – | | | | | | |
| D | 4 | A, B | | | | | | |
| E | 7 | B | | | | | | |
| F | 5 | D | | | | | | |
| G | 10 | D, E | | | | | | |
| H | 8 | C, F, G | | | | | | |
| I | 3 | C, G | | | | | | |
| J | 2 | H, I | | | | | | |

6. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 2 | – | | | | | | |
| B | 7 | A | | | | | | |
| C | 10 | A | | | | | | |
| D | 5 | A | | | | | | |
| E | 4 | B | | | | | | |
| F | 4 | B, C | | | | | | |
| G | 3 | C | | | | | | |
| H | 6 | C, D | | | | | | |
| I | 3 | D | | | | | | |
| J | 6 | E, F, G | | | | | | |
| K | 8 | F, G, H | | | | | | |
| L | 5 | H, I | | | | | | |
| M | 3 | K, L | | | | | | |

7. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 3 | – | | | | | | |
| B | 5 | – | | | | | | |
| C | 6 | A | | | | | | |
| D | 9 | A, B | | | | | | |
| E | 4 | A, B | | | | | | |
| F | 6 | B | | | | | | |
| G | 5 | C, D | | | | | | |
| H | 12 | D, E | | | | | | |
| I | 7 | D, E, F | | | | | | |
| J | 9 | E | | | | | | |
| K | 10 | G, H, I | | | | | | |
| L | 6 | I, J | | | | | | |
| M | 4 | G, I | | | | | | |
| N | 2 | K | | | | | | |

8. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 3 | – | | | | | | |
| B | 10 | A | | | | | | |
| C | 7 | A | | | | | | |
| D | 6 | B | | | | | | |
| E | 5 | B, C | | | | | | |
| F | 4 | C | | | | | | |
| G | 2 | D | | | | | | |
| H | 4 | D, E | | | | | | |
| I | 10 | E | | | | | | |
| J | 6 | E, F | | | | | | |
| K | 4 | G, H, I | | | | | | |
| L | 2 | H, I | | | | | | |
| M | 1 | J, L | | | | | | |

9. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|
| A | 5 | – | | | | | | |
| B | 7 | A | | | | | | |
| C | 10 | A | | | | | | |
| D | 5 | A | | | | | | |
| E | 9 | A | | | | | | |
| F | 6 | B | | | | | | |
| G | 4 | B, C | | | | | | |
| H | 8 | B, C, D | | | | | | |
| I | 2 | C, D | | | | | | |
| J | 5 | E | | | | | | |
| K | 8 | F | | | | | | |
| L | 9 | E, G | | | | | | |
| M | 7 | F, G, H | | | | | | |
| N | 3 | F, G, H, I | | | | | | |
| O | 6 | H, I | | | | | | |
| P | 4 | M, N, O | | | | | | |
| Q | 3 | K, L | | | | | | |
| R | 5 | L, M | | | | | | |
| S | 4 | J, P | | | | | | |
| T | 6 | Q | | | | | | |
| U | 4 | Q, R | | | | | | |
| V | 1 | T, U, S | | | | | | |

10. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | Lag | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|---|
| A | 5 | – | | | | | | | |
| B | 6 | A | | | | | | | |
| C | 4 | A | 3 | | | | | | |
| D | 5 | A | | | | | | | |
| E | 3 | B | | | | | | | |
| F | 2 | C, B | | | | | | | |

11. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | Lag | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|---|
| A | 4 | – | | | | | | | |
| B | 9 | – | | | | | | | |
| C | 6 | A | | | | | | | |
| D | 4 | A | | | | | | | |
| | | B | 2 | | | | | | |
| E | 4 | B | | | | | | | |
| F | 2 | B, C | | | | | | | |
| G | 6 | D | | | | | | | |
| | | E | 3 | | | | | | |
| H | 3 | F, G | | | | | | | |

12. For the following schedule, draw the node network, perform the CPM calculations, mark the critical path, and complete the table.

| Activity | Duration | IPA | Lag | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|---|
| A | 5 | – | | | | | | | |
| B | 6 | A | | | | | | | |
| C | 4 | A | 3 | | | | | | |
| D | 5 | A | | | | | | | |
| E | 9 | B | | | | | | | |
| F | 7 | B | 2 | | | | | | |
| | | C | | | | | | | |
| G | 6 | C | | | | | | | |
| H | 8 | C | | | | | | | |
| | | D | 4 | | | | | | |
| I | 3 | D | | | | | | | |
| J | 7 | E, G | | | | | | | |
| | | F | 2 | | | | | | |
| K | 4 | F, G, H | | | | | | | |
| L | 1 | H | 3 | | | | | | |
| | | I | | | | | | | |
| M | 2 | K, L | | | | | | | |

13. Repeat exercise 1 with an imposed finish date of 16 and then 21 days.
14. Repeat exercise 2 with an imposed finish date of 23 and then 29 days.
15. Repeat exercise 3 with an imposed finish date of 15 and then 20 days.
16. Repeat exercise 4 with an imposed finish date of 18 and then 24 days.
17. Repeat exercise 5 with an imposed finish date of 26 and then 35 days.
18. Repeat exercise 6 with an imposed finish date of 25 and then 32 days.
19. Repeat exercise 7 with an imposed finish date of 35 and then 40 days.
20. Repeat exercise 8 with an imposed finish date of 29 and then 36 days.
21. Repeat exercise 9 with an imposed finish date of 35 and then 44 days.
22. Repeat exercise 11 with an imposed finish date of 22 and then 28 days.
23. Repeat exercise 12 with an imposed finish date of 25 and then 34 days.
24. Repeat exercise 4 with an imposed constraint on activity D: "start on or after day 10."
25. Repeat exercise 5 with an imposed constraint on activity F: "finish on day 18."
26. Repeat exercise 6 with an imposed constraint on activity F: "start on or after day 15."
27. Repeat exercise 4, assuming activities F, G, and I are performed by the same crew and the contractor has only one crew. Will the project completion date be delayed? If yes, by how many days?
28. If one activity in exercise 7 can be called a *hub*, which one will you choose? Why?
29. Repeat exercise 8 with an imposed constraint on activity F: "start on or after day 18." What activities are impacted, if any?
30. Repeat exercise 9, assuming activities E, F, and L are performed by the same crew and the contractor has only one crew. Will the project completion date be delayed? If yes, by how many days?
31. What is the main reason for the overuse of date constraints? How do you minimize such overuse?
32. Create a WBS for building a house. Use four levels of details and provide activity codes for each breakdown element.

Chapter 5

# Precedence Networks



Interstate 4 and US 17/92 intersection in Sanford, Florida

## DEFINITION AND INTRODUCTION

Precedence networks, also known as *Precedence Diagramming Method*, was originally developed by Stanford University professor Johan Fondhal (1924–2008) in the early 1960s. Precedence networks are node networks that allow for the use of four types of relationships: **finish to start (FS)**, **start to start (SS)**, **finish to finish (FF)**, and **start to finish (SF)**. To understand the idea of precedence networks, consider the simple project of laying 1,000 LF (linear feet) of a utility pipe. The logic is simple: dig a trench, provide a 6-inch-thick gravel subbase (bedding), lay the pipe, backfill, and compact—five consecutive activities. However, are they actually "consecutive?" Do you need to finish excavating the entire 1,000 LF before you can start the subbase? Do you need to finish the subbase completely before you start laying the pipe? If the answer is yes, your bar chart may look like the one shown in Figure 5.1.

Most likely, though, the answer to the preceding questions is no. Practically, once you have dug a reasonable amount, say 100 LF, your second crew can start providing the subbase, while the first crew continues digging. Once digging reaches about 200 LF (say 20%), the subbase is about 10% complete, and your third crew can start laying the pipe. As a result, the bar chart for the project looks like the one shown in Figure 5.2. Clearly, relationships exist among these activities, but not the traditional FS relationship. The activities are said to be ***overlapping***. This project may be represented

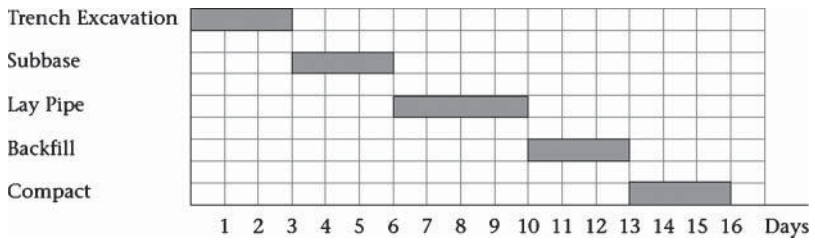



**Figure 5.1 Bar chart for five consecutive activities**

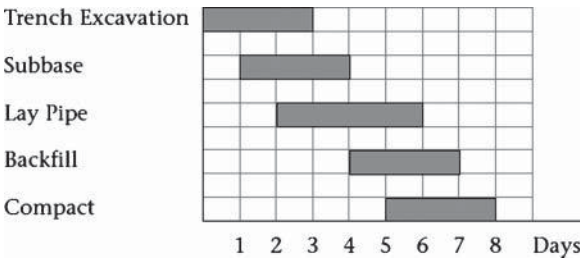



**Figure 5.2 Bar chart for five overlapping activities**

in one of two common ways. A third method, using the Linear Scheduling Method, will be discussed in Chapter 11.

1. *The stair-type relationship*: In this method, each activity is divided into two or more parts (Figure 5.3): After Excavation I is complete, both Excavation II and Subbase I can start. Once Subbase I is finished, Subbase II and Pipe I can start (probably Excavation III as well), and so on. This method is well known and widely acceptable. It is popular for projects such as heavy construction (highway, utilities, etc.) in which activities are few but large and have long durations. It is customary to divide the activities of these projects into phases, steps, or "subactivities." The main drawbacks of this method are the increase in the number of activities and the confusing similarity of their titles. For instance, in the example shown in Figure 5.3, a 5-activity project became a 15-activity project.
2. *The precedence diagramming method*: The project can alternatively be represented as shown in Figure 5.4. The activities in this network have SS relationships. This means Subbase cannot begin till Excavate has started, Lay Pipe

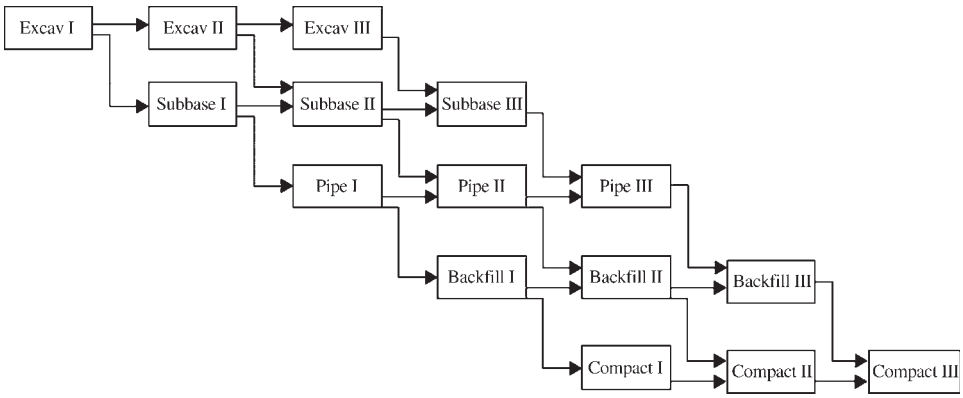



**Figure 5.3 Stair-type schedule for utility pipe installation project**

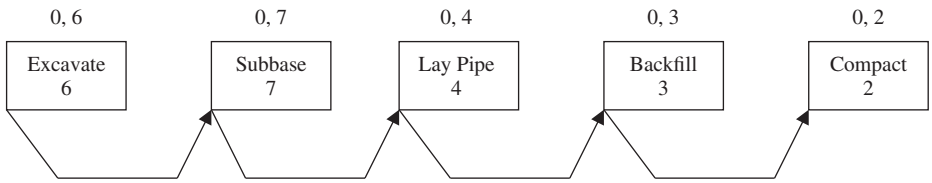



**Figure 5.4 Precedence diagram, for utility pipe installation project, using start-to-start relationships with no lags**

cannot begin till Subbase has started, and so on. Theoretically, all five activities can start simultaneously (one immediately after the other), then the project can finish in 7 days (the largest single duration). However, this scenario may be a little too unrealistic. In real life, a portion of excavation must be done (say 20%) before Subbase can start. The same can be said of the other steps.

We can add lags to the network shown in Figure 5.4, as shown in Figure 5.5. In Figure 5.5, if Excavate starts on day 0 (*remember*: the end of day 0 means the beginning of day 1), Subbase can start 1 day later, at the end of day 1. Lay Pipe can start 2 days later (on day 3), Backfill can start on day 4 (3 + 1), and Compact can start on day 5 and finish on day 7.

With careful estimates of both durations and lags, this method can work well. However, what may result is an awkward situation in which a successor finishes before the predecessor.[1] For example, we just calculated the finish of the last activity in the project: Compact, on day 7. However, by that date, the second activity, Subbase, has not finished. This situation is unacceptable, so we must either increase the lags or add FF relationships, as shown in Figure 5.6. FF relationships ensure that no successor can finish before its predecessor. Thus, Subbase cannot finish till Excavate is finished, Lay Pipe cannot finish till Subbase is finished, and so on. Since we did not add lags to the FF relationships, theoretically two or more activities

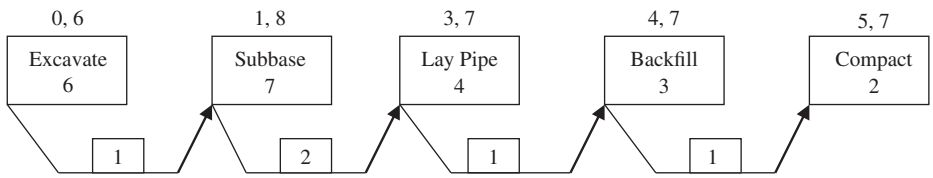



**Figure 5.5 Precedence diagram, for utility pipe installation project, using start-to-start relationships with lags**

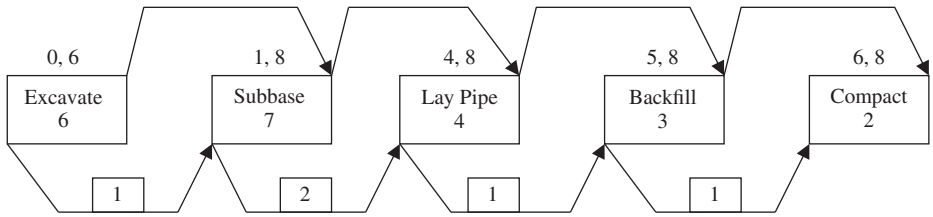



**Figure 5.6 Precedence diagram, for utility pipe installation project, using a combination relationships and lags**

[1] This situation may be acceptable in some, but not all, cases. For example, if the predecessor is Clear & Grub and the successor is Excavate Foundation; you may have to lag the start of excavation a few days after starting Clear & Grub. However, you may finish excavation before finishing clearing and grubbing because the completion of the two activities is independent.

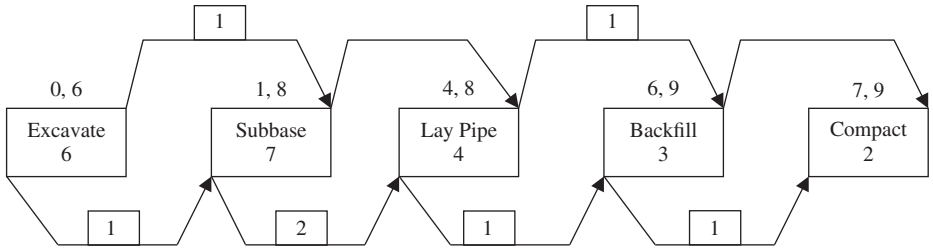



**Figure 5.7 Precedence diagram, for utility pipe installation project, using a combination relationships and more lags**

could finish at the same time. If this possibility is unacceptable, we can add lags, as shown in Figure 5.7. In the network shown in Figure 5.7, Subbase cannot finish till 1 day after Excavate has finished, and Backfill cannot finish till 1 day after Lay Pipe has finished.

*One important note*: These relationships are "driving in one way," which means that you can exceed the lag in one direction but not the other. For example, Subbase cannot start till *at least* 1 day after Excavate has started. It is allowed to start *more than 1 day* after the start of Excavate. The same argument holds for the FF relationship: Subbase cannot finish earlier than 1 day after the finish of Excavate, but it can finish more than 1 day after the finish of Excavate.

The relationships shown in Figures 5.6 and 5.7 are called *combination relationships*. In this type of relationship, two activities are related by two relationships. Some computer software, such as Microsoft (MS) Project, does not allow combination relationships.

## THE FOUR TYPES OF RELATIONSHIPS

As mentioned previously, four types of relationships are possible in precedence networks:

1. *Finish-to-start (FS) relationship*: The most common type of relationship is the FS relationship. Many project managers still insist on using only this type. Many examples of this type exist, such as the following:

   - The concrete cannot be placed (poured) until the formwork has been built.
   - The doors cannot be hung until door frames have been installed.

2. *Start-to-start (SS) relationship*: The SS relationship is common and extremely useful. Examples of this type are as follows:

   - Excavation for the foundation cannot start until clearing and grubbing begins (usually with a certain lag; i.e., a certain percentage is completed).
   - Laying felt on the roof cannot start until sheathing has started (also usually with a lag).

3. *Finish-to-finish (FF) relationship*: The FF relationship is also common and useful. Examples of this type are as follows:
   - Landscaping cannot finish until the driveway is finished.
   - Backfilling a trench cannot finish until the pipe in the trench has been laid.
4. ***Start-to-finish (SF) relationship***: The SF relationship is uncommon and almost nonexistent in construction projects.

#### Important Comments about the Four Types of Relationships

1. Practically, the only two types of relationships that can be combined are SS and FF, as shown in the previous example.
2. You can always use lags and leads with the four relationships. In fact, you will have more need to use lags with SS and FF relationships than with the traditional FS relationship.
3. With regard to critical path method (CPM) calculations (discussed later in this chapter), when you are using a combination relationship (SS and FF), usually only one of the two relationships becomes binding (driving). This situation may change if some criterion—such as duration, lag, or logic—changes.

## THE PERCENT COMPLETE APPROACH

O'Brien and Plotnick (2009, p. 159–160) suggested a slightly different approach. The relationship shown in Figure 5.8a means that activity B can start after A is at least 50% complete. In Figure 5.8b, the final 30% of activity B cannot progress until A is completely finished. Although this approach makes sense, it did not gain popularity. Perhaps the main reason is that in the CPM, early and late dates of an activity are calculated using lags that have a definite number of days (constant) rather than a percentage of completion of another activity (variable), although the conversion of this variable to a constant is simple.

We must note here that MS Project accommodates such relationships. For example, the relationship shown in Figure 5.8a can be entered as follows: B's predecessor is A, relationship: *SS* + 50%. Oracle Primavera P6 does not accept a relationship in this form: it must be in number of days.

In reality, the lags we use in the CPM are nothing but an estimate of the portion (percent complete) of the preceding activity that must be completed before the succeeding activity can start (or finish). For example, Figures 5.8a and 5.8b can be redrawn as shown in Figures 5.8c and 5.8d. Note that the relationship shown in Figure 5.8b is not equivalent to that shown in Figure 5.8d, but close enough. If you try to do CPM calculations for both, assuming activity A starts the project, you will find A's early dates are (0, 5). The last 30% of activity B is about 2 days. Thus, the last 2 days of B must follow A (i.e., occur on days 6 and 7). However, the early start of activity B is not restricted, so it can be zero (start of the project), in which case the early dates of B are (0, 7), which is also true in Figure 5.8d, unless activity B is

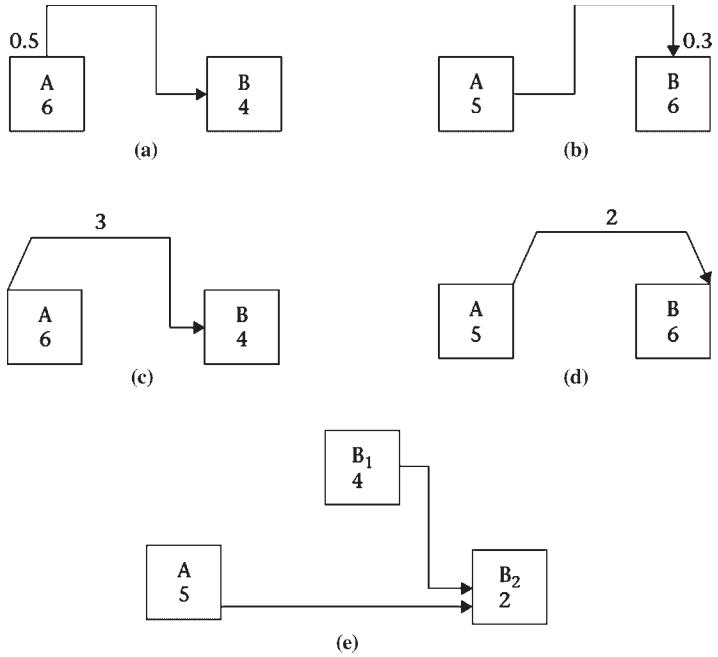



**Figure 5.8 Percent complete approach: (a) activity B starts after activity A is at least 50% complete; (b) final 30% of activity B progresses only after A is complete; (d) Figure 5.8a with lags; (e) Figure 5.8b with lags; (f) activity B split**

contiguous. In this case, early dates for B are (1, 7). (Contiguous and interruptible activities are discussed later in this chapter.)

Another way we can redraw the relationship shown in Figure 5.8b is by splitting activity B. This redrawing is shown in Figure 5.8e.

**Tip Box 5.1**

In many situations where you see two activities connected with a Finish-to-Start relationship, take another look: does the predecessor really need to be completed before the successor can start.

## FAST-TRACK PROJECTS

The term *fast-track* in the construction world means starting the construction process while the design is still under development. Under normal circumstances (i.e., the traditional way), the design must be complete before construction can start, see Figures 5.9a. In some situations, time may be tight that the owner or project

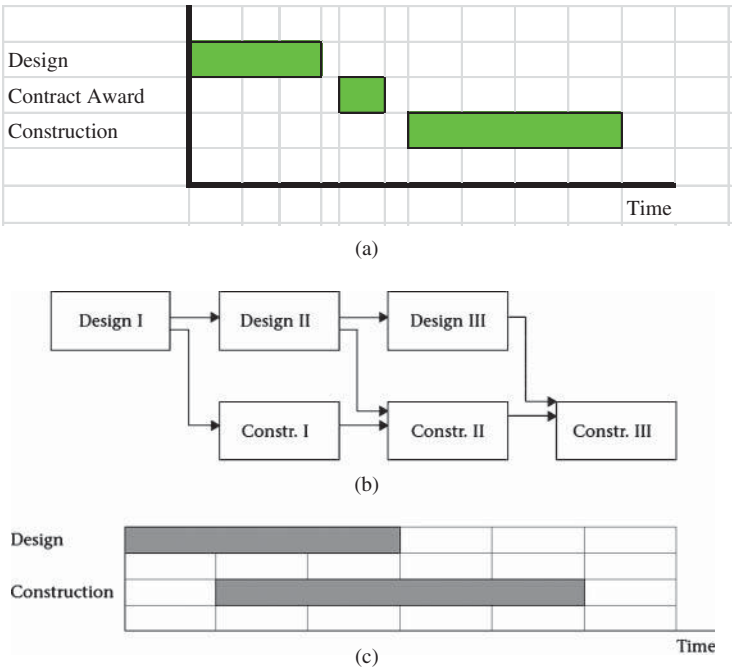



**Figure 5.9 (a) Traditional way: Design-Bid-Build; (b) Stair-type diagram and (c) Bar chart for a fast-track project**

management team decides to "fast-track" the project. In this case, the project is divided into several phases, and the construction of a phase proceeds after the design of that phase is complete, while the design of latter phases may not yet completed, as shown in Figures 5.9b and 5.9c.

In many cases, the design development (DD) stage is identified with a certain percentage, such as DD 30%, DD 60%, and so forth. The number represents an approximation of the completeness of the design. Obviously, the higher the percentage, the more well defined the design and the fewer assumptions must be made.

Fast-tracking takes advantage of precious time, but with a cost. The concept is to start building something that you have a general, but not an exact, idea of what it is. Doing so minimizes the ability of the contractor, and other participants to practice value engineering and constructability studies (see the definitions of *value engineering* and *constructability* in Chapter 8). Fast-tracking may also lead to more change orders and higher cost. For obvious reasons, contractors usually do not take these types of projects on a lump-sum basis, so owners may not know the final cost of the project until it is complete. To counterbalance this unknown, the contractor may give the owner an estimate with a "guaranteed maximum budget." Refer

to the project management books listed in the Bibliography for more discussion on this concept.

## A PARALLEL PREDECESSOR?

You learned in Chapters 3 and 4 that a predecessor is an activity that must happen before another one can happen. For example, if A is a predecessor of B, then A must happen before B can start, but not necessarily immediately after A (Figure 5.10a).

If A is a predecessor of B with an SS relationship, both may occur in parallel (Figure 5.10b). Would A still be called a *predecessor*? The answer is yes because A must start first (even with zero lag). If B starts several days after A starts, the logic is not violated. However, if B starts first—by any amount of time—the logic *will* be violated. Activity A, thus, controls activity B and is still called a *predecessor*. Note the direction of the arrow in Figure 5.10b: it points from the activity that controls to the activity that is controlled.

Realistically, a portion (maybe small) of A must occur before B can start. Popescu and Charoenngam (1995) defined a *predecessor* as "an activity that has some measurable portion of its duration logically restraining a subsequent activity or activities" (p. 438). In reality, we may show two activities with an SS relationship and zero lag, but a certain—possibly small—portion of the predecessor must occur before the successor starts.

One observation that may occur in computer software: Oracle Primavera P6 provides a report after the CPM calculations mentioning dangling activities; i.e., those with no predecessor and/or successor. To the program, activity B in Figure 5.10b (assuming it has a successor, activity C) is not dangling because it has a predecessor and a successor. In reality, it is dangling because its end is not connected to any activity. Thus, its late finish date will be same as the project completion date and it may have large total float. The same situation can happen in cases such as when we use a negative lag (lead). In the case shown in Figure 5.21(b), even though the end of activity A show as connected to activity B, but in reality, activity A is dangling unless it is connected to another activity. This is because the first 4 days of A are a predecessor

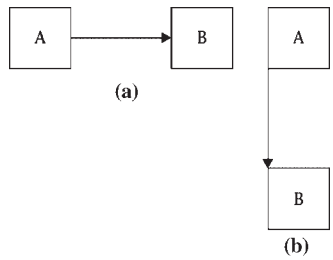



**Figure 5.10 (a) Typical predecessor relationship; (b) parallel predecessor relationship**

to activity B, while the next 6 days are open-ended or dangling. Such cases are not detected by the computer software and needs an expert eye to catch.

## CPM CALCULATIONS FOR PRECEDENCE DIAGRAMS

The CPM calculations for precedence diagrams differ from those for standard arrow or node diagrams. However, before we start the CPM calculations, *we must establish an important distinction: Are the activities contiguous (continuous) or interruptible?* In other words, once an activity starts, can it be performed on intermittent basis (paused, resumed, etc.) or must it proceed continuously until it is finished? In real life, both scenarios are possible, but the assumption whether the activities are contiguous or interruptible makes a substantial difference in the calculation method used and possibly in the calculated finish date of the entire project.

### Interruptible Activities

Let us start with the simple three-activity project depicted in Figure 5.11. The three activities are tied with only SS relationships, with no lags. Theoretically, all three activities can start at the same time. The project is complete when the activity with the longest duration, A, finishes. Thus, activity A is critical. Activities B and C have floats equal to the difference between their duration and the duration of A (the float for B is $10 - 5 = 5$ and the float for C is $10 - 3 = 7$). Now, let us add some lags, as shown in Figure 5.12.

In Figure 5.12, we are forcing a delay in the start of activities B and C, maybe because we want to see a certain percentage of activity A finished before B can start, and a certain percentage of activity B finished before C can start. We find that, in this example, activity B is the critical activity, since it takes 11 days to finish (6-day lag + 5 days' duration). The problem is that activity C may finish early, on day 10, which is 1 day *before* activity B is scheduled to finish (in reality, this situation may or may

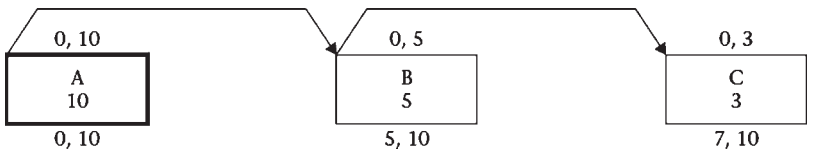



**Figure 5.11 Three-activity project using a start-to-start relationship**

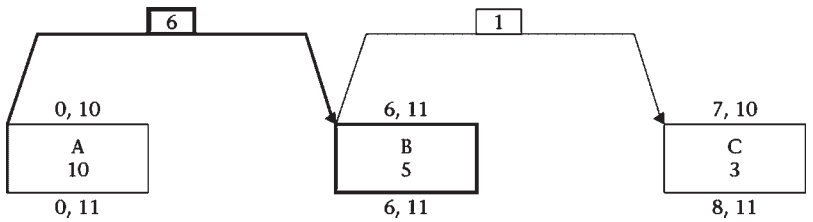



**Figure 5.12 Three-activity project using a start-to-start relationship with lags**

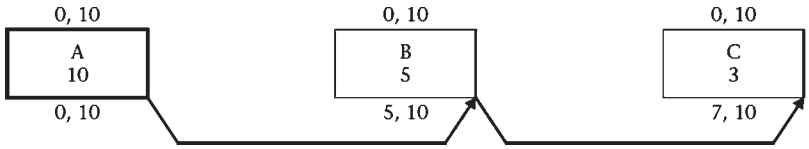



**Figure 5.13 Three-activity project, with 10-day duration, using a finish-to-finish relationship**

not be a problem). Consequently, let us try to tie the ends of the activities with FF relationships rather than the SS relationships (Figure 5.13).

In Figure 5.13, the finish of each activity is restricted to the finish of the predecessor. Activity B cannot finish till A is finished. Activity C cannot finish till B is finished. No restriction is put on their start other than the start of the project. Thus, not only is activity A (the activity with the longest duration) critical but also the *ends* of activities B and C are critical. This criticality can change if, for example, activity B has 12 days' duration, as shown in Figure 5.14.

In Figure 5.14, B has become the driving activity. It has no control over the completion of its predecessor (activity A), but it has control over the finish of activity C. Activity B automatically becomes critical (since it has the longest duration). The end of activity C is still critical, since it is tied to (follows) the end of B. Activity A has 2 days' "unrestricted" float.

If we tie both the start and the end of the activities shown in Figure 5.13, we get Figure 5.15. The relationships shown in Figure 5.15 combine those shown in Figures 5.11 and 5.13. As mentioned previously, in the case of two activities tied with two relationships, in most cases, one of these two relationships governs (i.e., becomes driving). In an unlikely case, both relationships govern (become driving). The main difference between Figures 5.15 and 5.11 is that we did not allow activities B and C in Figure 5.15 to finish before day 10, the finish date for activity A. There are no differences—as far as dates are concerned—between Figures 5.13 and 5.15. However, a logic difference exists between the two cases, but as a result of the durations of

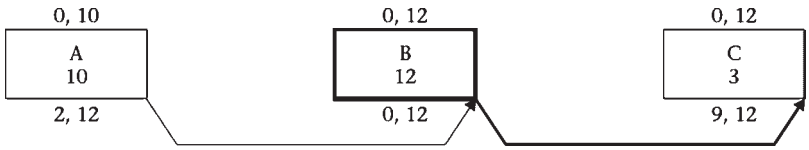



**Figure 5.14 Three-activity project, with 12-day duration, using a finish-to-finish relationship**

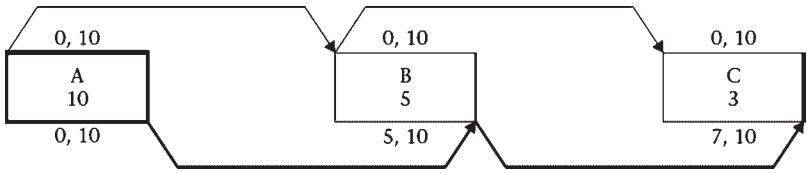



**Figure 5.15 Three-activity project, with a 10-day duration, using a combination relationship**

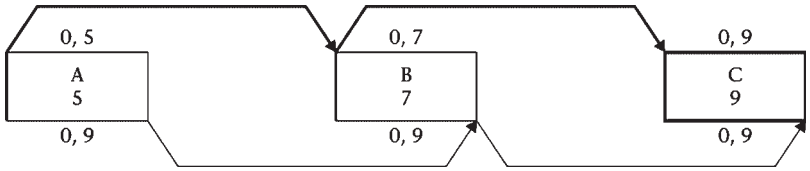



**Figure 5.16 Three-activity project, with 9-day duration, using a combination relationship**

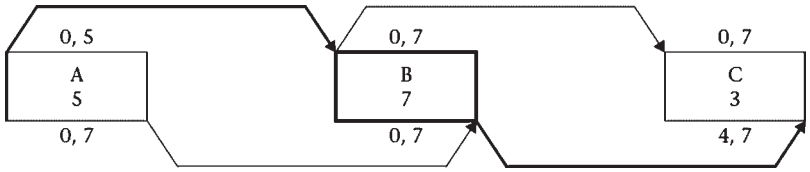



**Figure 5.17 Three-activity project, with 7-day duration, using a combination relationship**

the activities, the FF relationships control. This control can change with a change in duration, as shown in Figures 5.16 and 5.17.

Note that, in all the preceding cases—Figures 5.11 through 5.17, the duration of any activity may be longer than the difference between its finish and start dates: $EF - ES$ or $LF - LS$. This means it may stretch across a period that is longer than its duration (i.e., started, stopped, and then resumed), which is in accordance with our assumption of interruptible activities.

#### *The Simplistic Approach*

CPM calculations for precedence diagrams are similar to, but not the same as, the CPM calculations discussed in Chapter 4. The differences can be summarized by the following three points:

1. In Chapter 4 (arrow and node diagrams), we had only the FS type of relationship. Activities were always connected in only one way: from the end of an activity's predecessor to its start, and from its end to the start of its successor. In precedence diagrams, we use four types of relationships. Thus, you must be careful about the type of relationship chosen. An activity can be controlled (driven) not only from its start but from its end as well.
2. In precedence diagrams, we may use combination relationships (mainly SS and FF). Doing so creates a condition in which each relationship yields a different set of dates, but one set is rejected and the other prevails. Let us go through the calculations for Figure 5.17, for example:

    a. In the forward pass, activity A starts the project. $ES = 0$; $EF = 0 + 5$ (duration) $= 5$.

b. Activity B is connected to A by a combination relationship:

   i. The SS relationship (with no lag) means B can start just after A has started. This means activity B's $ES = 0$.
   $EF = ES + Dur = 0 + 7 = 7$ so the early dates are (0, 7)

   ii. The FF relationship (with no lag) means B can finish just after A is complete:
   $$EF(\text{B}) = EF(\text{A}) + Lag\ (\text{if any}) = 5 + 0 = 5$$
   $ES = EF - Dur = 5 - 7 = -2$ so the early dates are (−2, 5)
   The second answer violates the SS relationship so the first answer prevails.

c. The same method applies to activity C:

   i. The SS relationship (with no lag) means C can start just after B has started. This means activity C's $ES = 0$.
   $EF = ES + Dur = 0 + 3 = 3$ so the early dates are (0, 3)

   ii. The FF relationship (with no lag) means C can finish just after B is complete:
   $EF(\text{C}) = EF(\text{B}) + Lag\ (\text{if any}) = 7 + 0 = 7$
   $ES = EF - Dur = 7 - 3 = 4$ so the early dates are (4, 7)
   The first answer violates the SS relationship so the second answer prevails.

d. In the backward pass, we start at the end of activity C with its finish no earlier than day 7: $LF = 7$; $LS = LF - Dur = 7 - 3 = 4$, so the late dates are (4, 7)

e. For activity B:

   i. The FF relationship (with no lag) means B can finish just before C is complete, $LF(\text{B}) = LF(\text{C}) - Lag = 7 - 0 = 7$. $LS = LF - Dur = 7 - 7 = 0$, so the late dates are (0, 7)

   ii. The SS relationship (with no lag) means B can start just before C starts, $LS(\text{B}) = LS(\text{C}) - Lag = 4 - 0 = 4$. $LF = LS + Dur = 4 + 7 = 11$, so the late dates are (4, 11)
   The second answer delays the completion of the project, so it is rejected. The first answer prevails.

f. Activity A:

   i. The FF relationship (with no lag) means A can finish just before B is complete, $LF(\text{A}) = LF(\text{B}) - Lag = 7 - 0 = 7$. $LS = LF - Dur = 7 - 5 = 2$, so the late dates are (2, 7)

ii. The SS relationship (with no lag) means A can start just before B starts, $LS(A) = LS(B) - Lag = 0 - 0 = 0$. $LF = LS + Dur = 0 + 5 = 5$, so the late dates are (0, 5)

The first answer delays the completion of the project (by delaying the start of B), so it is rejected. The second answer prevails.

3. Note that unlike in Chapter 4, the durations may not be equal to $EF - ES$ or $LF - LS$. Furthermore, all or some of the total float may be restricted. This will be elaborated in the detailed approach (discussed subsequently). Total float is always calculated by using this simple equation:

$$TF = LF - Dur - ES$$

Free float (FF) is calculated the same way as in Chapter 4 and is always less than or equal to total float.

#### *General Notes on the Simplistic Approach*

Two points regarding the simplistic approach should be noted:

1. The position of the relationship arrows (i.e., from top or bottom of the same side) is a matter of aesthetics and is left to the user's choice. It has nothing to do with the choice of early or late dates. For example, the network of Figure 5.17 can be redrawn as shown in Figure 5.18.
2. We may have dangling activities in precedence diagrams. Dangling activities are tied from one end only. In other words, dangling activities have either no predecessors or no successors. As mentioned previously, we like to always start the network with one activity (e.g., Notice to Proceed) and end it with one activity (e.g., Final Completion). As an example of dangling activities, you may have a Clear & Grub activity with an SS relationship to the next activity, Excavation, with a 4-day lag (Figure 5.19). Nothing controls the end of the Clear & Grub activity (other than the end of the project). In this case, the LF date of the Clear & Grub activity is the end of the entire project. Another example

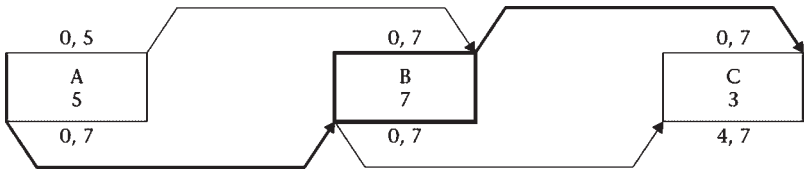



**Figure 5.18 Figure 5.17 redrawn**

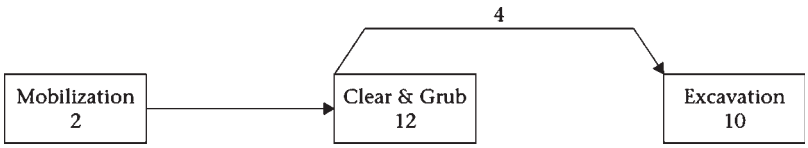



**Figure 5.19 Example of a dangling activity**

is when the start of Order & Deliver Equip. is not tied logically to another activity, but its finish controls the Install Equip. activity near the end of the project (let us imagine the activities in Figure 5.20 at the end of a large project network). In this case, the ES of Order & Deliver Equip. is the start of the entire project (day 0).

You should not leave any dangling activities. Instead, tie them to the most reasonable predecessor or successor. For example, you can make Order & Deliver Equip. in Figure 5.20 a successor to Submittals or another activity. Scheduling software such as Oracle Primavera P6 lists all activities with no predecessors or successors in its scheduling report. Ideally, you should have only one—not several—of each.

### *Alternative Approach*

Let us consider the activities shown in Figure 5.21. After performing the calculations for the three sets, we get the same results: the dates for A are (0, 10) and the dates for B are (4, 12), for both early and late dates. However, are the three approaches equivalent? The answer is no. In Figure 5.21a, the finish of A may be delayed without delaying B (if A is interruptible). In Figure 5.21c, the start of both activities is independent. In addition, if the duration of A changes, the three scenarios will yield different results. The scheduler must be careful, when choosing the logical ties (relationships), to reflect the actual relationship as much as possible.

In general, a positive lag means "after" and a negative lag (lead) means "before." The author has introduced a new relationship (DML) that performs more consistently in all these scenarios without the pitfalls. It is explained in Chapter 12.

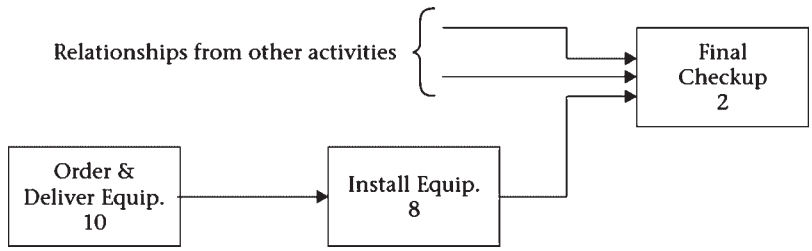



**Figure 5.20 Another example of a dangling activity**

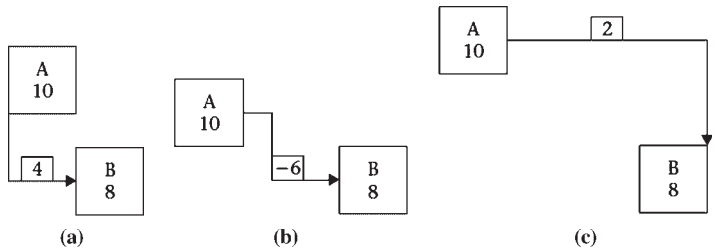



**Figure 5.21 Three alternative approaches (a) Activity B can start at least 4 days after the start of Activity A (b) Activity B can start no more than (at most) 6 days before the finish of Activity A (c) Activity B can finish at least 4 days after the finish of Activity A**

**Example 5.1**

Perform the CPM calculations for the network shown in Figure 5.22.

**Solution**
**Forward Pass**

1. Start the project at activity A. *ES* = 0. *EF* = 0 + 2 = 2.
2. Activity B can start as soon as activity A is finished. *ES* = 2. *EF* = 2 + 6 = 8.
3. Activity C can start 1 day after A has started. *ES* = 1, *EF* = 1 + 11 = 12.
4. Activity D can start 2 days after activity B has started. *ES* = 2 + 2 = 4. Use the later of *EF* = 4 + 7 = 11 and the *EF* (for B) = 8. We choose *EF* = 11.
5. Activity E can start as soon as B is finished. *ES* = 8. Use the later of *EF* = 8 + 4 = 12 and *EF* (for C) + 5-day lag = 12 + 5 = 17. We choose *EF* = 17.
6. Activity F has no restriction for its start (dangling activity). *ES* = 0, *EF* = 0 + 8 = 8.
7. Activity G can start after both D and E are finished. *ES* (for G) = 17 (the later of 11 and 17). Use the later of *EF* = 17 + 3 = 20 and *EF* (for F) + 4-day lag = 8 + 4 = 12. We choose *EF* = 20.
8. The calculated early finish date for the project is day 20 (project duration is 20 days).

**Solution**
**The Backward Pass**

1. Start at activity G. *LF* = 20, *LS* = 20 − 3 = 17.
2. Activity F must finish 4 days prior to the finish of G (i.e., *LF* = 20 − 4 = 16; *LS* = 16 − 8 = 8).
3. Activity E must finish before G can start. *LF* = 17. *LS* = 17 − 4 = 13.
4. Activity D must finish before G can start. *LF* = 17. *LS* = 17 − 7 = 10.
5. Activity C must finish 5 days before the finish of E. *LF* = 17 − 5 = 12. *LS* = 12 − 11 = 1.
6. Activity B must finish before D has finished, on day 17, and before E has started, on day 13. *LF* = 13 (the earlier). Use the earlier of *LS* = *LF* − *Dur* = 13 − 6 = 7 and 2 days before the LS for D (i.e., 8). We choose the earlier: *LS* = 7.

7. Activity A must finish before B can start. *LF* = 7. Use the earlier of *LS* = 7 − 2 = 5 and LS (for C) − 1-day lag = 1 − 1 = 0. We choose *LS* = 0.
8. The critical path is the start of A, all of C, the end of E, and all of G (Figure 5.23).
9. The total float equals 5, 5, 6, 5, and 8 for A, B, D, E, and F, respectively. Some of this float is restricted; some is not. This subject is discussed in the following section.

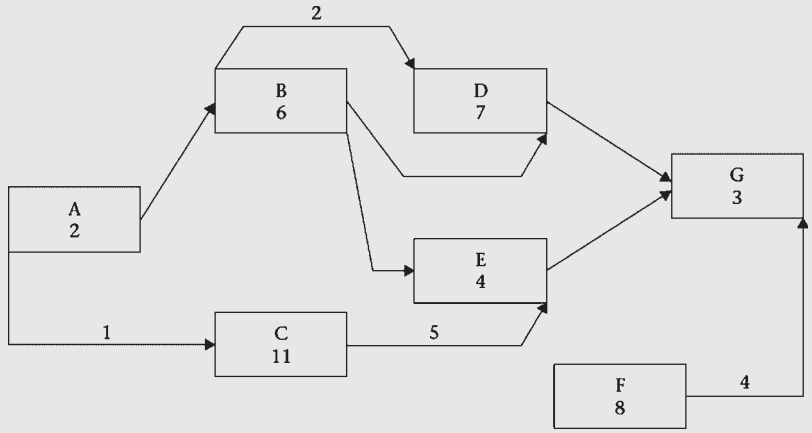



**Figure 5.22 Network for example 5.1**

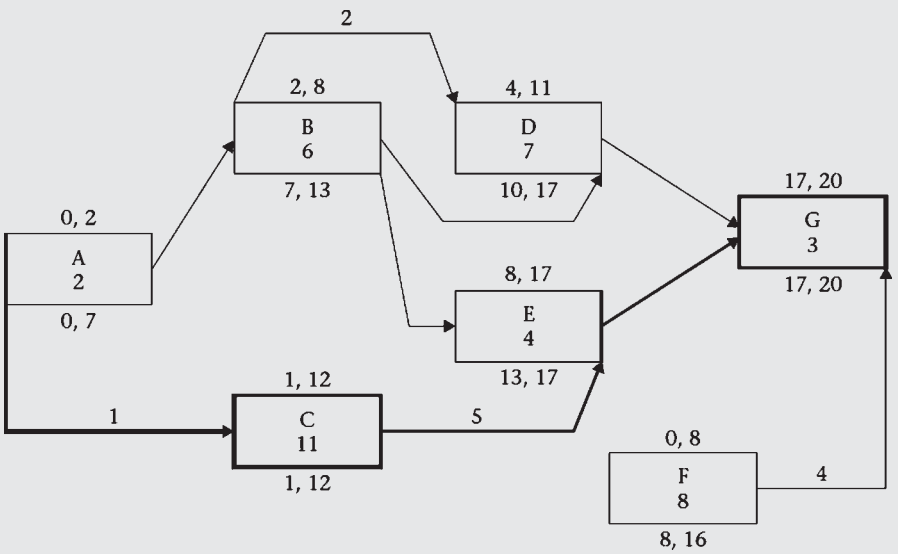



**Figure 5.23 Solution for example 5.1**

## THE DETAILED APPROACH

Unlike the arrow and node diagrams in Chapter 4, precedence diagrams may show the start or finish of an activity to be critical while the rest of the activity is not. This is the situation in Figures 5.12 through 5.21. Let us add a twist to this scenario, as shown in Figure 5.24.

In this case, both activities A and C are completely critical. Activity B has a critical start and a critical finish but is not critical between.

Looking at Figures 5.12 through 5.24, we also notice that, contrary to the arrow and simple node diagrams in Chapter 4, the duration of an activity may not always be equal to its $EF - ES$ or $LF - LS$. What does this mean? In Figure 5.17, for example, activity A must start on day 0; otherwise, the start of activity B, which is critical, will be delayed. The only restriction on the finish of activity A is that it should not delay the LF of activity B, which is day 7. This leaves activity A with 7 days, but it has only 5 days' duration. Therefore, activity A has 2 days of *restricted float*, which we explain later in this chapter. The crew for activity A has three options:

1. Start the activity on day 0, work nonstop, and finish early on day 5.
2. Start the activity on day 0, perform a certain portion, take a break of 1 or 2 days, and then resume and finish the activity by day 7.
3. Reduce production rate (by reducing crew size or work hours/day) so the duration stretches from 5 to 7 days.

A forth float option, which activity A *does not* have, is to delay its start. If its start is delayed, the start of B will be delayed, which will delay the whole project. This is why we call it *restricted float*. This particular type of restricted float is called start-restricted float. Looking at activity C in Figure 5.17, we also find that C has 4 days of float in its start. However, no matter when it starts, it must finish on day 7; not before, not after. We conclude that activity C has 4 days of restricted float, or finish-restricted float. The work crew has the following three options:

1. Start the activity on day 0, finish a certain portion, take a break (or breaks) of 1 to 4 days, and return and finish the activity by day 7.
2. Delay the start of the activity till day 4, work nonstop, and finish on day 7.
3. Reduce production rate (by reducing crew size or work hours/day) so the duration stretches from 3 to 7 days.

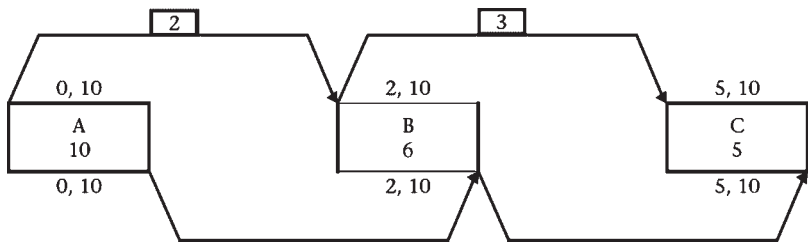



**Figure 5.24 Network for the detailed approach**

A forth float option, which activity C *does not* have, is to start early *and* finish early on day 3. It cannot finish before activity B is finished.

Looking at Figures 5.14 through 5.16, we find activities A and B in Figure 5.16 with *start-restricted floats*. Activity C in Figure 5.14 and activities B and C in Figure 5.15 have *finish-restricted floats*.

Activity B in Figure 5.24 must start on day 2 and must finish on day 10. We note that it has only 6 days' duration but must fill an 8-day time interval. We call the difference $(8 - 6 = 2)$ *start-finish-restricted float*, or, for short, double-restricted float.

Activity B in Figure 5.11 has unrestricted float. The work crew can use this float in one of three ways:

1. Start the activity on day 0, work nonstop, and finish early on day 5.
2. Start the activity on day 0, finish a certain portion, take a break (or breaks) of 1 to 5 days, and return and finish the activity by day 10.
3. Delay the start by 1 to 5 days, work nonstop, and finish on or by day 10.

This type of float is similar to the total float discussed in Chapter 4. We call it unrestricted float. *Total float* is the combination of all types of float, whether restricted or unrestricted.

#### Definitions

*Start-restricted float*: The amount of time we can delay the rest of the work in the activity, after it has started on its critical start date, without delaying the entire project.

*Finish-restricted float*: The amount of time we can delay the start of work on the activity, or the rest of it if it has started, then finish on its critical finish date without delaying the entire project.

*Double-restricted float*: The amount of time we have to delay the rest of the work in the activity after it has started on its critical start, then finish on its critical finish date without delaying the entire project. It happens with combination (SS + FF) relationships; and both of them are driving.

*Unrestricted float*: The amount of time we can delay all or part of the activity without delaying the entire project.

#### The Equations

For calculation purposes, let us put both *start-restricted float* and *finish-restricted float* under one category, single-restricted float (*SRF*), as compared with *double-restricted float (DRF)* or *unrestricted float (URF)*. As mentioned previously, in this chapter, *total float (TF)* includes all types of float, restricted or unrestricted.

For calculations, follow these steps:

1. Calculate the DRF:

$$DRF = \max[(EF - LS - Dur), 0] \tag{5.1}$$

2. If $DRF = 0$, apply these equations:

$$URF = \min[(LS - ES), (LF - EF)] \tag{5.2}$$

and

$$SRF = \text{abs}|(LS - ES) - (LF - EF)| \tag{5.3}$$

or

$$SRF = TF - URF^{2} \tag{5.4}$$

3. If $DRF > 0$, apply these equations:

$$URF = \min[(LS - ES), (LF - EF)] \tag{5.5}$$

and

$$SRF = \max[(LF - LS), (EF - ES)] - Dur - DRF \tag{5.6}$$

4.

$$TF(URF + SRF + DRF) = [LF - ES - Dur] \tag{5.7}$$

The preceding equations combine start-restricted float and finish-restricted float as single-restricted float. You can distinguish between the two types mostly by simple observation, or by the following rule:

If $(LF - EF) > (LS - ES)$, then $SRF$ is start restricted.

However,

If $(LF - EF) < (LS - ES)$, then $SRF$ is finish restricted.

#### Contiguous (Uninterruptible) Activities

Let us assume that our activities cannot be interrupted (contiguous activities). In other words, once they start, they must continue till they are finished.[3] All types of restricted float are eliminated. The activity becomes like an indivisible unit: If there is float, the whole activity slips or does not slip. In this case, activities become, simply, either critical or noncritical. Calculations are much simpler, but they may give you a different (later) project finish date than those for interruptible activities.

[2] See equation for TF.

[3] Even with this assumption, a real-life interruption can occur. In computer programs such as Primavera P3/P6 or MS Project, there is a special (manual) function to suspend or pause an activity, then resume it. This type of manual suspension and resumption is not factored into the calculation. Programs still treat the activity as one unit. The suspension time may not count as part of the duration of the activity but will certainly affect the succeeding activities and possibly the entire project.

Let us return to Figure 5.12: With activity A asacontiguous, it becomes entirely critical, with both early and late dates as (0, 10). Activities B and C in Figure 5.13 become entirely critical, with both their early and late dates as (5, 10) for B and (7, 10) for C. The same is true of activity C in Figure 5.14. Its early and late dates become (9, 12). In Figures 5.15 and 5.16, all activities also become critical.

In the preceding cases, the finish date of each project does not change, despite the change in assumption from interruptible to contiguous. The only change is that activities with restricted float lose their float and become totally critical. However, this may not always be the case. In Figure 5.24, if activities become contiguous, the dates change per Figure 5.25, and the entire project is pushed back 2 days. CPM calculations for such cases are similar to those described previously for interruptible activities, with one exception: We must satisfy the following equation:

$$Dur = EF - ES = LF - LS$$

This can force the early dates to be pushed forward (to a later date) or late dates to be pushed backward (to an earlier date). In the previous example (Figure 5.24), we find that the early dates for activity B violate the preceding equation:

$$Dur = 6 < (EF - ES)$$

We have to move one of the two dates. Moving the EF date to day 8 will satisfy the equation but will violate the FF relationship between B and A. The only choice we have is to move the ES date to day 4. Then, the early dates for activity B are (4, 10). The same argument applies to late dates. All three activities in this case are critical and have no float of any type.

To formalize the rules, we can say that activities with a combination (SS and FF) relationship, say A and B, for example, will have two sets of early dates and two sets of late dates. One set will prevail:

a. In the forward pass, the SS relationship (plus lag if any) determines the $ES_1$ date for activity B, which is *ES* (for A) + 2 (lag) = 2. The $EF_1$ for B is calculated as $EF_1 = ES_1 + Dur = 2 + 6 = 8$. The first set of early dates for activity B is (2, 8).

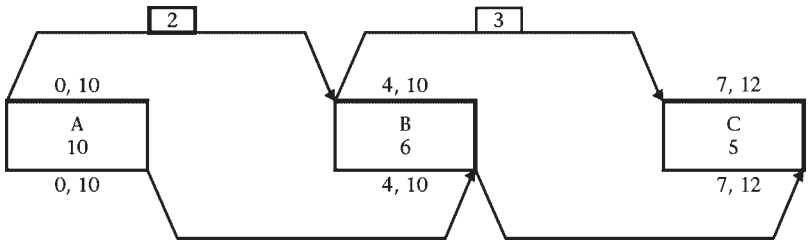



**Figure 5.25 Network in Figure 5.24 with contiguous activities**

b. The FF relationship (plus lag, if any) determines the $EF_2$ date for activity B. The EF date for activity A is day 10, which is the same for B (since the lag on the FF relationship is 0). The $ES_2$ for activity B is then calculated as $ES_2 = EF_2 - Dur = 10 - 6 = 4$. The second set of early dates for activity B is (4, 10).

c. Pick whichever date set—($ES_1$, $EF_1$) or ($ES_2$, $EF_2$)—is later; that is (4, 10).

d. In the backward pass, the SS relationship (minus lag if any) determines the $LS_1$ date for activity B, which is *LS* (for C) − 3 (lag) = 7 − 3 = 4. The $LF_1$ for B is calculated as $LS_1 + Dur = 4 + 6 = 10$. The first set of late dates for activity B is (4, 10).

e. The FF relationship (minus lag if any) determines the $LF_2$ date for activity B as *LF* (for C) − Lag (0 in this case) = 12 − 0 = 12. The $LS_2$ for B is calculated as $LF_2 - Dur = 12 - 6 = 6$. The second set of late dates for activity B is (6, 12).

f. Pick whichever date set—($LS_1$, $LF_1$) or ($LS_2$, $LF_2$)—is earlier; that is (4, 10).

The preceding process looks complicated in theory but is actually intuitive. Total float and free float are calculated the same way as in Chapter 4. If we re-solve example 5.1 using contiguous activities, we will get the same finish date for the project; day 20. The only difference will be that activities A and E will be completely critical. As mentioned previously, this is not always true. Let us look at example 5.2:

### Example 5.2

Perform the forward and backward passes on the precedence network shown in Figure 5.26, on the basis of the following: interruptible activities and contiguous activities.

### Solution with Interruptible Activities

| Activity | ES | EF | LS | LF | DRF | SRF | URF | TF |
|---|---|---|---|---|---|---|---|---|
| A | 0 | 10 | 3 | 54 | 0 | 41 | 3 | 44 |
| B | 0 | 12 | 0 | 12 | 0 | 0 | 0 | 0 |
| C | 3 | 7 | 6 | 33 | 0 | 23 | 3 | 26 |
| D | 2 | 30 | 5 | 33 | 0 | 0 | 3 | 3 |
| E | 0 | 38 | 22 | 54 | 2 | 22 | 16 | 40 |
| F | 12 | 22 | 12 | 22 | 0 | 0 | 0 | 0 |
| G | 22 | 42 | 22 | 42 | 0 | 0 | 0 | 0 |
| H | 30 | 39 | 33 | 42 | 0 | 0 | 3 | 3 |
| I | 42 | 54 | 42 | 54 | 0 | 0 | 0 | 0 |

### Solution with Contiguous Activities

| Activity | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|
| A | 0 | 10 | 0 | 10 | 0 | 0 |
| B | 0 | 12 | 2 | 14 | 2 | 0 |
| C | 3 | 7 | 3 | 7 | 0 | 0 |
| D | 2 | 30 | 2 | 30 | 0 | 0 |
| E | 24 | 38 | 24 | 38 | 0 | 0 |
| F | 12 | 22 | 14 | 24 | 2 | 2 |
| G | 24 | 44 | 24 | 44 | 0 | 0 |
| H | 30 | 39 | 35 | 44 | 5 | 5 |
| I | 44 | 56 | 44 | 56 | 0 | 0 |

The simple difference between the two solutions is that in the case of contiguous activities, we do not allow restricted float. Once an activity starts, it must continue till it is finished. Calculations were going similar until activity E. The early dates (24, 38) were calculated from its FF relationship with activity D. This is not good enough for activity G, whose critical start on the 22nd day depends on the start of activity E. This forces a delay in activity G, which will delay the entire project by 2 days. As a result, the critical path becomes: A, C, D, E, G. This leaves only three noncritical activities: B, H, and F. Activities B and F were critical in the "interruptible activities" solution but now gained a float of 2 days as a result of forcing this 2-day delay on activity G.

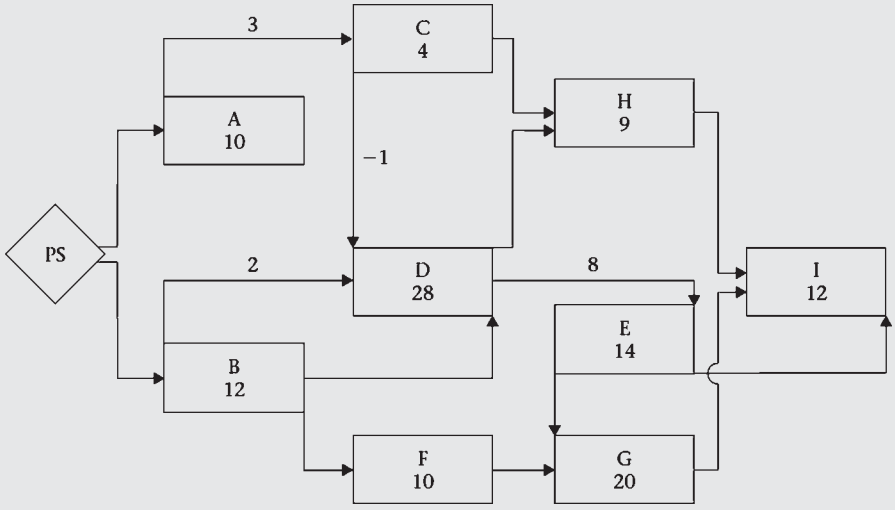



**Figure 5.26 Network for example 5.2**

Activity H had 3 days of total float in the "interruptible activities" solution, and now the float has added 2 days to become 5.

Note also that a relationship between two critical activities is not necessarily critical. For example, the FF relationship between activities E and I is not driving and, thus, is not critical.

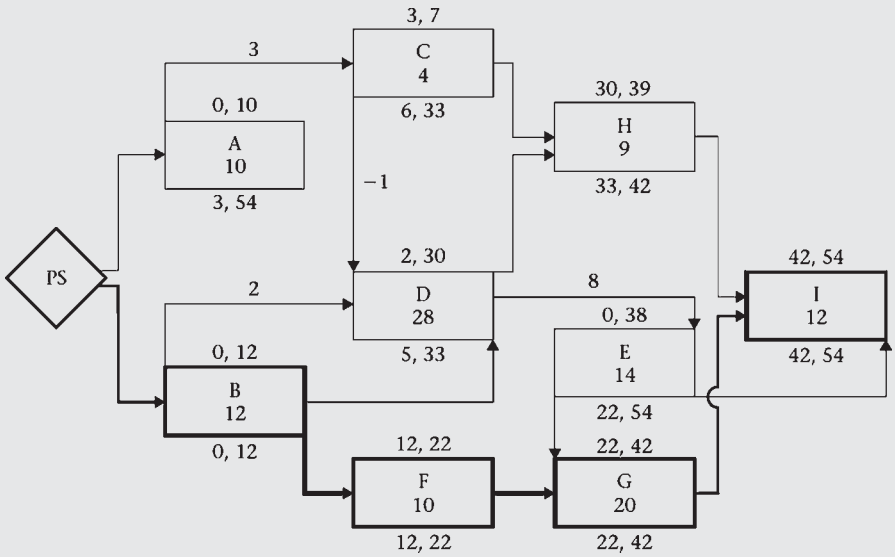



**Figure 5.27 Solution for example 5.2 with interruptible activities**

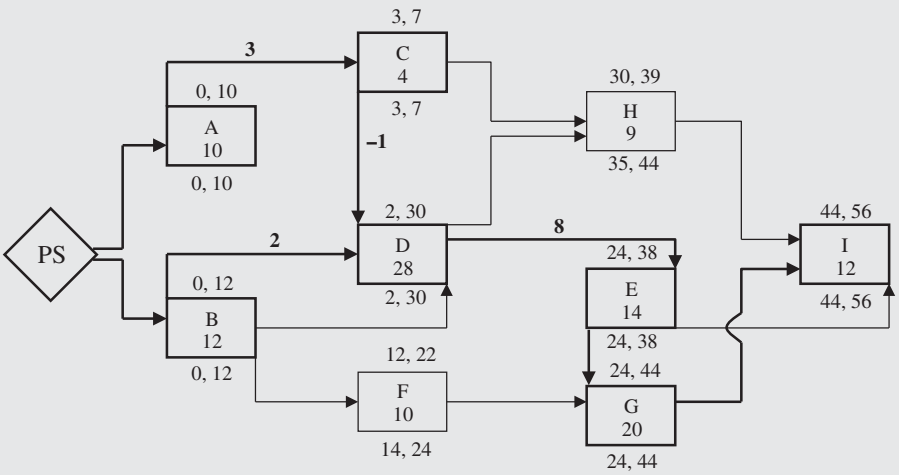



**Figure 5.28 Solution for example 5.2 with contiguous activities**

### Remedy for Interruptible Activities

As mentioned earlier, the interruption in the activity duration meant in this context is a planned one; not stoppage due to unpredicted and/or uncontrolled circumstances. Some CPM software programs allow the user to choose between contiguous and interruptible activities. However, unfortunately this choice is on "all or none" basis, thus, it is safer to stay with the contiguous option then deal with interruptible activities on a case by case basis.

As you saw earlier in the interruptible activities case, an activity may have a critical start but a flexible finish, or vice versa. In other words, it may have a time slot to fill that is larger than its duration (see many examples in Figures 5.12 through 5.18). The difference in this time slot (LF−ES) contains the duration plus the restricted float. If this activity becomes contiguous, the restricted float disappears and the activity is pushed forward or backward (depending whether its finish or start was critical). We proved in Example 5.2 that going from interruptible to contiguous type of activity may cause a later completion date for the schedule. For the case shown in Figure 5–25, two solutions are suggested:

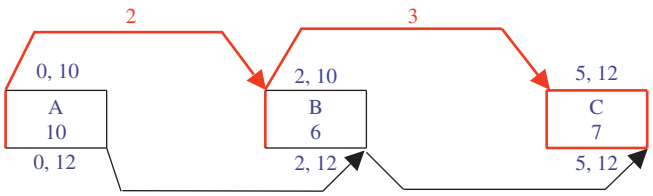



**Figure 5.29(a) Network with interruptible activities**

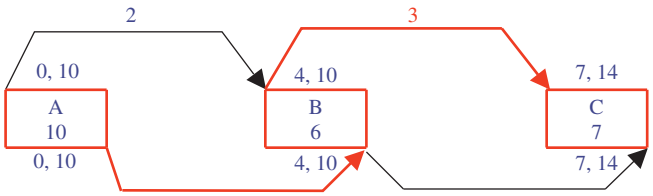



**Figure 5.29(b) Network with contiguous activities**

1. Stretch the activities that have restricted float till they fill the "restricted duration", i.e., eliminate restricted float. Unrestricted float (where the entire activity can move as one unit) can stay without being absorbed. In this case, the contractor has to reallocate (reduce) resources so the total resource allocation stays the same after stretching.
2. Split the activities that have restricted float. The duration of each portion depends on the dependency between that portion and the predecessor or successor, which usually equals the lag between them. In our case, activity

B (successor) can start after two days of work performed in activity A. Thus, the first portion of A has to be at least two days. Similarly, the first portion of B has to be at least three days. Note also that the two portions of A (A1 and A2) can be done consecutively while the two portions of B (B1 and B2) cannot due to the restrictions on B: First part has to start no later than day 2 so it will not delay the start of C, and the second part cannot finish before A is completed.

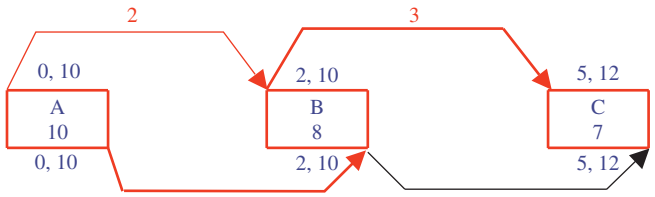



**Figure 5.29(c) Remedy 1: Network with elastic (stretchable) activities**

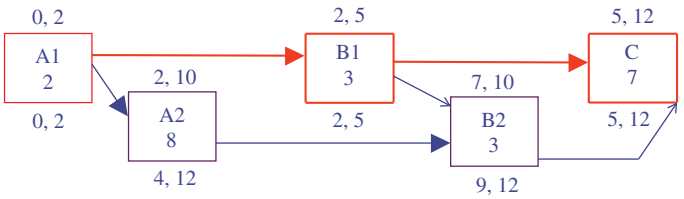



**Figure 5.29(d) Remedy 2: Network with split activities**

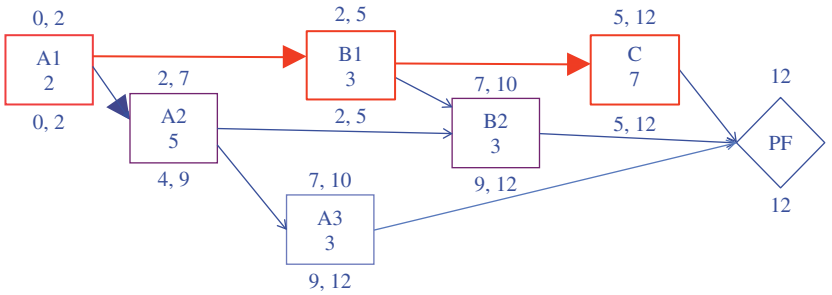



**Figure 5.29(e) Remedy 2: Network with Split Activities and only FS relationships**

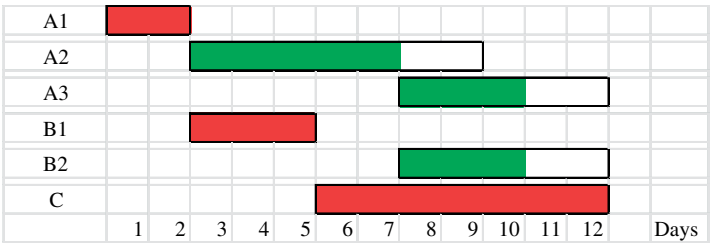



**Figure 5.29(f) Bar Chart for the networks in Figures 5.29 (d) and (e)**

With both solutions, we were able to get the earlier project finish date (12 days) as compared to the later date (14 days) with the contiguous activities option.

**Tip Box 5.2**

While "interruptible activities" may be an option, it is simpler to split these activities into two or more contiguous ones.

## THE CRITICAL PATH REVISITED

In Chapter 4, we defined the critical path as the longest continuous path from start to finish, taking in consideration all time-consuming and time-impacting factors. The definition still holds without any change, however, its application in a network with some or all interruptible activities has to be more careful, as the critical path will include part of (start or finish) some activities. For example in Figure 5.15, the critical path is: Activity A, FF relationship to end of activity B, and FF relationship to end of activity C. In Figure 5.17, it is start of activity A, SS relationship to activity B, all of activity B, the FF relationship to end of activity C. In Figure 5.23 it is: Start of activity A + SS lag (A-C) + activity C + FF lag (C-E) + Finish of activity E + activity G.

In Figure 5.24 (interruptible activities with double-restricted float), there are two critical paths: Path 1: Start of activity A, SS relationship to activity B with 2-day lag, SS relationship to activity C with 3-day lag, all of activity C. Path 2: All of activity A, FF relationship to activity B, FF relationship to activity C.

So basically, the definition of Chapter 4 holds with the note that the SS + FF combination relationship may produce two critical paths.

## FINAL DISCUSSION

Four final points should be considered:

1. The subject of precedence diagrams can be somewhat complicated. It is easy for someone in the field to use the "sour grapes" excuse and say, "Who uses these things anyway?" There is nothing wrong with making assumptions that simplify our life. However, if these simplifications mean avoiding a subject that we perceive as complicated or unfamiliar to us, we may be missing something important. Understanding the nature of relationships among activities is extremely important. Making the assumption of interruptible or contiguous activities is also important. It can result in a difference of several days in the

project's completion date. We just proved this when we compared Figures 5.24 and 5.25. Maybe the project manager does not need to discuss the types of float with his or her work crews, but he or she *must* understand—in layperson's terms—that some activities must start with a certain portion (but not all) of them finished before a succeeding activity can start. Failure to understand this point may result in an inaccurate schedule and a possible conflict between field operations and the office-prepared schedule.

2. In reality, most project managers and schedulers overlook the issue of interruptible or contiguous activities and may also overlook the type of relationship and lags. They try to compensate for the inaccurate logic by "correcting" it through schedule updates. For example, the baseline schedule may show a Clear & Grub activity with 12 days' duration followed by an Excavation activity (FS relationship). Once the project starts, you may indicate an Actual Start for Excavation only 4 days after Clear & Grub had started, a clear violation of the set logic. The scheduling report may indicate "Activity started; predecessor has not finished." The calculation of the updated schedule will depend on whether you want to apply Retained Logic (i.e., schedule the remainder of Excavation *after* the predecessor, Clear & Grub, has finished) or to apply Progress Override by allowing Excavation to continue independently of the Clear & Grub activity (this topic is explained in more detail in chapter 7). This option is available with some computer software programs, but the author's observation has been that many software users never pay attention to this choice. As a result, the program always uses the more conservative assumption—Retained Logic—which may result in a later calculated finish date for the project.
3. At the same time, the scheduler should use the KISS (keep it simple and smart, not stupid) approach as much as possible. Sometimes, instead of having a combination (SS and FF) relationship with lags, splitting the predecessor activity into two activities and then using the traditional FS relationship, may be simpler and more efficient. The precedence diagramming method is an effective and powerful tool, but it should be used in a reasonable and effective way.
4. Computer programs, to the best of the author's knowledge, either do not give the user the choice of (interruptible or contiguous activities) or allow it only at the entire project level only. In the latter case, the user must decide whether *all* activities are interruptible or contiguous (although the user can choose the contiguous option, then manually interrupt and resume certain activities). Real-life activities are not exactly one way or the other. This puts the responsibility back into the scheduler's hands (remember the discussion on the scheduler's qualifications at the end of Chapter 1). He or she must make intelligent and informed decisions that should align the schedule assumptions with reality as closely as possible within the limitations of computer programs and practicality. Remember, it is the human being behind the computer, not the computer itself, who makes the important decisions.

## CHAPTER 5 EXERCISES

1. Explain the main differences between the standard node diagram (covered in Chapter 4) and precedence diagrams.
2. What is the *stair-type relationship?* What is the advantage of precedence diagrams over it? Draw a network for a roofing job (install trusses, install sheathing, install felt, install shingles), using each method (i.e., draw two diagrams, one for each method).
3. Give a practical example for each of the following:
   a. Start-to-start (SS) relationship only
   b. Finish-to-finish (FF) relationship only
   c. Combination SS and FF relationship
4. What does the following relationship mean?
   a. Activity B must start exactly 3 days after the start of A.
   b. Activity B can start at least 3 days after the start of A.
   c. Activity B can start at most 3 days after the start of A.
   d. None of the above
5. What does the following relationship mean?
   a. Activity B must finish exactly 2 days after the finish of A.
   b. Activity B can finish at least 2 days after the finish of A.
   c. Activity B can finish at most 2 days after the finish of A.
   d. None of the above
6. What does the following relationship mean?
   a. Activities A and B must start simultaneously, but B must finish exactly 2 days after the finish of A.
   b. Activity B can start after the start of A but must finish at least 2 days before the finish of A.
   c. Activity B can start before the start of A but must finish at most 3 days after the finish of A.
   d. Activity B can start after the start of A but must finish at least 2 days after the finish of A.
7. What does the following relationship mean?
   a. Activity A can start 2 days before the start of activity B.
   b. Activity B can start 2 days after the completion of activity A.
   c. Activity B can start 2 days before the completion of activity A.
   d. Activity B has to start at least 2 days before the completion of activity A.

8. Define a *fast-track operation*. Briefly discuss its pros and cons.
9. Mention examples in which using fast-tracking is bad, good, or a "must" option.
10. From the following table, draw the precedence network, perform the CPM calculations, and complete the table entries, assuming interruptible activities.

| Activity | Duration | IPA | Type Rel[a] | Lag | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 3 | – | | | | | | | | |
| B | 5 | A | SS | 3 | | | | | | |
| C | 2 | A | | | | | | | | |
| D | 6 | B | FF | | | | | | | |
| | | C | | | | | | | | |

[a]If the relationship type is not mentioned, it is finish to start (FS). If no lag is mentioned, it is zero.

11. From the following table, draw the precedence network, perform the CPM calculations, and complete the table entries, assuming interruptible activities.

| Activity | Duration | IPA | Type Rel[a] | Lag | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 4 | – | | | | | | | | |
| B | 3 | – | | | | | | | | |
| C | 8 | A | SF | | | | | | | |
| D | 7 | A, B | | | | | | | | |
| E | 6 | D | SS | 3 | | | | | | |
| F | 3 | D | | | | | | | | |
| G | 5 | F | SS | 2 | | | | | | |
| | | F | FF | | | | | | | |

[a]If the relationship type is not mentioned, it is finish to start (FS). If no lag is mentioned, it is zero.

12. From the following table, draw the precedence network, perform the CPM calculations, and complete the table entries, assuming interruptible activities.

| Activity | Duration | IPA | Type Rel[a] | Lag | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 5 | – | | | | | | | | |
| B | 7 | A | SS | 2 | | | | | | |
| C | 8 | A | | | | | | | | |
| D | 10 | A | SS | 3 | | | | | | |
| | | | FF | | | | | | | |
| E | 4 | B | FF | 2 | | | | | | |
| F | 6 | C, D | | | | | | | | |
| G | 2 | E, F | | | | | | | | |

[a]If the relationship type is not mentioned, it is finish to start (FS). If no lag is mentioned, it is zero.

13. Repeat exercise 10 using contiguous activities.
14. Repeat exercise 11 using contiguous activities.

15. Repeat exercise 12 using contiguous activities.
16. Prove that using interruptible activities in the following project allows the project to finish 5 days earlier than if the activities were contiguous.

| Activity | Duration | IPA | Type Rel[a] | Lag | ES | EF | LS | LF | TF | FF |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 7 | – | | | | | | | | |
| B | 6 | A | SS | 3 | | | | | | |
| | A | FF | 4 | | | | | | | |
| C | 2 | B | SS | 1 | | | | | | |
| | B | FF | | | | | | | | |
| D | 6 | C | SS | | | | | | | |
| | C | FF | 4 | | | | | | | |
| E | 10 | D | SS | 3 | | | | | | |
| | D | FF | 2 | | | | | | | |

[a]If the relationship type is not mentioned, it is finish to start (FS). If no lag is mentioned, it is zero.

17. Give real-life (not necessarily construction) examples for the following:
    a. An SS (start-to-start) relationship without lag. No FF (finish-to-finish) relationship is required.
    b. An SS relationship with lag. No FF relationship is required.
    c. An SS and FF combination relationship
    d. An FF relationship, with or without lag
18. A subcontractor must do the following:
    a. Framing (5 days)
    b. Drywall installation (4 days)
    c. Drywall finish and paint (3 days)

    Assuming he wants to make sure each activity finishes as least 1 day after its predecessor has finished, draw these three activities in a precedence diagram and calculate how much time the subcontractor would need to finish all three activities.
19. Look at your solution to the previous exercise. Is it a unique solution, or can you achieve the same result with different logic?
20. Give an example for each of the following:
    a. Start-restricted float
    b. Finish-restricted float
    c. Double-restricted float
    d. Unrestricted float

Chapter 6

# Resource Allocation and Resource Leveling



Lauderhill City Hall, Lauderhill, Florida

## INTRODUCTION

The term *resource* is used in many fields and contexts. Most companies have *human resources* departments, which match the need for employees with the appropriate supply by hiring and laying off workers. The term *financial resources* is commonly used to indicate available monetary sources. In project management, we use the term *resources* to indicate three main categories: labor (human), equipment, and materials. Ultimately, everything is translated into a monetary quantity that may be—for the accounting department—a part of the financial resources.

## THE THREE CATEGORIES OF RESOURCES

All expenses, in any construction project, can be classified under one of the three categories just mentioned: labor, equipment, and materials.

### Labor

Labor can be further classified into the following two subcategories:

1. *Salaried staff*: These individuals include the project manager, superintendent, project engineer, secretary, and any other person who is tied to the corporate office or a project but is not tied to one particular activity or work package in a project. Salaried persons usually get paid a fixed salary for the duration of the project or their assignment. Their salaries usually count as part of the company's indirect expenses (overhead), not as labor.
2. *Hourly workers*: These individuals are hired to perform a specific task or activity. Examples include carpenters, masons, ironworkers, electricians, foremen, and so forth. They are usually paid for actual hours worked.

### Equipment and Materials

Equipment and materials also can be further classified into two subcategories:

1. *Construction equipment and materials*: This type of equipment and materials is used for the construction process but is not permanently installed in the project. Examples of *construction equipment*[1] are bulldozers, backhoes, scrapers, cranes, power generators (if not permanently installed), forklifts, mechanical trowels, heaters, and blowers. Inexpensive personal tools are usually treated differently (either as a lump sum for all tools or as the laborer's personal property). Examples of *construction materials* are formwork materials and scaffolding.
2. *Installed equipment and materials*: This type of equipment and materials stays permanently in the project after completion. Examples of *installed equipment*

[1] In the United Kingdom, this type of equipment is called *plant*.

are heat pumps, emergency power generators (usually installed in hospitals, industrial projects, and some other projects), kitchen equipment, and other specialized equipment in industrial projects. Examples of *installed materials* are concrete, rebar, concrete masonry units (CMUs), brick, mortar, insulation, framing wood, paint, roof shingles, floor tile and carpet, bathroom accessories, plumbing pipes and fittings, and electrical wires. Elevators and escalators may be classified as either installed equipment or installed materials, but in most cases, they are installed by the same vendor and in the estimate are considered a subcontractor cost.

For estimators, the *equipment* category includes mostly construction equipment. Installed equipment falls in the *materials* category.

## WHAT IS RESOURCE ALLOCATION?

**Resource allocation** is the assignment of the required resources to each activity, in the required amount and timing. Resource allocation is also called *resource loading*.

## RESOURCE LEVELING

### What Is Resource Leveling?

*Resource leveling* is minimizing the fluctuations in day-to-day resource use throughout the project. It is usually done by shifting noncritical activities within their available float. It attempts to make the daily use of a certain resource as uniform as possible.

### Why Level Resources?

When the contractor adds the daily total demand for a specific resource for all activities, he or she must provide the required amount, or work will be delayed.

This daily demand for a certain resource naturally fluctuates during the life cycle of the project, depending on the work being performed every day (i.e., activities requiring that resource) and the amount demanded from that resource for each activity. This fluctuation (say, 10 carpenters for the first two weeks, 6 for the following week, 18 for weeks 4 and 5, 12 for week 6, etc.) is not practical or economical because the contractor either has to maintain the maximum amount demanded even when it is not being utilized or keep hiring and laying off workers.

Leveling may also be necessary for an expensive piece of equipment such as a crane (which may cost money not only in rental expenses but also in mobilization, setup, operation, maintenance, and demobilization). Say, for example, two activities require a tower crane at the same time. If you can delay the start of one activity (the more critical) until the other (the less critical) has finished, you will re-assign the tower crane, or any other major resource, to the other activity. By doing this, you will have reduced the maximum demand of tower cranes at any time to only one, which will save expenses.

### Do All Resources Have to Be Leveled?

Not all resources need to be leveled. The main idea of resource leveling is to improve work efficiency and minimize the cost of the project. This concept applies to resources that are hired or rented—namely, labor and (major) construction equipment. This is because these resources cost the contractor money just for their being on site—working or idle.

The need for such resources may vary significantly as some activities start (they pull new resources) and other activities finish (they release their resources). Likewise, the resource requirement of some activities changes during their duration.

In general, materials do not need to be leveled. For instance, it is not an uncommon practice to place 100 CY (cubic yards) of concrete in one day, place no concrete for one week, place more concrete the week after, and so on. Materials must be managed using a completely different concept, as will be discussed at the end of this chapter.

### Multiproject Resource Leveling

Some resources may be shared among projects. The question is which resources and how much should be shared. For small projects in a relatively close vicinity, for example, some staff (project manager, safety manager, quality manager, secretary, etc.) and equipment can be shared. A project manager must make decisions when the situation looks like a borderline case: for instance, whether it would be more efficient to have someone travel between two jobs versus hiring another person, even though that person would not be fully occupied of the time. The same argument holds true for equipment. In general, convenience and simple economics are mostly the driving criteria in making such decisions. However, other issues may be considered, such as the short- and long-term need; future market expectations; staff morale, fatigue, and satisfaction; relationships with stakeholders; the possibility of a need suddenly occurring, and so forth. Keep in mind that transferring resources from one project to another permanently is frequently and normally done, and it is not considered sharing.

#### Example 6.1

Assume a project engineer costs his employer $63 per hour ($50 wage + $13 benefits). Two projects are within *x* miles of each other. The engineer travels at an average speed of 40 miles per hour and costs the company $1 per mile to travel between the two projects. Assume that the following four statements are true:

1. The engineer is needed a minimum of 3 hours per day in each project.
2. Travel between the two projects occurs only once a day (the engineer starts his or her day on job A, travels to job B, and then comes back home near job A).

3. Overtime, if needed, is compensated at 1.5 times the regular rate (of wages only, assuming benefits are constant per hour).
4. A second engineer costs the same amount as the first one.

What is the maximum distance between the two projects that makes sharing the same engineer efficient?

**Solution**

Let's consider two situations.

*First—no overtime*: No overtime means that the engineer travels between the two jobs (round trip) for no more than 2 hours (3 hours at job A + 3 hours at job B + 2 hours' travel time = 8 hours per day).

Maximum distance = 2 hours $*$ 40 mph = 80 miles round-trip or 40 miles one way. Car cost = 80 $*$ \$1/mile = \$80 per day. Total cost per day = \$63 $*$ 8 + \$80 = \$584 and

$$\text{Average cost per hour} = \$584/8 = \$73$$

It is clearly more economical to use one engineer than to hire two engineers at a combined cost of \$63 $*$ 2 = \$126 per hour.

*Second—with overtime*: Let us assume that the two jobs are 100 miles apart. The engineer will have 5 hours of driving time (2.5 hours each way), or 11 hours of work per day.

Car cost = 200 $*$ \$1/mile = \$200 per day

Overtime compensation =

3 $*$ \$50 $*$ 1.5 = \$225

Regular-time compensation = 8 $*$ \$50 = \$400

Benefits = 11 $*$ \$13 = \$143[2] and

Total cost per day = 200 + 225 + 400 + 143 = \$968

This cost is slightly less than \$63 $*$ 8 $*$ 2 = \$1,008 per day (for two engineers), but the difference is less and hiring a second engineer may be a good idea, depending on other factors, such as the length of need and future expected need, the long-term effect of driving and working overtime on the engineer (fatigue, low morale, higher probability of a traffic accident), the consequences of suddenly needing the engineer while he/she is on the other project.

[2] The benefits may actually be a little less, since some of them are based on regular hours only. However, this small error is ignored here for simplicity.

Staff members who do not have to be present at the job site every day can be spread out, either by dividing their day between two or more jobs or by assigning certain entire days to different jobs. Certain high-paid staff, such as safety officers, schedulers, and project control managers, who need to spend only one day every week or every two weeks at the job site, may even fly hundreds of miles between jobs. With the advancement of telecommunications tools (phones, Internet, video conferencing, etc.), many functions can now be performed from a remote location.

**Tip Box 6.1**

Sharing resources among projects is simply a matter of feasibility and economy.

#### Assigning Budgets in Computer Scheduling Programs

Without going into accounting details, let us briefly cover budgeting in this chapter, but only in the context of project control and resource leveling. In scheduling programs, two methods are available for assigning budgets to activities (this subject is discussed further in Chapter 10):

1. Assigning a lump-sum amount without explaining (in the program) how the number was derived or what resources were used. You may still need to supply a cost accounting code in some software packages, which helps track the cost.
2. Assigning a number of units of certain resources (e.g., one foreman, one equipment operator, two laborers, one bulldozer, and one hydraulic excavator) to the activity. The program will calculate the budget for a particular activity from the "resource dictionary" in the project database.

The second method has six advantages:

1. You can level and manage your resources only when you assign resources to the activity.
2. You can produce procurement reports, specifying the resources needed by type, quantity, date, and cost. You can link your schedule with the accounting (and estimating) system, match your demand with supply, and trace each expense in your project. You can do this, too, with the first method, but you will see only dollar amounts without any breakdown details.
3. This method helps more in project control and earned value management.
4. In case there is a change in the cost or availability of a resource that is being used for one or more activities, the scheduling program will reflect the impact of the change at the entire project level.
5. You may be able to use a "resource calendar." This type of calendar is defined for a specific crew. For example, if the plumbing crew is available for work on

Wednesday through Saturday only, the program will automatically schedule work only during those days for the activities to which this crew has been assigned.

6. **Resource-driven schedules** are possible. Under certain conditions, you can allow your resources to control the duration of an activity. For example, if a **resource-driven activity** requires four painters for 10 days, the program uses a total of 40 man-days, or 320 man-hours, for its basis. Depending on the painters' availability and logic among activities, the scheduling program may assign a fluctuating number of painters to the activity to finish the job in the most efficient way (from a resource management perspective). The result may be an increase or a decrease in the duration, with the same budget of 320 man-hours. This option may also be turned off to maintain the original duration.

One interesting scenario that pertains to point 4 occurs when resources are priced through a certain date and then increase. Suppose that a union contract calls for a carpenter's pay rate of \$34 per hour through 30 June 2014. After this, it will increase to \$36.50 per hour. Assume that a particular activity requires 128 carpenter man-hours and is scheduled to take place in June 2014. The total cost for the carpenters is $128 * \$34 = \$4,352$. Now, suppose that the activity schedule slips to July. The cost will increase by $128 * \$2.50 = \$320$, for a new budget of \$4,672. You have to be careful in such cases as to whether to allow the resource dictionary to drive the budget or to treat the budget as a fixed amount.

#### Leveling Resources in a Project

Resource leveling is a mathematically complex process. The resource-leveling method is called the *minimum moment algorithm*, as discussed by Robert B. Harris (1978) in his classic textbook, *Precedence and Arrow Networking Techniques for Construction*, and other references. Fortunately, computer programs have eliminated the difficult part of this process. Let us deal with resource leveling manually for a simple example.

#### Example 6.2

A subcontractor needs to install flooring in two areas:

1. *Area 1*: This area has old vinyl tile that must be removed and replaced with new vinyl tile.
2. *Area 2*: This area has a concrete slab that needs to be topped with ceramic tile.

This simple project is broken into the activities shown in the following table, along with the logic, the duration, and the required number of laborers for each activity.

| Activity ID | Activity Description | IPA | Duration (Days) | Laborers |
|---|---|---|---|---|
| A | Purchase & Deliver Materials | – | 5 | 2 |
| B | Remove Old Vinyl Tile | – | 7 | 4 |
| C | Install Ceramic Tile | A | 3 | 3 |
| D | Install New Vinyl Tile | A, B | 5 | 3 |
| E | Clean Up & Inspect | C, D | 2 | 2 |

Do the following:

1. Draw the precedence network and perform the CPM calculations.
2. Allocate the required resources and then level them so that the subcontractor does not use more than six laborers at any time.
3. Find ways to improve the labor usage profile.

For the sake of simplicity, assume that any laborer can perform any task.

## Solution

Figure 6.1 shows the precedence diagram for this example, and Figure 6.2 shows the bar chart and **resource usage profile**, or laborer usage profile.

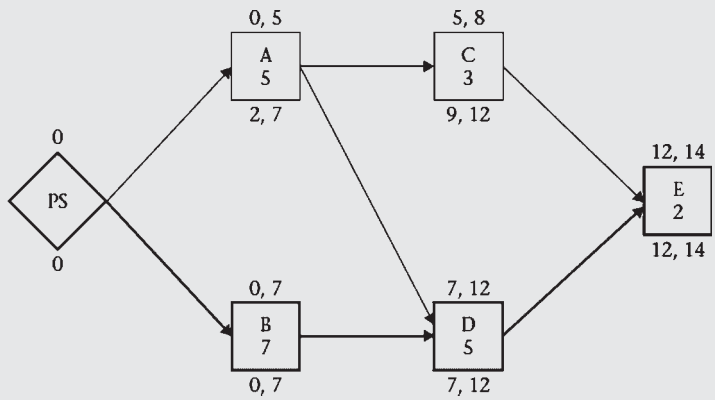



**Figure 6.1 Precedence diagram for example 6.2 (PS, project start)**

Using the early dates, we note that on days 6 and 7, the subcontractor needs seven laborers, one over the limit. The subcontractor then decides to use 2 days of the float for activity C (Figure 6.3). This shift eliminates the labor-use spike on days 6 and 7 and increases the use of laborers on days 9 and 10 from three to six.

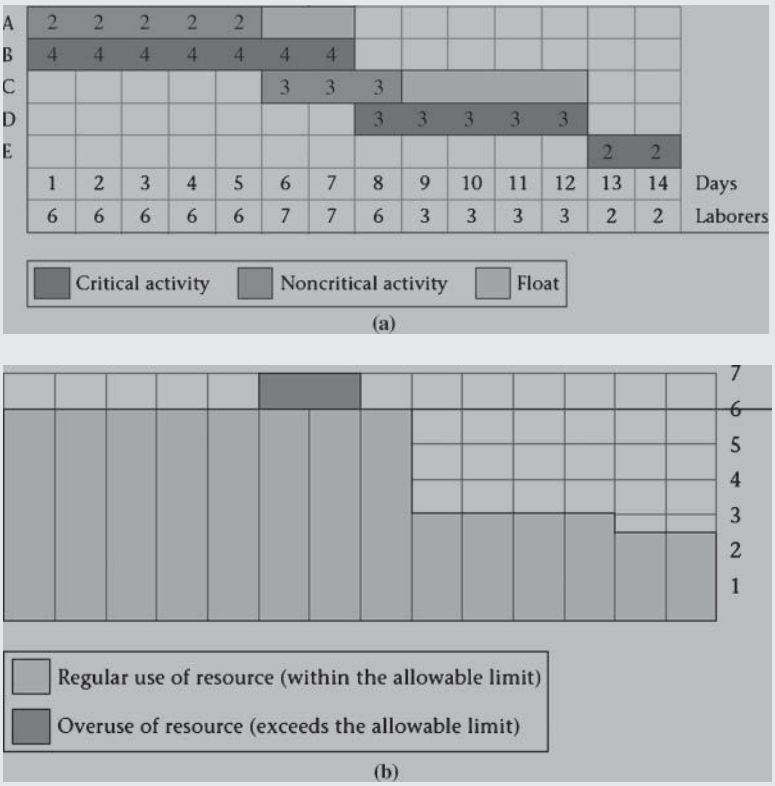



**Figure 6.2 (a) Bar chart for example 6.2 with an unleveled labor assignment (typically following early dates); (b) resource, or labor, usage profile for example 6.2, showing overallocation**

The subcontractor observes that, even though he or she did not exceed the limit on the number of laborers per day (six) in Figure 6.3, the labor usage profile can be improved by minimizing the fluctuations, as shown in Figure 6.4.

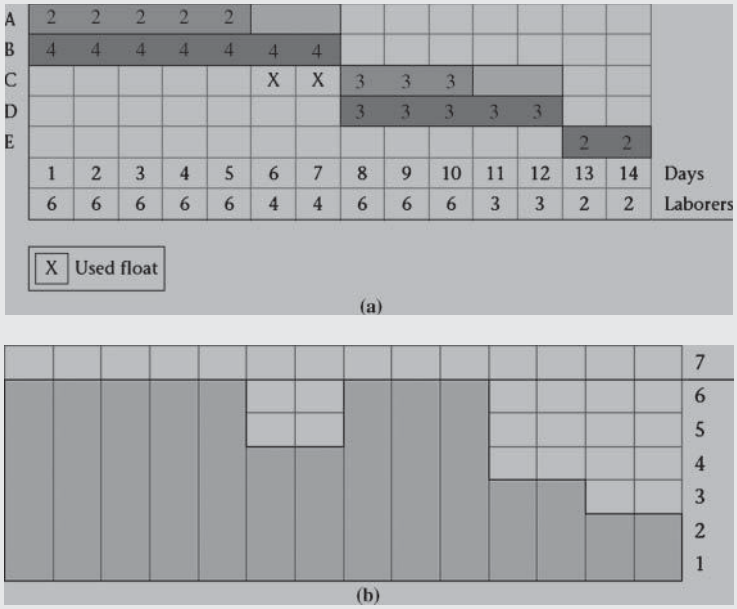



**Figure 6.3 (a) Bar chart for example 6.2 with a leveled labor assignment (within the allowable limit); (b) resource, or labor, usage profile for example 6.2, with a labor assignment within the allowable limit**

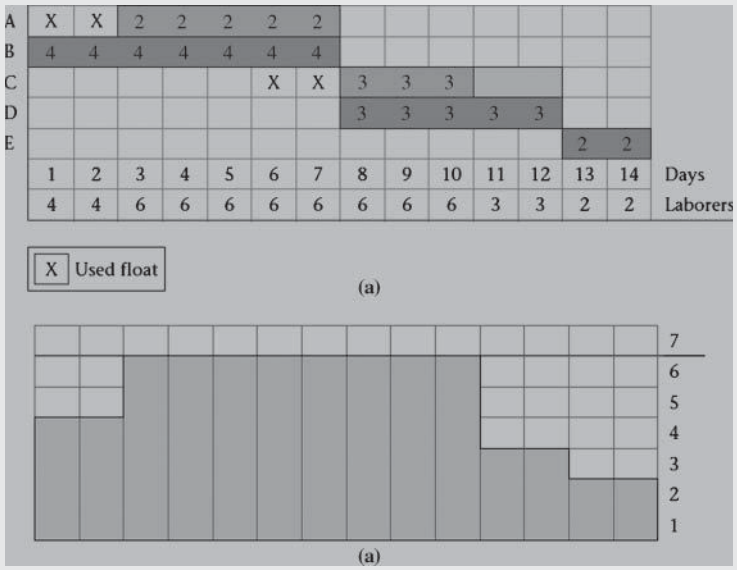



**Figure 6.4 (a) Bar chart for example 6.2 with the labor assignment leveled and more efficiently distributed; (b) resource, or labor, usage profile for example 6.2 with the labor assignment efficiently distributed within the allowable limit**

### Example 6.3

Let us consider a more complicated example, which is still far less complicated than real projects, which have hundreds of activities and tens of resources.

| Activity ID | Activity Description | Duration (Days) | IPA | Laborers |
|---|---|---|---|---|
| A | Excavation & Foundation | 6 | – | 4 |
| B | Slab on Grade (SOG) | 3 | A | 3 |
| C | Framing | 10 | B | 4 |
| D | Plumbing | 4 | B | 2 |
| E | Electrical Wiring | 3 | C[a] | 3 |
| F | Drywall | 5 | C[a] | 3 |
| G | HVAC[b] Rough-in | 3 | C[a] | 4 |
| H | Roof | 5 | C | 3 |
| I | Paint | 4 | F | 2 |
| J | HVAC Finish | 2 | G, H | 2 |
| K | Flooring | 4 | D, I | 3 |
| L | Electrical Finish | 1 | E, H | 2 |
| M | Punch List & Cleanup | 1 | J, K, L | 2 |

[a]This is a combination SS + FF relationship with no lags.
[b]HVAC is an acronym for heating, ventilation, and air-conditioning.

For each of the following scenarios, determine how to level the resources:

a. An unlimited number of laborers
b. Only 10 laborers available at any time
c. Only 8 laborers available at any time
d. Only 8 laborers available at any time, but activities may be interrupted
e. Only 8 laborers available at any time, but the labor resource may drive the durations of activities

### Solution

Figure 6.5 shows the precedence network solution for Example 6.3.

a. *An unlimited number of laborers*. As shown in Figure 6.6], the project finishes in 28 days. Using the early dates results in a maximum labor use of 14 laborers per day on days 17, 18, and 19.
b. *Only 10 laborers available at any time*. Only one adjustment is necessary: Delay activity G by 3 days (it had 6 days of total float), as shown

in Figure 6.7. Another scenario is shown in Figure 6.8 with the peak use pushed to days 23 (9 laborers) and 24 (10 laborers) by delaying activities E by 3 days, G by 6 days, and J and L by one day each. We can still meet the original finish date, 28 days, with no delay.

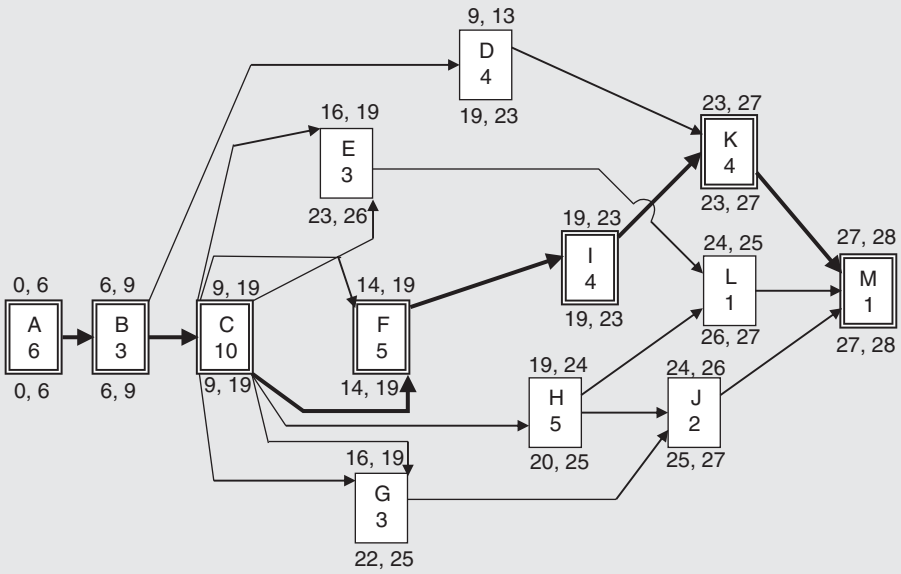



**Figure 6.5 Logic network solution for Example 6.3**

c. *Only 8 laborers available at any time*. In this case, the project must be delayed by 1 day (Figure 6.8). This is an example of *forward resource leveling*, in which resources are not available to both satisfy the demand for all activities and finish on time. This situation is discussed at the end of this example.

d. *Only 8 laborers available at any time but allow activities to be interrupted*. Even with interruptible activities, we could not satisfy the activities' need for resources and maintain the total resource daily usage within 8 laborers, yet finish in 28 days. We need 29 days (Figure 6.9). In Figure 6.10, we managed to do it in 28 days with one minor violation of the logic: we allowed activity K to start one day before the completion of activity I.

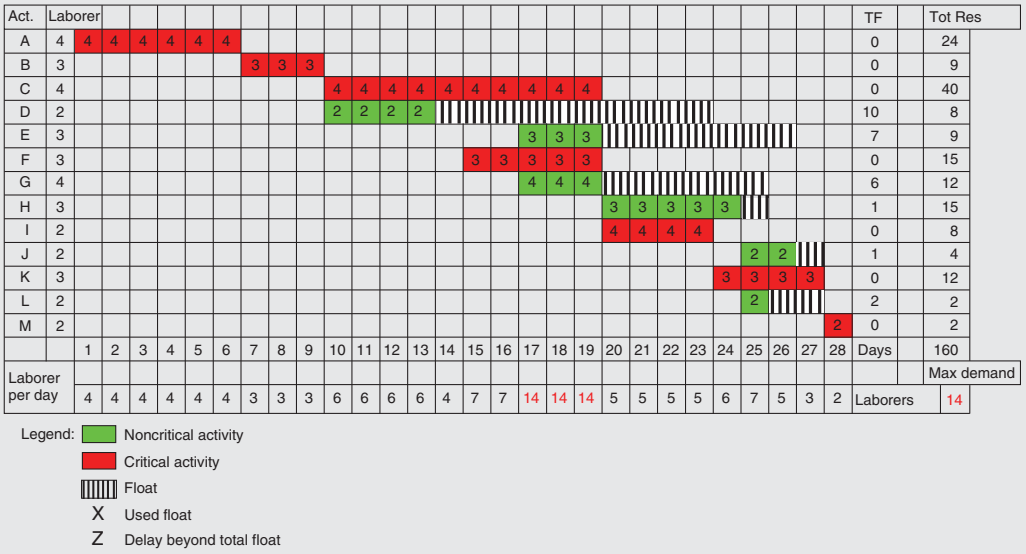



**Figure 6.6 Bar chart for example 6.3 with an unleveled labor assignment**

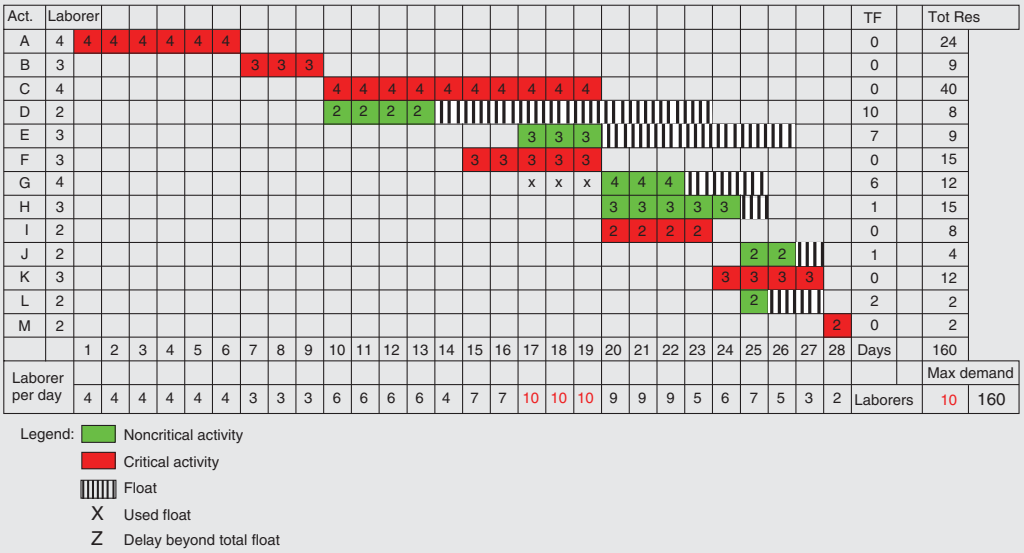



**Figure 6.7a Bar chart for example 6.3 with the labor assignment leveled and a maximum of 10 laborers per day**

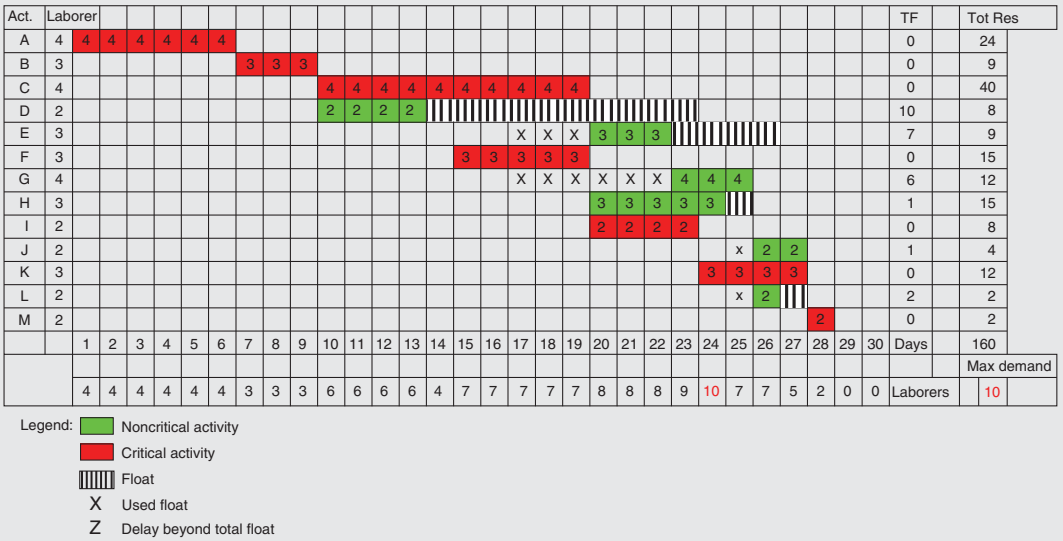



**Figure 6.7b Bar chart for example 6.3 with the labor assignment leveled and a maximum of 10 laborers per day (2nd scenario)**

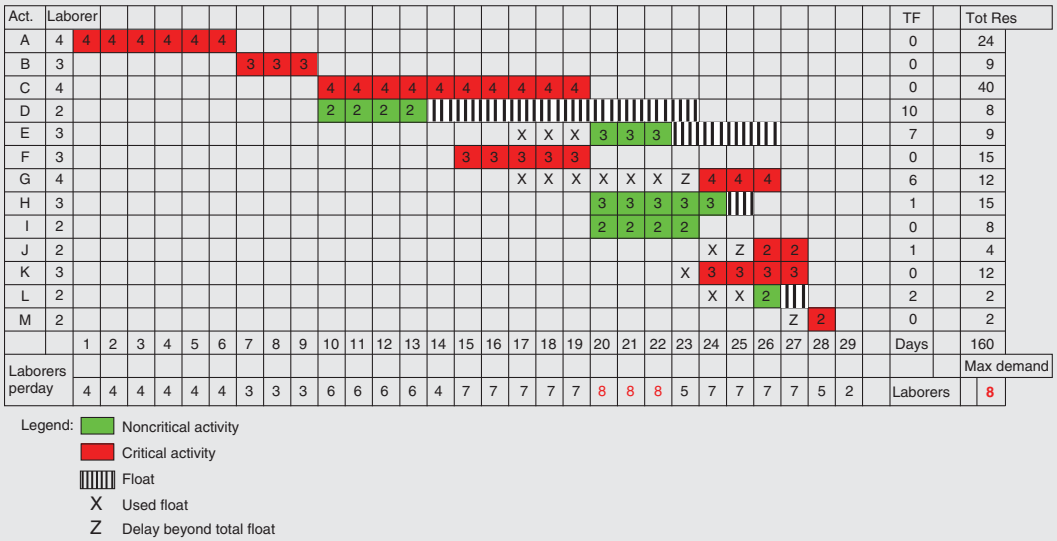
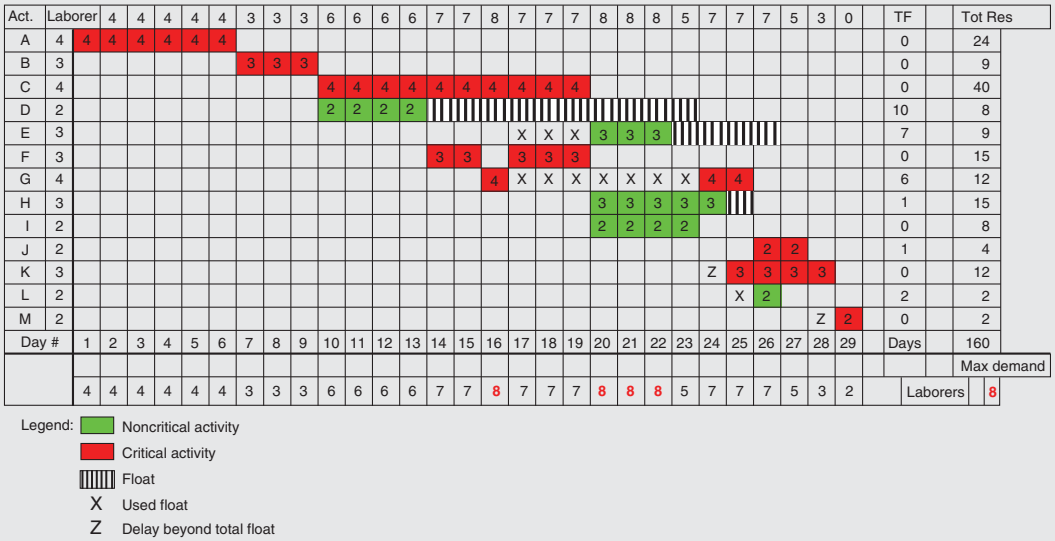



**Figure 6.8 Bar chart for example 6.3 with the labor assignment leveled and a maximum of 8 laborers per day**


Act. Laborer 4 4 4 4 4 3 3 3 6 6 6 6 7 7 8 7 7 7 8 8 8 5 7 7 7 5 3 0 TF Tot Res
A 4 4 4 4 4 4 4 24
B 3 3 3 3 0 9
C 4 4 4 4 4 4 4

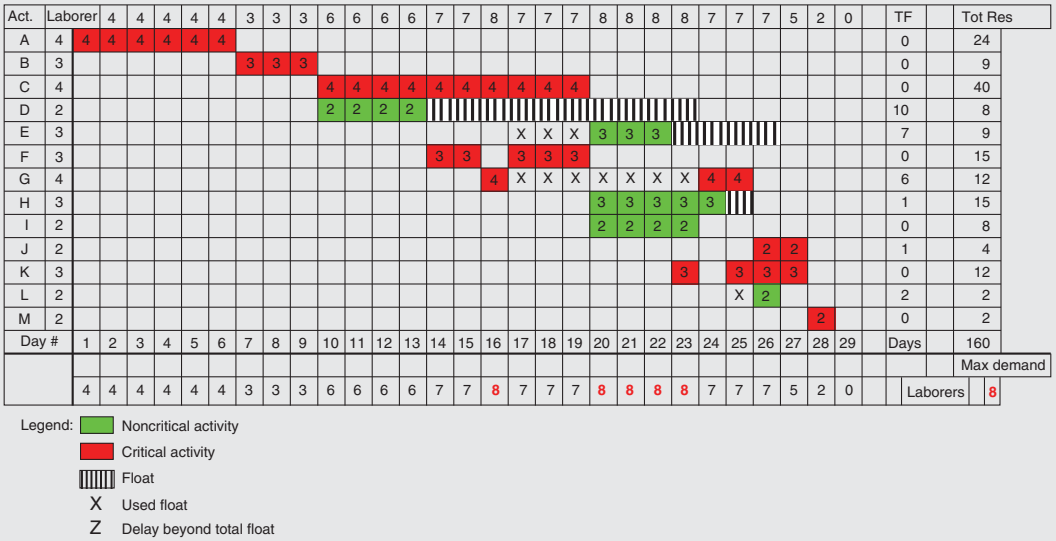



**Figure 6.10 Bar chart for example 6.3 with the labor assignment leveled, a maximum of 8 laborers per day, interruptible activities, and activity K is allowed to start one day before activity I is complete**

| Act. | Laborer | | | | | | | | | | | | | | | | | | | | | | Tot Res |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 4 | 8 | 8 | 8 | | | | | | | | | | | | | | | | | | | 24 |
| B | 3 | | | | 5 | 4 | | | | | | | | | | | | | | | | | 9 |
| C | 4 | | | | | | 8 | 8 | 8 | 8 | 2 | 2 | 2 | 2 | | | | | | | | | 40 |
| D | 2 | | | | | | | | | | | | | | | 4 | 4 | | | | | | 8 |
| E | 3 | | | | | | | | | 1 | 2 | 2 | 2 | 2 | | | | | | | | | 9 |
| F | 3 | | | | | | | | | 3 | 3 | 3 | 3 | 3 | | | | | | | | | 15 |
| G | 4 | | | | | | | | | 2 | 1 | 1 | 1 | 3 | 4 | | | | | | | | 12 |
| H | 3 | | | | | | | | | | | | | | 4 | 4 | 4 | 3 | | | | | 15 |
| I | 2 | | | | | | | | | | | | | | | | | 4 | 4 | | | | 8 |
| J | 2 | | | | | | | | | | | | | | | | | | 4 | | | | 4 |
| K | 3 | | | | | | | | | | | | | | | | | | | 6 | 6 | | 12 |
| L | 2 | | | | | | | | | | | | | | | | | | | | 2 | | 2 |
| M | 2 | | | | | | | | | | | | | | | | | | | | | 2 | 2 |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | Days | 160 |
| Laborer/day | | 8 | 8 | 5 | 4 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 8 | 6 | 8 | 2 | | max | 8 |

(a)

| Act. | Laborer | | | | | | | | | | | | | | | | | | | | | | Tot Res |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 4 | 8 | 8 | 8 | | | | | | | | | | | | | | | | | | | 24 |
| B | 3 | | | | 5 | 4 | | | | | | | | | | | | | | | | | 9 |
| C | 4 | | | | | | 8 | 8 | 8 | 8 | 8 | | | | | | | | | | | | 40 |
| D | 2 | | | | | | | | | | | 2 | 2 | 4 | | | | | | | | | 8 |
| E | 3 | | | | | | | | | | | | | | | | | 3 | 6 | | | | 9 |
| F | 3 | | | | | | | | | | 6 | 6 | 3 | | | | | | | | | | 15 |
| G | 4 | | | | | | | | | | | | | | | | 7 | 5 | | | | | 12 |
| H | 3 | | | | | | | | | | | | | 4 | 4 | 6 | 1 | | | | | | 15 |
| I | 2 | | | | | | | | | | | | | 4 | 4 | | | | | | | | 8 |
| J | 2 | | | | | | | | | | | | | | | | | | 2 | 2 | | | 4 |
| K | 3 | | | | | | | | | | | | | | | | | | | 6 | 6 | | 12 |
| L | 2 | | | | | | | | | | | | | | | | | | | | 2 | | 2 |
| M | 2 | | | | | | | | | | | | | | | | | | | | | 2 | 2 |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | Days | 160 |
| Laborer/day | | 8 | 8 | 5 | 4 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 8 | 8 | 6 | 8 | 8 | 8 | 8 | 8 | 2 | max | 8 |

Legend:
- Noncritical activity
- Critical activity
- Float
- X — Used float
- Z — Delay beyond total float

(b)

**Figure 6.11 Bar charts for example 6.3 with the labor resource driving the durations of activities and a maximum of 8 laborers per day (a) for scenario 1 and (b) for scenario 2**

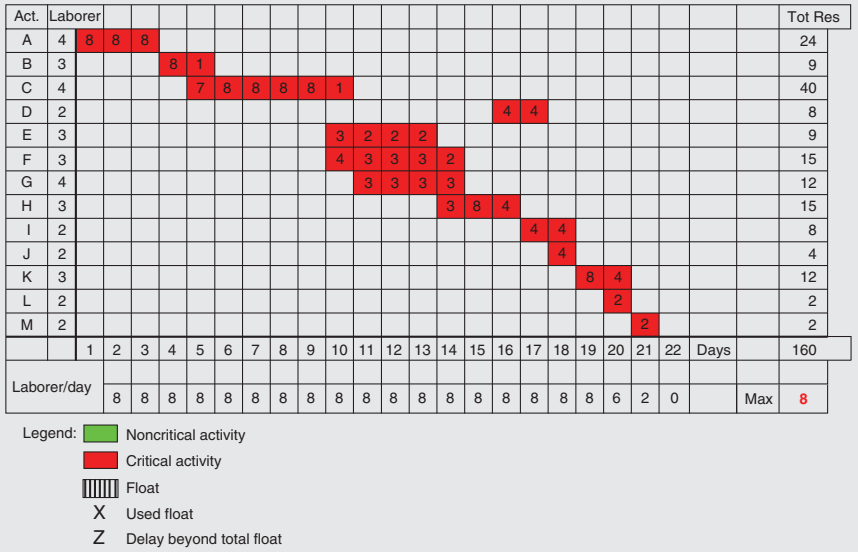



**Figure 6.12 Bar chart for example 6.3 with labor resource driving the durations of activities, a maximum of 8 laborers per day, and activity C is allowed to start on the last day of activity B**

e. *Only 8 laborers available at any time, but the laborer resource may drive the durations of activities*. We show two scenarios in Figures 6.11a and 6.11b. Other scenarios may lead to the same project duration, 22 days, or more, but not less. In this case, we "played with" activity resource allocations, allowing durations to fluctuate on the basis of supply (available resources) and demand (total resource requirements for activities). Even though we did not allow resource use to exceed 8 laborers per day, we were able to finish the project in 22 days (vs. 29 days in case d). If we allow activity C to start on the last day of activity B, we can cut the project duration to 21 days, as shown in Figure 6.12. Also, if we allow activity M to occur in parallel with activity L, we can cut another day of the duration without going over the 8 laborers per day limit. In fact, this would be the ideal case from the point of view of resource leveling. since we will be using the same number of resources, 8 laborers per day, throughout the entire project. Practically speaking, however, this is unlikely.

***Discussion of Example 6.3***

You may notice that in some of the figures in example 6.3, we did not use notation on the bars to indicate critical and noncritical activities. In fact, all activities may be considered "critical" in a way but not necessarily unique. Moving an activity—even if doing so does not violate the logic—may disturb the resource allocation and may result in overallocation in certain periods. Therefore, logic and resource constraints must be met at the same time. You can use different combinations of resource allocations to maintain the following four criteria:

1. No more than eight laborers used on any day
2. A correct total labor-day (or labor-hours) allocation for each activity
3. Satisfied logic
4. The earliest possible Project Completion date

If we classify activities as critical and noncritical and then try to use the total float of a noncritical activity, we may impair the resource leveling. The author believes that this area needs more research and development, particularly in the software industry, before it can reach a stage at which the user is given all options, in a user-friendly way, to make educated decisions. The software should be able to display different scenarios (in layman's language), such as the following:

- You can finish the project in 92 days with no resource leveling (unlimited resources) and no activity interruption.

- You can finish the project in 83 days with no resource leveling (unlimited resources) but allowing activities to be interrupted.
- You can finish the project in 98 days with a certain limit for resource use.
- You can finish the project in. . .

***More Discussion***

As defined previously, leveling resources involves shifting activities within their available float to minimize the fluctuations in daily resource use. This "shifting" may involve one or a combination of the following:

- Delaying the start of an activity to any date up to and including its late start date.
- Interrupting an activity and resuming it later (breaking the activity into two or more segments) but finishing it no later than its late start date. The idea is to put "chunks" of the activity in the "schedule gaps" where resource use is low.
- Fluctuating the amount of resources assigned to an activity, day to day, according to resource availability, until the activity gets all the required resource demand.

**Tip Box 6.2**

Even if you don't do resource leveling, remember that resources are *not* unlimited!

***Important***

Note that the last two options often require special rules settings in computer programs. These programs may be set for default rules that do not allow such practices.

As mentioned previously, in some cases, staying within the available resource limits yet completing the project by the finish deadline is not possible. In such cases, the project manager must choose one or a combination of the following:

- Increase the limits on the availability of certain resources. This increase may be for the entire duration of the project, for a "one-time use," or for an assigned period. It may also be for one or more particular resources.
- Start the project on the planned start date but maintain the resource limits and allow the project to finish later than the finish deadline. This option is typically considered *forward resource leveling*.
- If feasible, start the project earlier than the planned start date by a calculated number of days so that you can finish the project on the required finish date without raising the resource limits. This method usually levels resources starting from the project finish date and then working backward until the required start date. It is referred to as **backward resource leveling**.

- The preceding three practices are all based on the assumption that the logic cannot be changed. In reality, the relationships of some activities can be relaxed somewhat. The most common reason for this is when, for example, activity B requires only a portion of activity A to be finished before it can start. Project managers tend to assign finish-to-start (FS) relationships for all types of cases. A more in-depth inspection of the schedule by the scheduler and the project manager may reveal some of these cases. Changing the FS relationship to an SS relationship (possibly with a lag) may open the schedule a bit by giving some activities more float and, hence, more flexibility. In Figure 6.13, the two-activity setup in part (a) takes 18 days, whereas the one in part (b) takes only 11 days.
- Make some activities interruptible. To the author's best knowledge, commercial software scheduling programs do not give the user the option of having certain (but not all) activities be interruptible and then allowing the program to interrupt (split) them in the optimum way from a resource-leveling viewpoint. However, some programs allow manual interruption (pause, resume). As a remedy (discussed in Chapter 5), you can split the activity into two or more activities if this interruption was planned, or "pause and resume" if it was not planned. Oracle Primavera P6 allows the user to manually pause and resume activities. In this case, the interrupted activity does not show as a group of small bars. Rather, it shows as one long bar that includes work and stoppage/pause periods (e.g., in Figure 6.10, the bars for activities F, G, and K stretch throughout their durations). The actual duration will be distributed within the bar without violating logic constraints (such as finishing E, F, or G before finishing C).

**Tip Box 6.3**

Splitting activities (those that can be performed in different batches) may help the scheduler in the resource-leveling effort.

- In Oracle Primavera P6, the resources (or budget) are distributed evenly throughout the duration of the activity. You may change this by assigning another distribution (e.g., triangular, normal, bell-shaped curve). You may define your own type of distribution by dividing the resource (or budget) into 11 increments throughout the duration of the activity. Increment 1 is usually

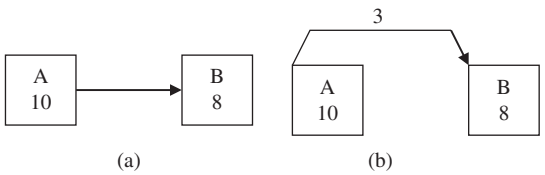



**Figure 6.13 The effect of changing (a) an FS (finish-to-start) relationship to (b) an SS (start-to-start) relationship: a decrease in duration from 18 days to 11 days**

assigned 0% because it represents 0% completion. The next 10 increments represent 10%, 20%, …, 100% completion. For example, increments of 0, 1, 3, 8, 15, 23, 23, 15, 8, 3, and 1 represent a bell-shaped curve. Note that the 11 increments must total 100%. With such a tool, you can concentrate the resources at the beginning, middle, or end of the duration of the activity. In the bell-shaped curve, the resources are concentrated in the middle. The contractor may use this feature to concentrate the budget at the beginning of the activity (**front-end loading the cost**).

### Resource Leveling from the General Contractor's Perspective

For the past few decades, subcontracting has increased to the point that many general contractors subcontract everything in a project and perform nothing with their own workforce, if they have any. Yet, the general contractor is still responsible for maintaining the project schedule for the owner. In this case, resource leveling no longer becomes a concern to the general contractor because the resources are not directly managed by him or her. Instead, the general contractor must manage the overall work of the subcontractors. However, the general contractor may still be concerned with the following four issues:

1. Keeping up with the subcontractors' schedules and the number of workers each subcontractor has, each day. The general contractor must make sure that the site is not congested to the point of impeding work or causing safety issues. The general contractor must also be convinced that the subcontractors have sufficient resources in order to make adequate progress.
2. If the owner's purchased equipment and materials are to be used, the general contractor must be in full coordination with the relevant subcontractor with regard to the time and method of delivery.
3. When the general contractor is providing equipment such as a crane to the subcontractors, the general contractor must coordinate the use of this equipment and prioritize the subcontractors' needs, using the concept of resource leveling.
4. For project control, the general contractor must enter the budget of each activity into the computer program and then record and verify the progress of that activity so that the subcontractor is paid in a timely and accurate manner.

In such cases, each subcontractor may do his or her own resource leveling, with one important difference: the subcontractor's schedule is part of the general contractor's **master schedule**. As is typical of any critical path method (CPM) schedule, each **subschedule** may contain a range of dates for noncritical activities (i.e., early start, early finish, late start, and late finish). In many cases, the general contractor requires "scheduled dates" for certain activities (i.e., a single set of dates chosen between the early and

late dates). This approach is used especially for activities that require coordination with the general contractor or other subcontractors. In such cases, the subcontractor loses the float for such activities and his or her scheduled dates become critical. The subcontractor must then be careful not to change the start or finish dates of these activities, for any reason. without consulting the general contractor.

**Tip Box 6.4**

A general contractor does not typically level his subcontractor's resources but must require subcontractors coordination if they level their resources in order to maintain control of the master schedule.

**Tip Box 6.5**

Upon leveling the resources, all activities become "critical" from a resource-leveling point of view. This means that any activity shift, even within its float, may disturb the resources usage profile and resource set limits, and this negates the purpose of resource leveling.

This author also has observed that only a minority of contractors/schedulers level the resources in CPM schedules. In fact, a good percentage of them don't even resource-load the schedules. This is fine as long as the project manager realizes that most resources are not unlimited, so the project manager has to pay attention to the daily consumption of resources, particularly the important ones. Of course, this still may not result in the most efficient use of the resources.

#### *Resource Calendars*

Certain resources may be available only on certain dates or days of the week. The scheduler can create a special calendar with workdays matching those of the specific resource. For example, if the safety officer for a construction project is available only on Monday and Tuesday (perhaps because she spends other days of the week on other projects), we can create a "Safety Inspection" calendar with only two workdays per week: Monday and Tuesday. If this calendar is assigned to an activity, this activity can only be scheduled during these two days of the week.

#### *Work Space as a Resource*

Some experts like to deal with work space as a resource since it is shared by all workforce members and is limited. This author does not prefer to do so, but space has to be managed efficiently throughout the project. What is important in this context is

to realize that the number of workers changes almost daily, and their required space differs as well (a welder or a carpenter cutting wood, for example, may need more space than an average worker). The general contractor "owns" the site, so he or she must make sure that at all times the following occur:

- The site is safe for all workers.
- Every worker has sufficient and efficient work space.
- Logistics are not impeded.
- Storage is located appropriately for the best work and cost efficiency.
- Overall, the objectives of work space management are safety, work efficiency, and optimum cost. Compatibility with local laws and regulations is a given.

## MATERIALS MANAGEMENT

**Materials management** is defined as an integrated process for planning and controlling all necessary efforts to make certain that the quality and quantity of materials and equipment are appropriately specified in a timely manner, are obtained at a reasonable cost, and are available when needed. (Construction Industry Institute Best Practices, Definitions, 2014).[3] A materials management system includes the major functions of identifying (project planning and material takeoff), acquiring (vendor inquiry and evaluation, purchasing, expediting, and transportation), distributing (field material control and warehousing), and disposing of materials needed for a construction project (Construction Industry Institute, 1986b, 1988b). Four important objectives of materials management are as follows (Construction Industry Institute, 1988b):

1. Ensure that materials meet the specifications and are on hand when and where they are required.
2. Obtain the best value for purchased materials.
3. Provide efficient, low-cost transport, security, and storage of materials at construction sites.
4. Reduce any surplus to the lowest level possible.

Materials management is an important component of the project schedule. This function starts early with the planning phase of the project. When developing the materials plan, the general contractor must consider various factors, such as project size, scope, and location; cash-flow requirements; schedule and lead times of critical purchases; the owner's philosophy; owner approvals; the number of project participants;

[3] https://www.construction-institute.org/scriptcontent/bp.cfm?section=aboutcii

inspection roles; use of owner purchase agreements; acceptable bidders' or suppliers' list; and extent of prefabrication (Construction Industry Institute, 1988b).

Some authors (Ahuja, Dozzi, and Abourizk, 1994; Hendrickson and Au, 1989) have identified four materials cost categories, as follows:

1. *Purchase costs*: Purchase costs are what the vendor charges for the materials, including transportation and freight costs. Usual practice is for vendors to give a volume discount as well as an incentive for prompt payment. For example, the invoice may have the term *2/10 NET 30*, which means a 2% discount if the bill is paid fully within 10 days of the delivery date or the full amount is due in 30 days. After 30 days, interest and/or a penalty may apply.
2. *Order costs*: Order costs are the administrative costs for preparing the purchase order, which may not be a simple task, because it may involve making requisitions, analyzing alternative vendors, writing purchase orders (with required specifications), receiving materials, inspecting materials, checking on and expediting orders, and maintaining records of the entire process.
3. *Holding costs*: Holding costs include held capital (interest or lost opportunity) and handling, storage, obsolescence, shrinkage, and deterioration costs. Many of these costs are difficult for the project manager to predict, especially those that involve high-tech items, such as computers and computerized equipment. Insurance and taxes may be added to the holding costs as well.
4. *Shortage (unavailability) costs*: A shortage cost is the cost (or the loss as the result) of not having the required materials on the job site when needed. Shortages may delay work, which may result in the loss of labor resources or may delay the entire project.

Theoretically, there are two extreme materials management theories:

1. The **just-in-time theory**, which calls for delivering materials at the time of installation only. Thus, materials are not stored at the site.
2. The **inventory buffer theory**, which calls for all materials to be purchased, delivered, and stored on-site prior to installation.

The advantages of the first theory are less handling, no storage, no frozen capital, and less vulnerability to theft, vandalism, obsolescence, shrinkage, and deterioration—in other words, fewer handling costs. The disadvantages are higher order costs (more orders) and higher shortage costs (higher probability of not having materials on time). Conversely, the advantages of the second theory are lower purchase, order, and shortage costs. The disadvantage is higher holding costs.

In real life, the general contractor must strike a balance somewhere between the two extreme theories in order to obtain the least total costThis balance will vary from

one project to another, depending on several factors, such as the size of the project, the location of the project[4], the type and availability of materials, the locations of vendors, and weather. To illustrate this point, let us imagine two projects, one located in the middle of nowhere (desert or countryside); call it *project A*. The other project is located in the downtown area of a major city; call it *project B*. Project A has plenty of space for organized storage and is located away from urban areas. Thus, it is less vulnerable to theft and vandalism but is far away from vendors and suppliers. In this case, ordering most or all of the materials in advance (as in the inventory buffer theory) makes sense. In the case of project B, which is located in the downtown area of a major city, storage space is scarce, and theft and vandalism are more likely. At the same time, plenty of vendors and suppliers are located within a 10-mile radius and can deliver on short notice and for little cost. In this case, we probably want to manage materials by using an approach closer to the just-in-time theory.

Other factors influencing which theory should predominate are the type and the availability of materials. For instance, ready-mix concrete must be delivered on time in all cases because it cannot be stored. In fact, for projects at remote locations, it may be more practical and economical to have a concrete mix plant on-site, especially if the project is large. Expensive equipment may also need to be delivered on time for security reasons. Materials that are susceptible to deterioration are less likely to be stored for long periods of time. Also, chemicals and explosives have to be stored in a secure and safe manner and require special attention.

Weather (rain, snow, ice, wind, temperature, humidity) may be a factor that influences the delivery and storage decision. The 1976 Montreal Olympic Games reminds us of what can happen with poor planning. The precast posttensioned concrete beams were left on the ground (because of a labor strike), and water got into the tubes and froze before the cable had been threaded. Removal of the ice required expensive drilling and contributed further to a loss of time (Neil, 1982).

Another interesting weather-related case was a large project in northern Canada. The location was remote from any urban area or even paved roads. Moving equipment and materials was possible only by air, which was expensive. Work was planned to take place only during the warm months because of the harsh winter conditions. An efficient plan was prepared to move equipment and materials on sleds during the winter. Some icy roads and bridges had to be prepared for this purpose, but the transportation cost was a fraction of the alternative: airlifting. The equipment and materials were kept in shelters until the weather permitted the work to start.

For further information on materials management, refer to the books listed in the Project and Construction Management section of the Bibliography (especially see the Construction Industry Institute, 1986b, 1988b).

[4] The location of the project influences many aspects of the project, such as availability of space for storage, access to the project site, proximity to vendors and suppliers, the likelihood of theft or vandalism, local authority's restrictions, and others.

**Tip Box 6.6**

While we never apply the "just-in-time" or "inventory buffer" approach purely, we swing between the two theories. However, we lean more toward one of the two theories, depending on project location and circumstances.

***Interesting Comparison***

The following table summarizes some comparisons among the three main resources: labor, equipment, and materials. Keep in mind that elements of some of these comparisons vary in countries outside the United States, such as insurance and bonds.

| Comparison Category | Labor | Equipment | Materials |
|---|---|---|---|
| Cost money whenver in the possesion of the contractor | Yes | Yes | No[a] |
| Subject to productivity fluctuations | Yes | Yes | No |
| Add waste allowance | No | No | Yes |
| Overtime cost | > normal | ≤ normal | NA |
| Add taxes to cost | Yes[b] | Yes[b] | Yes[b] |
| Add transport/delivery cost | No | Yes | Yes |
| Initial cost can be depreciated/amortized over useful life | No | Yes | No |
| Add Operating Cost | No | Yes | No |
| Add fringe benefits to cost | Yes | No | No |
| May need resource leveling | Yes | Yes | No |
| May need safe storage | No | Yes | Yes |
| May be subject to damage, theft, or vandalism Protected by Builder's Risk Insurance | No | Yes | Yes |
| May be subject to death, injury, and illness Protected by Workers Compensation Insurance | Yes | No | No |

[a]The cost of storage and frozen capital is ignored.
[b]Taxes and fees differ among categories, depending on local laws.

## CHAPTER 6 EXERCISES

1. In the context of construction scheduling, what do we mean by *resources*?
2. What is *resource allocation*?
3. What is *resource leveling*?
4. Why should you level resources in construction projects?
5. Do all resources have to be leveled? Why or why not?
6. Discuss resource leveling in a multiproject environment.
7. Can you level resources in a multiproject environment? If so, what are the factors that will influence your decision?

8. Two methods are used to assign a budget to an activity in the schedule. Explain both methods and mention the pros and cons of each method.
9. In the following network, manually level your resources so that you may not use more than nine laborers per day at any time.

| Activity | Duration (Days) | IPA | Laborers |
|---|---|---|---|
| A | 2 | – | 3 |
| B | 4 | A | 2 |
| C | 6 | A | 4 |
| D | 9 | A | 3 |
| E | 5 | B | 4 |
| F | 7 | B, C | 2 |
| G | 3 | D, E, F | 4 |

10. In the following network, try to reduce the maximum resource need to less than eight laborers per day. Can you do this? If not, can you manually shift activities so that you improve the daily resource use? (Try to start low, increase the resource use gradually until it peaks around the middle of the project, and then gradually decrease it toward the end of the project.)

| Activity | Duration (Days) | IPA | Laborers |
|---|---|---|---|
| A | 6 | – | 2 |
| B | 2 | – | 3 |
| C | 8 | A | 3 |
| D | 5 | A, B | 5 |
| E | 3 | B | 4 |
| F | 6 | D, E | 3 |
| G | 5 | C, D | 2 |
| H | 2 | F, G | 3 |

11. In the following network, manually level your resources with a maximum of eight laborers per day. Also, improve the daily resource use (start low, increase the resource use gradually until it peaks around the middle of the project, and then gradually decrease it toward the end of the project).

| Activity | Duration (Days) | IPA | Laborers |
|---|---|---|---|
| A | 6 | – | 2 |
| B | 2 | – | 3 |
| C | 9 | – | 3 |
| D | 4 | A, B | 3 |
| E | 7 | B | 4 |
| F | 5 | D | 2 |
| G | 10 | D, E | 3 |
| H | 8 | C, F, G | 1 |
| I | 3 | C, G | 2 |
| J | 2 | H, I | 3 |

12. In exercise 9, can you improve the resource use by making the resources driving (i.e., they control the durations of activities)? Activities are still contiguous (noninterruptible).
13. In exercise 9, can you improve the resource use by making the resources driving and the activities interruptible?
14. In exercise 10, can you improve the resource use by making the resources driving (i.e., they control the durations of activities)? Activities are still contiguous.
15. In exercise 10, can you improve the resource use by making the resources driving and the activities interruptible?
16. In exercise 11, can you improve the resource use by making the resources driving (i.e., they control the durations of activities)? Activities are still contiguous.
17. In exercise 11, can you improve the resource use by making the resources driving and the activities interruptible?
18. In exercise 10, you are given only six laborers (rather than eight). Write a memo to the project manager discussing the situation and giving him or her the available choices (along with the consequences).
19. With regard to resource leveling, how does the role of a scheduler differ between working for a general contractor who does almost all of his or her work with his or her own workforce and working for a general contractor who subcontracts everything?
20. Assume that you are the scheduler for a large project. You work for the construction manager (CM), whose function is to manage the project and to coordinate the work of the subcontractors involved (there is no general contractor). You require that each subcontractor submit his or her schedule to you on a disk in Primavera Project Manager format. Where do you go from there? Write an itemized plan.
21. Why does materials management differ in principle from labor and equipment management? Briefly explain the concept of materials management.
22. What are the main objectives of materials management?
23. What types of costs are associated with materials management?
24. Materials management is a balance between two extreme theories. Explain this statement, mentioning the factors that influence your decision to lean more toward one theory than the other.
25. You are a southern California contractor. You have been awarded two projects: one in downtown Los Angeles and one near the Mojave reservation.
    a. Each project needs a bulldozer, a tower crane, and a safety manager. Do you share these resources between the two projects? Justify your answer.
    b. Which materials management theory would you lean toward in each project? Justify your answer.

Chapter 7

# Schedule Updating and Project Control



Cladding works Dubai Mall, Dubai, United Arab Emirates

## INTRODUCTION

Project schedules are, without a doubt, a useful tool for managing and controlling projects. However, this tool can be effective only if it is used properly. Colorful bar charts can be no more than decoration on the walls of the job trailer. They can also be a mere fulfillment of a bid or contract requirements. But if bar charts are well prepared and used seriously, consistently, and intelligently throughout the life cycle of the project, they can be an effective tool that informs the project management team of the project status at any point during the life of the project as well as a foundation for corrective action. The most important use of schedules is for *project control*: the scheduler compares actual performance with baseline performance and discerns any deviation. The project management team then deals with this deviation, analyzes it, and suggests solutions to bring the schedule back on track, if possible.

Using critical path method (CPM) scheduling as an effective tool requires a serious commitment from upper management to adopt and use the schedule throughout the project. There is a difference in attitude between a contractor who uses the schedule because he or she is convinced that it is an effective and powerful tool for project management and a contractor who uses the schedule just because the owner requires it.

## THE NEED FOR SCHEDULE UPDATING

Construction projects rarely, if ever, proceed as planned. Thus, expect some deviation from the baseline schedule. You will need to know where, how much, and why and then take corrective action whenever and wherever it is needed. Consider the following example: the army fires a long-range missile at a target that is 1,000 miles away. The missile has the coordinates of the target, so it flies at a certain accurate angle with a certain velocity. For various reasons, the missile goes astray by a fraction of a degree, and perhaps the actual speed differs, for whatever reason, from the planned speed. Central command tracks and communicates with the missile, reads the actual location, and compares it with where the missile is supposed to be at that moment. Central command then makes adjustments to the direction of the missile. This process occurs continuously to ensure that the missile hits its target accurately. An early uncorrected error of a few minutes (a *minute* is 1/60th of a degree) in direction may mean missing the target by a few hundred feet or even several miles.

## PROJECT CONTROL DEFINED

Project control is a continuous process that involves the following functions:

1. Monitoring work progress
2. Comparing it with the baseline schedule and budget (what they were supposed to be)

3. Finding any variances, determining where they are and the extent of the variances, and analyzing them to discover the causes
4. Taking corrective action whenever and wherever necessary in order to bring the project back on schedule and within budget

Along with these four basic functions, project control can help the project management in different aspects such as improving work efficiency, schedule acceleration, cost reduction, procurement and logistics, and other aspects of the project.

Project control in the context of this book involves both budget control and schedule control. It can also include quality control and safety control, but they usually occur in separate departments and are analyzed differently. A significant correlation exists between budget control and schedule control, as described later in this chapter.

The term *project monitoring* is sometimes used in lieu of *project control*. Project monitoring, by definition, is passive. Technically, it includes the first three functions of *project control*: monitoring, comparing, and finding. Although some people use this term to mean more, it simply means "observing." The term *project tracking* is also used in the same context (Oberlender, 2014). Depending on the intention and the role of the "tracker," tracking may or may not be equivalent to project control. The owner or construction manager (as an entity separate from the constructor) may "monitor" or "track" the project by observing the progress of the work and comparing it with the baseline budget, schedule, and quality. However, only the party who is physically doing the work—namely, the constructor—can do the "control," not only monitoring or tracking it but also taking corrective measures whenever and wherever necessary.

## SCHEDULE UPDATING

Schedule updating is just one part of the project control process. Schedule updating must reflect actual work and involves incorporating approved changes into the baseline schedule.

### What Is a Baseline Schedule?

A **baseline schedule**is a schedule that is prepared by the contractor, usually before the start of the project, and is used for performance comparison. If approved by the owner, the baseline schedule usually becomes a part of the contract documents.

The baseline schedule is also called a **target schedule**. The *as-planned schedule* is the schedule submitted by the contractor—as usually required by the contract—and approved by the owner before the start of the project (and sometimes before the signing of the contract). Sometimes, the baseline schedule is the same as the as-planned schedule, but not always. In many situations, the as-planned schedule is submitted and approved. Later on, some changes are implemented before the project starts, as a result of debugging, the owner's changes, or both. The baseline schedule should not be delayed beyond the start of the project, particularly if the contractor uses actual dates to build such a schedule. Otherwise, it will not be baseline.

The baseline schedule may be used by both the general contractor, who will execute the work, and the owner (or his or her representative) whose work is being executed. Sometimes both parties will use the baseline schedule for project control, from their own perspectives. A third party (professional construction management firm) may also monitor the schedule and compare it with the baseline schedule. The baseline schedule, when it is part of the contract documents, binds not only the general contractor but also all subcontractors, even if they were not part of the preparation of the baseline schedule. A general rule is that any condition or requirement in the contract between the owner and the general contractor automatically applies to all parties working under the general contractor and involved in the construction of the project.

In many cases, the as-planned schedule is also a part of the contract documents that bind both the owner and the contractor. It may provide a foundation for resolving any subsequent delay-claim disputes. It may also be used as a legal document in case of litigation.

In poorly planned projects, many change orders may be issued, and the baseline schedule will keep changing as a result. Such changes may shift the critical path and, thus, the focus of effort. Such a situation can be counterproductive to project management. The baseline schedule must incorporate design and other changes for fair and realistic comparisons. Therefore, a project may have two or more baseline schedules: one before and one after changes. It is strongly recommended that one of them be adopted for periodic comparison with actual performance. In some cases, it is possible and helpful to compare the current update with both the baseline schedule and the previous update. For example, if the current update shows the critical path with −10 days of (negative) float, this may be interpreted as bad news with regard to the "absolute measure" (as compared with the baseline schedule). However, if the previous update indicated −16 days of total float, the contractor is on the right track, bringing the project back to the baseline schedule.

Just like cost estimates, baseline schedules are predictions. Slight and sporadic deviations are always expected in construction projects. A sharp eye and an expert mind can discern a serious deviation from a minor "normal" variation.

Baseline schedules are prepared on the basis of expectations and previous experience. Thus, it is advisable to keep an accurate record of previous work to use for future estimates. As discussed in Chapter 4 (in the "Steps Required to Schedule a Project" section), the scheduling team must not only "crunch the numbers" (calculate durations and dates) but also deal with real work conditions and make reasonable adjustments whenever and wherever needed.

Baseline schedules must be reasonable and realistic. They must take into consideration the work and weather conditions; the size and complexity of the project; local codes and regulations; the location of and access to the project site; the labor market; materials and equipment availability, prices, and delivery; and other issues. Sometimes an overlooked activity, such as Obtain Permits, can hold up the entire project for a month or more. Likewise, a long lead or custom item may need to be ordered several months before the required delivery date. A contractor's acceptance of an unrealistically ambitious schedule may hurt the contractor's reputation and pocket, even

though his or her fieldwork may have proceeded at a normal and decent pace. The famous proverb, "Expect the worst and hope for the best," can be modified in this context as "Be conservative in your expectations and strive for the best."

Baseline schedules may initially be prepared as summary schedules. A summary schedule may contain only a few major components; the details are left for a later stage. For example, a schedule prepared by the architect may include the different design activities and milestones, with Construction represented by a single 9-month activity. Later, when construction details are known, this activity is divided into reasonably sized activities that have a combined duration of 9 months. Summary baseline schedules are not usually used for project control. However, such schedules may be prepared along with design development; the more you know about the project and the more details you have in the design, the more detailed the schedule becomes. This case applies particularly to fast-track projects (discussed in Chapter 5). With such projects, the project manager can use the following approach: divide the project into several phases (see Figure 5.9), with the initial (preliminary) design done for the entire project. Later, when the detailed design for phase I is finished, the detailed construction plan, including scheduling, must be prepared for phase I while phase II is still being designed. In this case, the detailed schedule for any phase is done just before actual construction starts on that phase. This process provides a baseline schedule, phase by phase.

The entire discussion on the baseline schedule applies also to the baseline budget, with the obvious difference being that a schedule deals with time, whereas a budget deals with money. The correlation between the two areas is explained subsequently, when the project control concept is discussed. Another difference is the level of detail: in schedule control, activities are connected by logical relationships. A delay in an activity may have an effect on other activities. In budget control, the effect of a budget overrun in an activity is mostly local and may not have a ripple effect on other activities (unless it is attributed to an increase in the price of resources, in which case all activities using these resources will be affected).

Oracle Primavera P6 creates baseline schedules as copies of project updates. These "baselines" are more snapshots than baselines. This concept, which Primavera Systems introduced, is extremely useful. It allows the scheduler to keep copies (updates) of the schedule at different points in the life cycle of the project and to store them as inactive copies along with the active, most recently updated schedule. The only caution is the name: Primavera calls them *baselines*, but they are not baselines according to our—and the industry's—definition.

### What Is an Updated Schedule?

**Schedule updating** reflects actual performance information—including time of occurrence and amount (or percentage) of work completed—on the schedule and indicates on the schedule any changes to future work. Popescu and Charoenngam (1995) defined an updated schedule as "a revised schedule reflecting project information at a given data date regarding completed activities, in-progress activities, and

changes in the logic, cost, and resources required and allocated at any activity level" (p. 566).

**Tip Box 7.1**

Why is updating schedules a must? The answer is simple: because construction projects never run exactly as planned!

### What Is the Data Date?

The **data date**is the date on which all progress on a project is reported. It is also called the **as-of date**, the *cut-off date*, and the **status date**. It is *not* the "current date" or the "time now," because the word *current* or *now* moves with time and is not tied to a specific time or date. For instance, the latest data date may be Friday, 19 FEB 2014. This means that the update contains all work completed up to and including that day. The report may not reach the scheduler until Monday, 22 FEB 2014, or later, and the scheduler may not actually update the schedule until a day or so after that. Thus, it would be wrong to call the data date the *current date* or the *time now*. The data date is similar to the closing date on your checking account or credit card statement. By the time you receive the statement, several days have passed, and the statement reflects the account activities as of that date. However, that date is not "current" or "now."

**Tip Box 7.2**

The data date reflects the end of the reporting period. It is not "time now" or the "current date" because these two terms represent moving, not fixed, dates.

### What Kind of Information Is Needed for Updating Schedules?

Any new information that was not known for the previous update and relates to the schedule must be recorded on and implemented in the schedule. This information falls into two main categories:

1. *Past information:* What has happened since the last update? Past information includes the following:

   a. Activities that have started and the actual start date, percent complete, and remaining duration of each
   b. Activities that are complete and the actual completion date of each
   c. Ongoing activities and their new percent complete and remaining durations
   d. The actual budget spending or resource consumption for each activity

This information can be further subdivided into *past* and *current* categories, in which *past* represents information about work that occurred prior to the previous update. Such information is considered history and must not be changed during the present update.[1] *Current* represents information about work that has occurred between the last update and the current update. This category is the main focus area for updating past information.

2. *Future information:* The *future* category comprises any changes to the schedule or schedule-related items, such as the following:

   a. Any activities that have been added, along with their information (duration, logic, budget, resources, constraints, etc.)
   b. Any activities that have been deleted (the scheduler must be sure to maintain proper logic after the deletion)
   c. Activities that have changed in duration, logic, budget, resources, constraints, or otherwise
   d. Any change to the imposed finish date for the entire schedule or the constraint date for certain milestones
   e. Any schedule-related, but not activity-specific, change, such as a change in the cost or availability of resources, a change in calendar workdays, or a change in responsibility (e.g., a subcontractor took over a portion of the general contractor's work, or a subcontractor was replaced)

   Note that added or deleted activities can also occur in the *past*. This can happen if a change order arrives on short notice: the activity is approved and added to the schedule and then performed (started/finished) between two updates, that is, after the previous update and before the current one.

Figure 7.1 defines the three information zones discussed above: "past" (prior to or to the left of the previous data date), "current" (between the previous data date and the current data date), and "future" (after or to the right of the current data date).

*Future* changes are of two types:

1. *Logic-driven changes:* Logic-driven changes are those that are not made directly by the scheduler but that occur as a result of changes in planned dates or logic. For example, the four activities shown in Figure 7.2a were planned to overlap and take 14 days overall. When updating, four days after the first activity, Framing, has started, it is found that the Framing activity will take 2 more days than originally planned (see Figure 7.2b). As a result, succeeding activities will be delayed by the same amount, that is, 2 days. It is similar to the domino effect: a delay in one activity will trigger a delay in the succeeding activities.

[1] Although sometimes project managers "revise" dates or other data that were reported previously, this practice may be considered a falsification of records if the owner is not fully informed of such revisions.

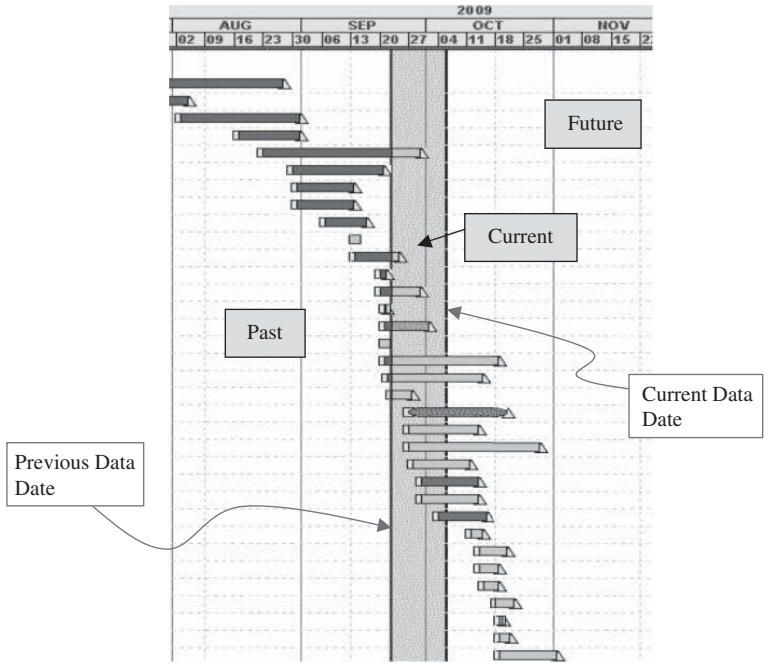



**Figure 7.1 Data date and update zones: past, current, and future**

2. *User's changes:* User's changes are those that are made directly and deliberately by the scheduler. They may not have anything to do with past events. Let's imagine in the example shown in Figure 7.2a that everything is going as planned; however, the contractor (or owner) decides to delay the start of one activity (Painting) for 2 days, using a constraint (see Figure 7.2c). This is a user-induced change that was not caused by predecessors, but it may have an impact on its successors.

**Tip Box 7.3**

Updating information includes the actual performance, whether it matches or is different from the baseline, as well as changes in future activities and other schedule information.

### Frequency of Updating

Construction schedules may be updated monthly, biweekly, weekly, or according to another time interval. Weekly and biweekly schedule updates are probably the most common. Project managers must achieve a delicate balance between a period between

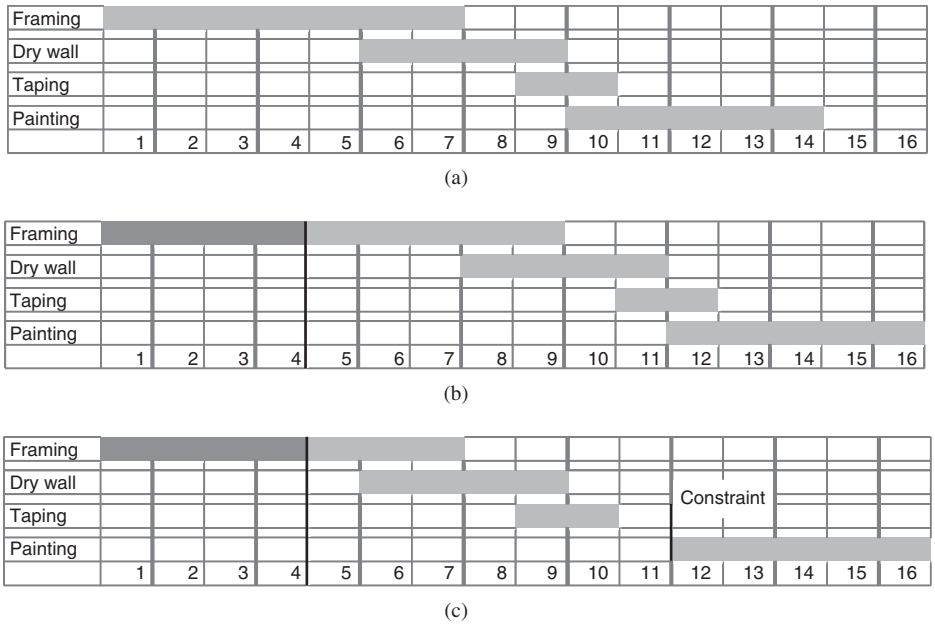



**Figure 7.2 (a) Four overlapping activities, planned to take 14 days overall; (b) when updating, the Framing activity is taking 2 more days than planned, triggering a 2-day delay in its successors; (c) when updating, the Framing activity is proceeding as planned, but the start of the Painting activity is deliberately delayed**

updates that is too long and one that is too short. The former case may yield negative consequences such as the following:

- Waiting too long to update a schedule may eliminate the effectiveness of updating as a control tool. By the time work progress is reported and analyzed, managers may not have the time or opportunity to take corrective action. This factor can be demotivating for them.
- The amount of work progress that occurred during the period may overwhelm the scheduler. Also, the superintendent or project manager may forget some information, such as when an activity actually started or finished, if the activity occurred a month ago and was not formally documented.
- Having a long reporting period may encourage procrastinators to put off corrective measures by using the logic, "We'll do it later. There is plenty of time."

Conversely, a reporting period that is too short may be costly in terms of time consumption, overhead, and reporting costs. It may also become a nuisance to the management team.

Typically, the frequency of updating increases at certain times, such as in the last month or two of a project or during a "crunch time" (e.g., before a deadline).

**Tip Box 7.4**

Having a "project update policy" is a must. Implementation and policing is also a must.

### Retained Logic or Progress Override

As explained previously, project managers often overuse the finish-to-start (FS) relationship. In many practical cases, an FS relationship is assigned between two activities, A and B, such that activity B cannot start until activity A is completed. In reality, when work starts, activity B starts shortly after activity A has started and prior to its completion. This situation violates the network logic. In the "execution report" of Oracle Primavera P6 or other programs, such a violation is reported (more as a warning than as an error). However, the question the user faces is: "Will the remainder of activity B depend on the completion of activity A, or is the FS relationship no longer required?" For example, look at activities A and B in Figure 7.3a. Suppose that 6 days

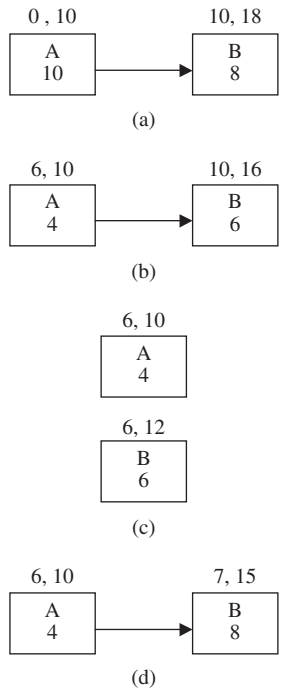



**Figure 7.3 (a) Activities A and B of a project; (b) retained logic after 6 days' work; (c) progress override after 6 days' work; (d) actual dates after 6 days' work**

after the start of the project, 6 days' worth of work is done on activity A (remaining duration = 4) and 2 days' worth of work is done on activity B (remaining duration = 6). Should we choose Retained Logic (the default value, Figure 7.3b) or **Progress Override** (Figure 7.3c)? The decision between the two choices may mean not only the difference in the project's completion date but perhaps also the start and finish dates of some succeeding activities. In this example, the decision means a 4-day difference in the completion date of activity B, and possibly the entire project. Oracle Primavera P6 also gives a third option: actual dates. This option works only if the scheduler assigns an actual start date that is after the data date.[2]

### Auto-Updating

Some software scheduling programs offer an option for automated updating. Although this option makes updating easy and saves time, a potential danger exists. Along with such options comes the assumption that everything that was supposed to have happened, between the last and current updates, has happened—on the planned dates and within the planned budget and resources. This assumption may be true in most but not all cases. The potential danger is that the scheduler will become accustomed to using this convenient tool and use it all the time. The scheduler should exercise extreme caution in using such automated procedures.

### Updating Schedules and Pay Requests

In many cases, project updating is tied to **payment requests (pay requests**, for short). The subject of pay requests is a broad one that is discussed in detail in other project management books. What concerns us in this chapter is how pay requests are tied to schedule updating. In general, a pay request is a document submitted by the contractor (using his or her own form, the owner's form, the American Institute of Architects Document G702, or other form) to the owner, asking for payment for work actually performed (whether finished or not) during the period since the last pay request. Materials stored on-site but not yet installed are generally ineligible for inclusion in pay requests, unless the contract allows for such payment. Typically, the owner verifies the amounts in the pay request (quantities and unit prices) and then, after approving it, issues a payment to the contractor that is equal to the approved amount minus any **retainage**.[3] Pay requests are usually done at the end of each month or billing period.

[2] It is like the past in the future! The author does not like such a practice, as it may lead to reporting false information if that event does not occur on the specified date.

[3] *Retainage* (also called *retention*) is a portion of the eligible progress payment that is held back by the owner until the contractor fulfills his or her contractual obligations. The contract usually specifies the amount and conditions of a retainage.

Subcontractors usually submit their pay requests to the general contractor, who rolls these requests in with his or her own pay requests and submits them to the owner. The owner requests a lien release or waiver from the general contractor and all subcontractors and vendors before issuing the payment. This document assures the owner that the signer has paid the subcontractors, workers, and vendors for work performed on the project for the period covered in the document. Once the general contractor receives payment, the general contractor pays the subcontractors.

If you are updating every 2 weeks, you can start by doing the pay request at every other update (i.e., every 4 weeks). However, the problem with doing this is that a month is slightly longer than 4 weeks. Schedulers and project managers like to update schedules on a certain day of the week (e.g., Wednesday). To circumvent the conflict between the biweekly update and the monthly pay request, schedulers choose one of the following five options:

1. If it is feasible for the project team, the updates are done on the 1st and 16th of each month. If either of these dates falls during a weekend or a holiday, the update is done on the closest workday.
2. When the update date is near the end of the month (say, within 1 or 2 days), the project manager estimates the work "to be done" between the current data date and the end of the month and counts this work as if it were done (with its real dates). The main drawback to this approach is approving an amount of work that physically has not yet been done. If this approach is used within certain limitations, it can be relatively safe. The project manager and the owner must agree on this practice. One argument may be made in support of this practice: since reports take a few days and a payment check may take 2 to 4 weeks, the work done during that time almost always offsets the problem of projecting a few days' work.
3. If the pay request must include work as of the end of day 30, the scheduler does the routine update on time, say, on the 28th of the month. A few days later, the project manager sends the work progress for days 29 and 30 to the scheduler for a "minor update" for the sake of the pay request. The scheduler must then separate "pure updates" and "pay request" schedules. This practice is not recommended.
4. When the update date is several days (say, 4 to 6 days) before the end of the month, the scheduler "skips" a week so that the next update is done during the first days of the next month. For example, an update is done on the 12th of the month. The next update is scheduled for the 26th of the month. It can be postponed to the 2nd or 3rd of the next month, on the same day of the week on which the 12th occurred.
5. If all contracting parties agree, the pay request may be a few days less or more than a month (i.e., you can close it on the 27th, 28th, or 29th of the month,

or on the 1st, 2nd, or 3rd of the following month). In this case, the actual data date is reflected on both the updates and the pay request. However, this practice may not please the accounting team because monthly accounts may not be accurate even though the bottom-line total will be correct.

When doing a pay request, you must start the month with a $0 amount for the **cost this period** by adding the amount remaining from the last period to the total **cost to date** (in Oracle Primavera P6, it is called **Store Period Performance**).

### "Degressing" an In-Progress Schedule to Create a Baseline Schedule

In some cases, the project schedule is developed as the work progresses. This is not a good practice. Some activities will have already started or even finished when they are added to the schedule. In this case, only an as-built schedule exists; there is no as-planned or baseline schedule for comparison. The scheduler may need to create a baseline schedule at this late stage (better late than never). The scheduler can do so by taking a copy of the schedule and reversing all work progress in it to "go back in time" to the starting point. Doing so requires reversing the progress on all activities, plus going back from the data date to the starting point of the schedule.

This practice is acceptable (even though it is not the best). However, one important pitfall exists. When entering completed (or even started) activities, the scheduler may ignore their relationships, since they are "history." Consider the following partial schedule, for example.

| Activity ID | Activity Description | Duration (Days) | IPA |
|---|---|---|---|
| 1000 | Mobilize | 2 | — |
| 1010 | Clear Land | 5 | 1000 |
| 1020 | Excavation | 6 | 1010 |
| 1030 | Dewatering | 20 | 1020 |
| 1040 | Drive Piles | 7 | 1030 SS-5 |
| — | — | — | — |

Suppose that this schedule is being created after the piles have been driven. The project manager or scheduler might just enter actual dates into the schedule without adding the relationships. He or she might also give actual durations as "original durations," not those estimated; see Figure 7.4a. Now, imagine that you "degress" the project; that is, you reverse all work progress and take the data date back to the start date; see Figure 7.4b. In this case, you can see all these activities starting simultaneously at the beginning of the project. There is no need for an explanation; there is no logic. For this reason, the logic must always be input, along with estimated durations. Never forget that this schedule can be—and in most cases is—a legal document that may be dissected later to prove or disprove a delay claim. Accuracy is always important.

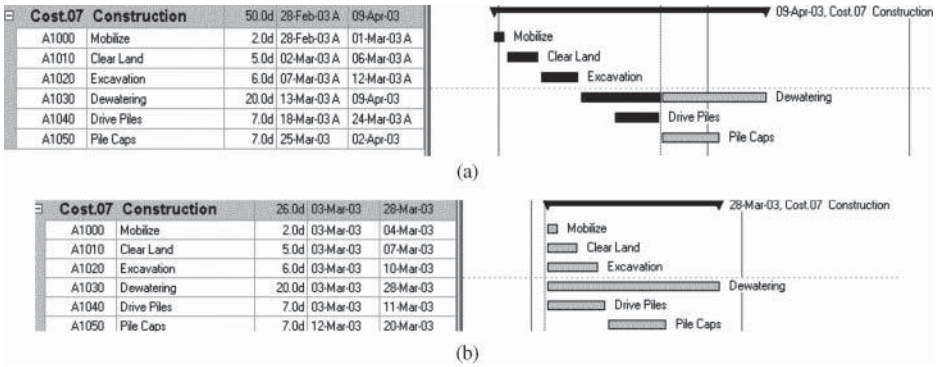



**Figure 7.4 (a) Schedule created after piles have been driven (actual durations given as "original durations" and no relationships entered); (b) "degressed" schedule**

### Effect of Adding or Deleting Activities on Logic

An activity in a schedule is usually like a link in a chain: removing a link may disturb the entire chain if it is not done properly. For example, deleting activity AS250 in the partial network shown in Figure 7.5 will remove any link between activities AS210 and AS245 on one side, and activities TL160 and AS260 on the other side. This may have a devastating effect on the schedule if removing such links was not the scheduler's intent. Therefore, it is strongly recommended that the scheduler review the logic before making any change by first printing a logic report showing all predecessors and successors for the activity to be deleted. Some computer programs, such as Oracle Primavera P6, have a function called **Dissolve an Activity**, which automatically assigns the predecessors of the dissolved activity to its successors (see Figure 7.6). The user must be careful when dissolving an activity that is tied to other activities with relationships other than the FS relationship or that have lags and must make sure that the logic is still correct after dissolving the unwanted activity. Regardless of the situation, the

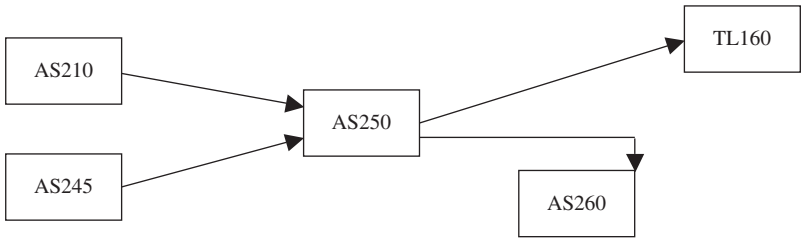



**Figure 7.5 Effect of removing an activity from a schedule: removal of AS250 would disturb entire chain**

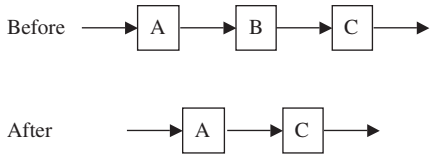



**Figure 7.6 Dissolving activity B**

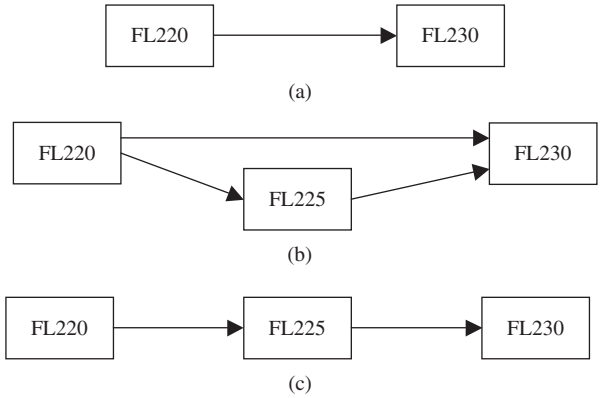



**Figure 7.7 Adding an activity to the schedule: (a) original logic; (b) resulting redundant relationship; (c) redundancy removed**

scheduler should neither let the computer make the decisions nor execute commands with which the scheduler is unfamiliar.

Adding a new activity usually has less potential for harming the logic than does deleting an activity. The common problem with adding an activity is redundant relationships. For example, let's say that we want to add activity FL225 to the partial network shown in Figure 7.7a. We assign activity FL220 as a predecessor and activity FL230 as a successor but do not pay attention to the existing relationship between these two activities. The result is a redundant relationship, as shown in Figure 7.7b. As mentioned previously, redundant relationships are not logically incorrect; they are just meaningless links that clutter the diagram. The **redundancy** in our example can be removed as shown in Figure 7.7c.

### Tip Box 7.5

When implementing change orders (adding or deleting activities) in the schedule, review the network logic after the changes are made. Make sure there are no logic errors, redundancies, loops, dangling activities, or discontinuities.

### Example 7.1

In example 4.3, 10 days after the project has started, you receive the following report:

Activities A and D are complete, actual dates: A (0, 2), D (5, 9).

Activity B started on day 5. Remaining duration = 2 days.

Activity C started on day 2. Some problems were encountered. Remaining duration = 4 days.

The duration for activity F was adjusted to 8 days.

Activity J has been canceled.

The duration for new activity P is 4 days. IPA = E and F. ISA (immediately succeeding activity) = K.

Update the logic. *Note*: When we delete activity J, the schedule must verify whether we should assign its predecessor to its successor. In other words, would activity F become a predecessor to activity K?

### Solution

*Example discussion:* Figure 7.8a shows the solution of Example 4.3. Figures 7.8b and 7.8c show the update process according to the information given in the exercise statement.

As we observe, the project in example 7.1 slipped by two days. This is the first part of the information. The other part is why the schedule slipped. There were several changes in the update, that is, departures from the original schedule:

a. Activity C took 2 more days than originally planned.
b. Activity F's duration increased from 5 to 8.
c. Activity P was added.
d. Activity B had not been completed, even though its early finish date was day 9.
e. Activity H had not started yet, even though its early start date was day 6.

Which one of these factors caused the 2-day delay in the completion of the schedule? Or, is it a combination of these factors?

The answer is "a. Activity C took 2 more days than originally planned." Activity C was and still is on the critical path. The increase in the duration of activity F consumed its total float and made it critical but did not add days to the duration of the project.

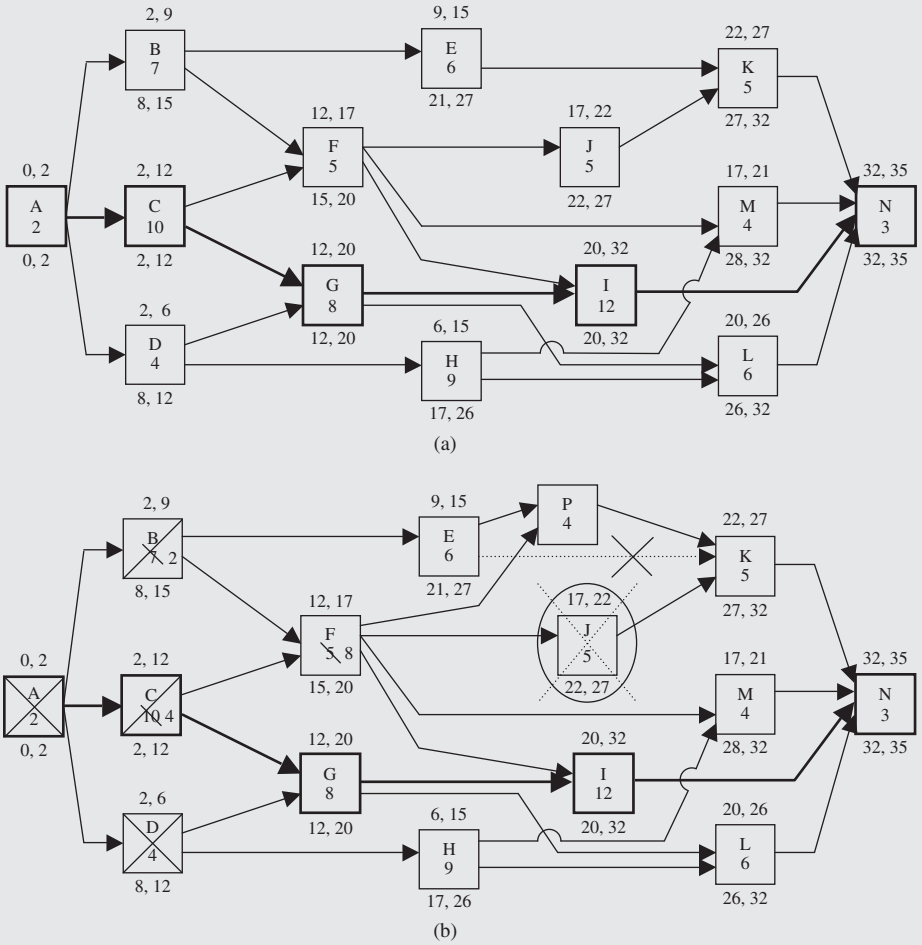



**Figure 7.8 (a) Original schedule; (b) updating the schedule; (c) updated schedule**

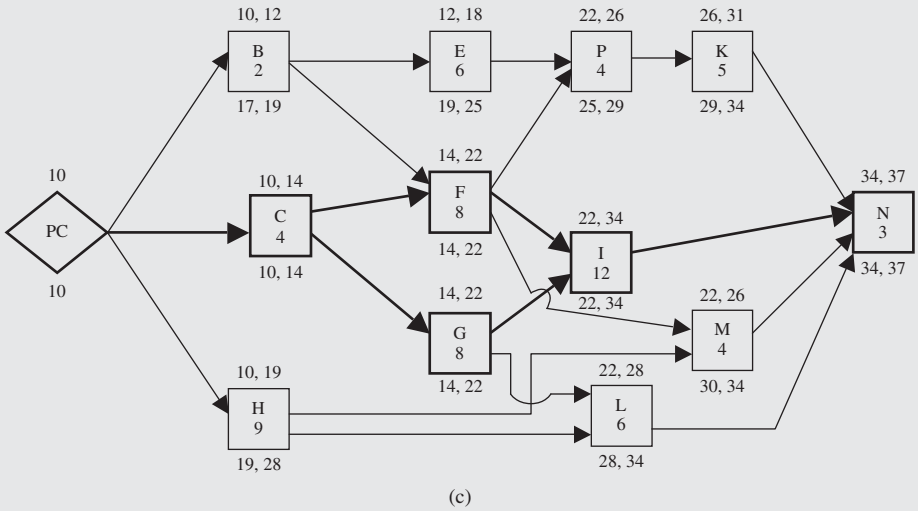



**Figure 7.8 (*Continued*)**

### Steps for Updating a Schedule

Updating a schedule includes the following five steps:

1. The project manager (or superintendent) prepares a list of the actual work progress, changes for individual activities, and all related information, as detailed previously.

   The author has had experience with both private companies and public agencies. In his experience with private companies, the scheduler represented the construction manager (CM) at risk (which is similar to a general contractor). The author used a simple tabular report with a project title, a data date, and a current date displayed at the top (Oracle Primavera P6 layouts, rather than reports, were used). The table contained columns for the activity ID, activity description, original duration, remaining duration, percent complete, and three empty columns with the following titles: Actual Start, Actual Finish, and Notes (Figure 7.9 shows a sample report). Other columns could have been added, such as Budgeted Cost, Cost To Date, Cost This Period (Figure 7.10). Activities that were completed prior to this report are usually filtered out. The superintendent fills in (preferably in red ink) the percent complete and actual start and finish dates. Alternatively, the superintendent may cross out the remaining duration and provide the new remaining duration in lieu of the percent complete. Another option is to provide an expected finish date. One good practice is to adopt a *single criterion*—percent complete, remaining duration, *or* expected finish date—for updating activities. Computer programs can

| ACTIVITY ID | ACTIVITY DESCRIPTION | ORIG DUR | REM DUR | % COMP | EARLY START | ACTUAL START | EARLY FINISH | ACTUAL FINISH | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| **Traffic control** | | | | | | | | | |
| **Southbound Outer Lane** | | | | | | | | | |
| P1N2100 | PLACE CONST. BARRIER | 12 | 3 | 75 | 06JAN00A | | 18JAN00 | | |
| **Northbound Outer Lane** | | | | | | | | | |
| P2N3100 | PLACE TEMP. CONST. BARRIER | 6 | 6 | 0 | 30MAR00 | | 06APR00 | | |
| P2N3225A | REMOVE TEMP. CONST. BARRIER | 5 | 5 | 0 | 07APR00 | | 13APR00 | | |
| P2N2196 | STRIPE ROADWAY | 9 | 9 | 0 | 11AUG00 | | 23AUG00 | | |
| P2N2198 | REMOVE TEMP. BARRIER | 4 | 4 | 0 | 24AUG00 | | 29AUG00 | | |
| **Signage** | | | | | | | | | |
| **General Construction** | | | | | | | | | |
| P1NP100A | PROCUREMENT OF NOISE BARRIER POST & | 10 | 3 | 70 | 02JUN99A | | 18JAN00 | | |
| P1N2190 | INSTALL SIGN SUPPORT STRUCTURE | 8 | 1 | 88 | 06JAN00A | | 14JAN00 | | |
| P1N2195 | ERECT SIGNS | 3 | 3 | 0 | 17JAN00 | | 19JAN00 | | |
| **Earthwork** | | | | | | | | | |
| **Southbound Outer Lane** | | | | | | | | | |
| P1N2115A | GRUB & STRIP TOPSOIL | 8 | 8 | 0 | 19JAN00 | | 28JAN00 | | |
| P1N2105B | INSTALL EROSION CONTROL DEVICES | 15 | 15 | 0 | 31JAN00 | | 18FEB00 | | |
| P1N2200 | INSTALL TEMP. SHEETING | 12 | 12 | 0 | 21FEB00 | | 07MAR00 | | |
| P1N2210 | EXCAVATE RETAINING WALL | 12 | 12 | 0 | 08MAR00 | | 23MAR00 | | |
| P1N2240 | PLACE POROUS FILL BEHIND WALL | 9 | 9 | 0 | 23MAY00 | | 02JUN00 | | |
| P1N2250 | BACKFILL RETAINING WALL | 7 | 7 | 0 | 05JUN00 | | 13JUN00 | | |
| **Northbound Outer Lane** | | | | | | | | | |
| P2N2115B | REMOVE GUIDE RAIL | 4 | 4 | 0 | 24MAR00 | | 29MAR00 | | |
| P2N2125A | EXCAVATE FOR ELECTRICAL | 10 | 10 | 0 | 30MAR00 | | 12APR00 | | |
| P2N3110 | REMOVE TEMP. PAVEMENT | 9 | 9 | 0 | 07APR00 | | 19APR00 | | |
| P2N3120 | REGRADE AREA | 7 | 7 | 0 | 20APR00 | | 28APR00 | | |

**Figure 7.9 Updating a report without costs listed (most common type of report)**

| ACTIVITY ID | ACTIVITY DESCRIPTION | ORIG DUR | REM DUR | % COMP | EARLY START | ACTUAL START | EARLY FINISH | ACTUAL FINISH | BUDGETED COST | COST TO DATE | COST THIS PERIOD | NOTE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Traffic control** | | | | | | | | | | | | |
| **Southbound Outer Lane** | | | | | | | | | | | | |
| P1N2100 | PLACE CONST. BARRIER | 12 | 3 | 75 | 06JAN00A | | 18JAN00 | | 17,799.84 | 13,349.88 | | |
| **Northbound Outer Lane** | | | | | | | | | | | | |
| P2N3100 | PLACE TEMP. CONST. BARRIER | 6 | 6 | 0 | 30MAR00 | | 06APR00 | | 9,999.12 | 0.00 | | |
| P2N3225A | REMOVE TEMP. CONST. BARRIER | 5 | 5 | 0 | 07APR00 | | 13APR00 | | 8,332.60 | 0.00 | | |
| P2N2196 | STRIPE ROADWAY | 9 | 9 | 0 | 11AUG00 | | 23AUG00 | | 10,000.08 | 0.00 | | |
| P2N2198 | REMOVE TEMP. BARRIER | 4 | 4 | 0 | 24AUG00 | | 29AUG00 | | 6,666.08 | 0.00 | | |
| **Signage** | | | | | | | | | | | | |
| **General Construction** | | | | | | | | | | | | |
| P1NP100A | PROCUREMENT OF NOISE BARRIER POST & | 10 | 3 | 70 | 02JUN99A | | 18JAN00 | | 12,000.00 | 8,400.00 | | |
| P1N2190 | INSTALL SIGN SUPPORT STRUCTURE | 8 | 1 | 88 | 06JAN00A | | 14JAN00 | | 6,895.36 | 6,033.44 | | |
| P1N2195 | ERECT SIGNS | 3 | 3 | 0 | 17JAN00 | | 19JAN00 | | 5,371.56 | 0.00 | | |
| **Earthwork** | | | | | | | | | | | | |
| **Southbound Outer Lane** | | | | | | | | | | | | |
| P1N2115A | GRUB & STRIP TOPSOIL | 8 | 8 | 0 | 19JAN00 | | 28JAN00 | | 12,533.12 | 0.00 | | |
| P1N2105B | INSTALL EROSION CONTROL DEVICES | 15 | 15 | 0 | 31JAN00 | | 18FEB00 | | 3,760.32 | 0.00 | | |
| P1N2200 | INSTALL TEMP. SHEETING | 12 | 12 | 0 | 21FEB00 | | 07MAR00 | | 9,347.04 | 0.00 | | |
| P1N2210 | EXCAVATE RETAINING WALL | 12 | 12 | 0 | 08MAR00 | | 23MAR00 | | 7,542.24 | 0.00 | | |
| P1N2240 | PLACE POROUS FILL BEHIND WALL | 9 | 9 | 0 | 23MAY00 | | 02JUN00 | | 11,107.08 | 0.00 | | |
| P1N2250 | BACKFILL RETAINING WALL | 7 | 7 | 0 | 05JUN00 | | 13JUN00 | | 7,770.84 | 0.00 | | |
| **Northbound Outer Lane** | | | | | | | | | | | | |
| P2N2115B | REMOVE GUIDE RAIL | 4 | 4 | 0 | 24MAR00 | | 29MAR00 | | 3,115.68 | 0.00 | | |
| P2N2125A | EXCAVATE FOR ELECTRICAL | 10 | 10 | 0 | 30MAR00 | | 12APR00 | | 6,141.20 | 0.00 | | |
| P2N3110 | REMOVE TEMP. PAVEMENT | 9 | 9 | 0 | 07APR00 | | 19APR00 | | 6,772.68 | 0.00 | | |
| P2N3120 | REGRADE AREA | 7 | 7 | 0 | 20APR00 | | 28APR00 | | 6,902.84 | 0.00 | | |

**Figure 7.10 Updating a report for a cost-loaded schedule (less common type of report)**

calculate the other two variables (unless percent complete and remaining duration are untied). It is important for each page of the report to be numbered so that any missing pages can be discovered. Also, a ruler or a straightedge should be used to aid in reading the information. This hand-marked progress report stays with the superintendent as part of the project records, but the scheduler should keep a copy.

In his experience with public agencies, the author was responsible for using Oracle Primavera P6 software (it was called P3e then) to update monthly a large number of public works projects. The schedules are similar and do not contain much detail. Rather, they ensure—from the public agency's viewpoint—that the contractor meets important deadlines. The data date is the last day of every month. The scheduler sends an e-mail reminder about 2 workdays before the data date to all project managers and their section managers, reminding them of the update. All update reports are due 2 workdays after the data date. A second reminder e-mail is sent on the morning of the due date. The monthly update includes two reports from each project manager:

a. A checklist (see Figure 7.11) that includes a list of all projects managed by the project manager. Next to each project, the project manager must check

**Washington County, Florida**

List of Projects by Project Manager

*Data Date: 3/15/2003*

Project Manager: John Doe

| Proj. No. | Project Name | Schedule | | Cost | |
|---|---|---|---|---|---|
| | | As Planned | Change | No change | Change |
| ABC1200 | Washington Street Drainage Improvement, Phase I | X | | X | |
| FGH3211 | Road Resurfacing, Main St. between 42nd and 52 Ave. | | X | X | |
| LMN4500 | Bridge No. 10345, U.S. 41 over Hillsborough River | X | | X | |
| XYZ7812 | Traffic Signal at Intersection of Busch Blvd. and Florida Ave. | | X | | X |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

**Figure 7.11 List of projects by project manager**

one of two choices: "As Planned" or "Schedule Change." If the project manager chooses the first, no further paperwork is needed for that project. The scheduler assumes that everything that was planned to happen during this update period did happen on the planned dates.

b. If the project manager chooses Schedule Change, he or she must submit a Schedule Update Form (see Figure 7.12) for the project. The form lists all project activities, with a Start Date column, an "A" column, a blank Start Date Change column, and similar columns for the end date. If an activity started, the project manager writes an *A*, indicating an actual date, next to the start date. If the actual start date differs from the planned date, the project manager writes the updated start date in the Start Date Change column. If a future start date is changed (say, postponed for 2 months), the new start date is written in the Start Date Change column without writing an *A*

**Schedule Update Form**

Data Date: 3/15/2003

PM ignature: Date:
Schedule Signature: Date:

PM: John Doe Project No.: FGH2133 Project Name: Office Building, downtown Tampa

| | Activity name | Start Date | A | Start Date Change | End Date | A | End Date Change | Orig. Dur. | Rem. Dur. | % Comp. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | NTP | 1/3/2003 | A | | | | | 0 | 0 | 100% |
| 2 | Mobilize | 1/6/2003 | A | | 1/8/2003 | A | | 3 | 0 | 100% |
| 3 | Dewatering | 1/9/2003 | A | | 1/19/2003 | A | | 11[a] | 0 | 100% |
| 4 | Excavation—North Side | 1/20/2003 | A | | 1/29/2003 | A | | 9 | 0 | 100% |
| 5 | Excavation—South Side | 2/3/2003 | A | | 2/25/2003 | A | | 10 | 0 | 100% |
| 6 | Drill Piles—North Side | 1/30/2003 | A | | 2/28/2003 | A | | 13 | 0 | 100% |
| 7 | Drill Piles—South Side | 3/3/2003 | A | | 3/19/2003 | | | 13 | 3 | 77% |
| 8 | Concrete Piles —North Side | 3/3/2003 | A | | 3/11/2003 | A | | 7 | 0 | 100% |
| 9 | Concrete Piles —SouthSide | 3/20/2003 | | | 3/28/2003 | | | 7 | 7 | 0% |
| 10 | Pile Caps—North Side | 3/12/2003 | A | | 3/28/2003 | | | 13 | 10 | 23% |
| 11 | Pile Caps—South Side | 3/31/2003 | | | 4/16/2003 | | | 13 | 13 | 0% |
| 12 | Footings—North Side | 3/24/2003 | | | 4/4/2003 | | | 10 | 10 | 0% |
| 13 | Footings—South Side | 4/7/2003 | | | 4/22/2003 | | | 12 | 12 | 0% |
| 14 | Elevator Pit —North Side | 3/31/2003 | | | 4/9/2003 | | | 8 | 8 | 0% |
| 15 | Elevator Pit —SouthSide | 4/14/2003 | | | 4/23/2003 | | | 8 | 8 | 0% |

[a]This activity is on a 7-day per week calendar.

**Figure 7.12 Sample Schedule Update Form**

in the A column. The same is done for the end date columns. The project manager may or may not use the Original Duration, Remaining Duration, and Percent Complete columns. Some project managers prefer to give an expected finish date rather than the remaining duration or percent complete. The scheduler has to check if these numbers are accurate.

2. The scheduler enters the information into the computer scheduling program and updates the schedule.
3. The scheduler discusses the new situation with the project manager and makes sure that no more changes or adjustments are needed (in other words, the scheduler obtains the project manager's approval for producing the reports).
4. The scheduler prints new reports that show the updated schedule and distributes them, directly or through the project manager, to all involved parties—different reports to different parties. The scheduler may also give the project manager a short, descriptive analysis report. For example, if the expected finish date of the project was pushed back a few days, the scheduler may give the reason (e.g., a predecessor activity was supposed to finish by a certain date but did not). The scheduler tracks the delay from the end and works back to the activity or activities that caused the delay.
5. After producing the reports, the scheduler may receive feedback from different parties, some of which may have an impact on the schedule. The scheduler must filter any such feedback through the project manager. Only one point of contact (usually the project manager) should have the authority to approve any information before it is implemented in the schedule. Some schedule feedback received after the reports are printed may be kept until the next update.

   When the next updating cycle is due, the same steps are repeated. These steps are summarized in Figure 7.13.

**Tip Box 7.6**

The scheduler should not assume any responsibility for the data used in the update process.

It is possible to include a cost estimate update in the process. In this case, the checklist will include two choices for each project: cost estimate change or no cost estimate change. Similar to the process explained earlier, if there is a cost estimate change for a certain project, the project manager must attach a cost estimate change form for the project that clearly shows the changes.

#### *Keep Duration or End Date?*

In some instances, the project manager indicates, on the update report, a delay in the start of an activity. The project manager may fail to inform the scheduler of what happens to the end of the activity. For example, the "Design Development 90%" activity's

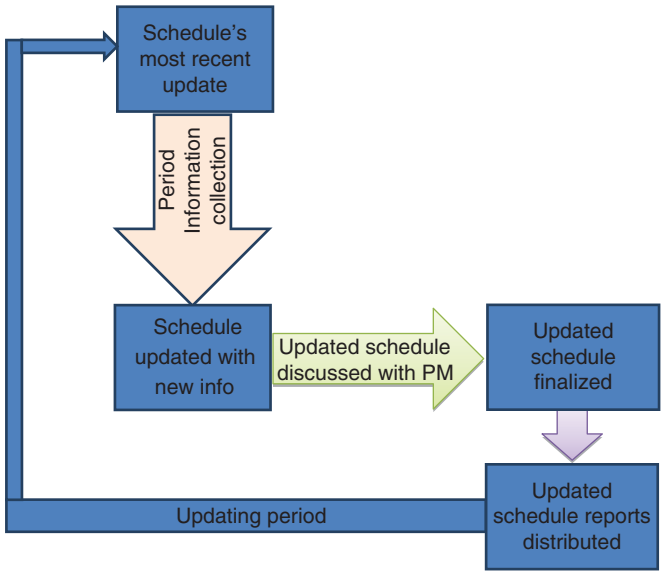



**Figure 7.13 Project update cycle**

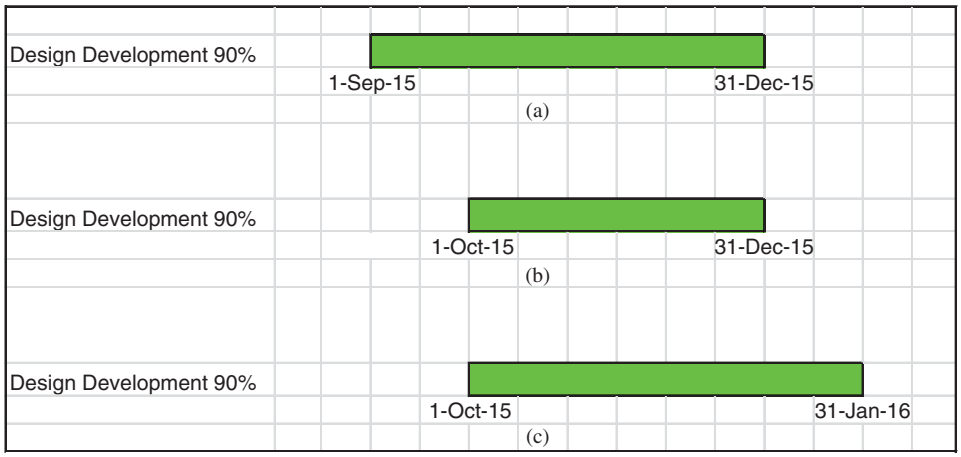



**Figure 7.14 Design development: (a) 90% activity as originally planned; (b) 90% activity with start delayed one month and finish date kept as planned; (c) 90% activity with start delayed one month and original duration maintained**

start was delayed 1 month (see Figure 7.14a). Unless the scheduler is told explicitly by the project manager, there are two possibilities:

1. Keep the end date, 31 DEC 2015, which means the duration will shrink by 30 days (Figure 7.14b).
2. Keep the original duration, which means the end date will slip by 30 days to 30 JAN 2016 (Figure 7.14c).

This case emphasizes the importance of communication and that the scheduler cannot and must not make assumptions without the knowledge and consent of the project manager.

#### *Importance of Updating Remaining Duration*

When updating a schedule, some activities may be in progress, that is, started but not completed. Actual duration is calculated automatically as:

$$\text{Actual duration} = \text{Data Date} - \text{Actual Start Date}$$

The finish date of the activity is usually determined when the scheduler inputs one of these three variables:

- Remaining duration
- Percent complete
- Expected finish date

If the activity is progressing as planned, remaining duration and percent complete will agree with each other. Scheduling computer programs such as Oracle Primavera P6 tie them together by default but allow the user to untie them. This untying is necessary when the activity is *not* progressing as planned. For example, the activity Install Doors had an original duration of 8 days (5 workdays per week, Monday through Friday). It started on Wednesday, 15 OCT 2014. The data date is (end of) Friday, 17 OCT 2014. If the activity is progressing as planned:

$$\text{Actual Duration} = 17\text{ OCT }2014 - 15\text{ OCT }2014 + 1^{4} = 3\text{ days}$$
$$\text{Remaining Duration} = 8 - 3 = 5\text{ days}$$
$$\text{Percent Complete} = \text{Actual Duration}/\text{Original Duration} = 3/8 = 37.5\%$$

Now, in a different scenario, let's assume that 3 days after its start, things are not going well. The activity Install Doors is only 25% complete, but the foreman believes he can pick up the slack and finish on time. The remaining duration is still 5 days. The scheduler has to untie the remaining duration and percent complete and then input them independently. The At Completion Duration is still 8 days. However, if productivity continues at the same pace as in the first 3 days, then there is no need to untie percent complete and remaining duration. When the scheduler inputs percent complete = 25%, the computer automatically calculates the remaining duration as 9 days. In this case, the At Completion Duration will be 3 + 9 = 12 days.

[4] We added 1 day because the start date in computer software is taken as the beginning of the day. We chose to have the data date as the end of the day. So, 3 days of the activity duration passed: 14, 15, and 16.

The Expected Finish date is a nice option in Oracle Primavera P6. The scheduler tells the program when the activity is expected to be finished. This input helps to then determine both the remaining duration and percent complete. Let's assume that, in the previous Install Doors activity, the scheduler was informed that the activity was expected to be completed on 28 OCT 2014:

$$\begin{aligned}\text{Remaining Duration} &= \text{Expected Finish date} - \text{Data Date}\\ &= 28\ \text{OCT}\ 2014 - 17\ \text{OCT}\ 2014 = 7\ \text{days}^{5}\\ \text{Percent Complete} &= \text{Actual Duration}/\text{At Completion Duration} = 3/10 = 30\%\end{aligned}$$

The scheduler has to be careful if the computer program calculates percent complete using At Completion Duration, not the Original Duration (a discussion on this issue will follow later in this chapter). If so, percent complete will be incorrect or at least will not reflect what the user thinks it reflects.

Updating the remaining duration is an important, but often overlooked, issue. Some schedulers and other software users focus more on the actual performance portion and ignore updating future expectations. For example, assume that the Install Doors activity, 3 days after starting, was not progressing as planned and needed 9, rather than 5, extra days. Also, assume that this activity is on a critical path. If the remaining duration was not updated correctly, the calculated finish date will be 4 workdays earlier than what it should be. This mistake can lead to inaccurate percent complete (mainly for the activity but with a small impact on the project percent complete). This may lead to an inaccurate calculated finish date for the project, overpayment to the contractor, and an inaccurate planned start date for successors (adverse consequences on successors' crews' schedules and materials delivery).

#### *More Recommendations*

Schedulers may receive verbal instructions from their superiors or from project management team members to make changes to the schedule, such as in activities' dates, durations, logic, or cost. Such changes must be formal and made in writing. It may be embarrassing for a junior scheduler to ask the project manager to put any requested changes formally in writing, but he must do so. Even with the assumption of good intentions, which unfortunately may not always be true, people tend to forget or misinterpret verbal communications. People also leave their jobs, so any verbal agreement will disappear with their departure. An alternative way is for the scheduler to send an e-mail to the person who requested the change: "This e-mail is to confirm your request/instruction to make the change of. . . ." This puts the ball in the other person's court.

#### *Who Has Authority to Update the Schedule?*

Sometimes project managers do their schedule updates themselves without having dedicated and specialized schedulers. This may be fine for small projects in small companies where the project manager has to wear several hats. However, in large organizations with many project managers and project management team members,

[5] Count only workdays.

only authorized professionals should be able to do so. This guarantees accuracy of the data and consistency in holding on to the organization's policy. This also limits the liability for the integrity of the data before upper management executives. This author recommends one of two approaches:

1. Project managers and other project management team members can view but not edit the schedule. Editing must be exclusively the responsibility of the scheduler.
2. Any project manager can view any project schedule but can edit only his or her schedule. The scheduler must review all projects, however.

**Schedule Comparisons:** Some commercial software programs on the market compare two schedules. For example, Claim Digger (originated by HST Software, Simpsonville, South Carolina, and later acquired by Primavera Systems) can compare two Oracle Primavera P6 schedules. In this case, you can compare the current update with the previous (or another) update and summarize changes that happened between the two updates. You can select all or certain criteria for comparison, such as added activities, deleted activities, added relationships, deleted relationships, percent complete, used resources, budget, constraints, and so forth. Comparison with the baseline schedule is still important. It tells you where you stand currently compared with where you are supposed to be (the baseline), which is—contractually—the bottom line. Nevertheless, comparisons with the previous update are important because they show whether you are moving in the proper direction.

Sometimes, after step 2 in the updating process (explained earlier) has been completed, negative total float values appear on the schedule for certain activities. This is a red flag that must be addressed. A negative float for an activity means that the activity is behind schedule by a number of days equal to the float amount. There could be one of two reasons for this:

1. The entire project (primarily, the critical path) is behind schedule. If the negative float values vary—say, one activity has a total float ($TF$) = −12 and another has a $TF = -8$, the critical path is the path with the most negative float.[6] This is the definition of the critical path (the longest path). You may argue that the activity with $TF = -8$ is "critical" as well. Oracle Primavera P6 even allows you to change the definition of critical activities. This issue is discussed further in Chapter 8.
2. One particular activity is behind its constrained start or finish date. The entire project may still be meeting its expected completion date. For example, you could have the milestone Building Dry-in with an early finish constraint date of 13 OCT 14. If the calculated early finish date is 16 OCT 14, you will have $TF = -3$ for this activity. Note that there will be activities with similar negative float on a continuous path, starting from the data date until that activity.

[6] Mathematicians consider −4 greater than −8, but using this notion in construction may be confusing. In this book, if we say the "larger" negative float, we mean in terms of absolute value.

These two scenarios are not mutually exclusive. They can occur concurrently. The project manager must find solutions to bring such activities back on schedule and to eliminate any negative float. The project manager may meet with the scheduler to discuss some "what-if" scenarios in order to work out or suggest a solution to the problem. The meeting may include the subcontractors (those whose activities are involved) so that their consent can be obtained for any proposed recovery plan (see the "Recovery Schedules" section in Chapter 8). However, we must caution against the usual "blame the contractor" attitude and consider the possibility that the contractor may not be at fault for the negative float. The delay may have been caused by the owner, unforeseen conditions, *force majeure*, or another situation that is beyond the contractor's responsibility.

#### Change in the Critical Path

Sometimes, the critical path changes after an update. This happens if any of the following occurs:

- The critical path gets shortened if either an activity (or activities) on the critical path takes less time than originally planned or an activity on the critical path is deleted so that the second longest path takes over.
- A noncritical (usually near-critical) path becomes longer if either an activity (or activities) on it takes more time than originally planned or an activity is added to the path so that it becomes the longest path.

The project management team must then shift its attention to the new critical path and determine why it has become critical (particularly in the latter case). For this reason, it is wise to always inspect near-critical activities along with critical activities. In almost every scheduling software package, you can run a filter that selects only activities with a TF less than a value set by the user. In the absence of a negative float, a number between 3 and 5 is suggested for the filter. Any activity with TF $< 3$ is practically critical and has a better chance than others of becoming critical during construction.

#### Float after the Update

For completed activities, float "expires"; that is, it no longer stays available to that activity. It may be "inherited" by succeeding activities. For example, if we examine activities D, H, L, and M in Example 7.1:

- Before the update, they had TF = 6, 11, 11, 6, respectively. Remember that total float is a path float, so the total float of activity D is part of the total float of activity H.
- After the update, the total float of activity D expired. As for activity H, it lost 4 days of its float (it had not yet started, even though it had an ES = 6, and

the data date = 10). If the project had not slipped, the TF for activity H would have been = 11 − 4 = 7, but the slippage of the project by two days made the H's TF = 7 + 2 = 9 days. Activity L had TF = 6 days and still the same value after the update because the driving relationship comes from activity G, which was delayed by 2 days. Activity M had TF = 11 days, but after the update, it became TF = 11 + 2 (project finish date slipped) − 2 (delay for activity C) − 3 (increase in activity F's duration) = 8 days.

It is important for the contractor and subcontractors to re-examine the float of every activity after the update. Float often changes with updates, since it is impacted by past performance and changes implemented in the update.

### Contractor-Created Float

When the general contractor or a subcontractor performs at a faster pace than planned, more float may be added to the remainder of the schedule. For example, if an activity finishes 2 days ahead of schedule, the result may be a float increase for some of the succeeding activities. If the activity was critical, the result may be an earlier finish date for the entire project. The author calls this type of float **contractor-created float**. This situation poses some interesting questions: Does the contractor or subcontractor who "created" this float own it? In other words, can he or she later "take back" this float for a succeeding activity? Can the owner take it if the contract gives ownership of the float to the owner? If the float was created by a subcontractor working on a critical activity and resulted in an early finish for the entire schedule, who gets the "bonus," if any? Does it work both ways: If the subcontractor delayed work and this delay resulted in a delay for the entire project, is the subcontractor responsible for any liquidated damages? The answers to these questions depend mostly on the contract. In many public projects, in which time is critical and the public's convenience is at stake, the government adds both "carrots" and "sticks" in the contract. In the aftermath of the Northridge earthquake, Caltrans (the California Department of Transportation) used this policy heavily. Penhall, an Anaheim-based demolition contractor, signed a contract that had a clause for a $75,000 bonus per day for each day finished ahead of schedule and a similar amount in liquidated damages for finishing late (Rosta, 1994a; Tulacz, 1994). C. C. Meyers received a $14.8 million bonus (the largest in the history of public contracts) for finishing 74 days ahead of schedule. This amount was based on a $200,000 per day bonus–liquidated damages clause in the contract (this case study is discussed in more detail in Chapter 8). In some bonus–penalty contracts, a limit is put on the bonus but not on the penalty. In 1995, Yonkers Contracting Co., Inc., Yonkers, New York, won a contract to modernize a four-lane, 2.5-mile stretch of the Northern State Parkway across Long Island. The contract included a $20,000 penalty for each day of delay after the deadline and a similar bonus amount for finishing ahead of schedule, with a $2.4 million cap on the bonus. There was no cap on the penalty (Cho, 1997). You may want to refer to the legal references listed in the "Construction Scheduling Law" section of the Bibliography for more details.

### Data and Information

Some people like to reduce the role of scheduling to just crunching numbers and producing colorful bar charts. In some simple, straightforward cases, the numbers may be sufficient. For example, suppose that an activity is scheduled to take 6 days. When updating, you observe that 3 days of work have elapsed and the activity is 50% complete. Not much explanation is needed. However, other cases are not as straightforward. For example, suppose that an activity is scheduled to take 8 days; 6 days have elapsed, but it is only 25% complete. Maybe an unforeseen condition occurred, maybe the work quantity was increased or underestimated, maybe the crew productivity decreased for some reason, or maybe another factor was involved. This observation must be recorded for project control and to prevent skewed estimates for future projects. Likewise, in some construction jobs, work may not be continuous. For instance, suppose that an activity with only 3 days' duration shows an actual start date that is 20 days ago, yet the activity is not complete. Even though computer programs have provisions for such a work interruption, most schedulers and project managers do not show it on the schedule as an interruption. It is important and necessary to explain the numbers, especially when a situation occurs that is not normal or average. Most software programs allow the addition of activity notes for this purpose. Oracle Primavera P6 allows the user to add notes for activities and also to add several "notebooks" for the project.

**Tip Box 7.7**

As a scheduler, you are supposed to provide project team members and other participants with more than just computer output (data). You need to explain the data and provide *information!*

## PROJECT CONTROL

### Measuring Work Progress

Probably the single most important step in schedule updating is measuring work progress, because it has an impact not only on the schedule's status but also on progress payments to the contractor and subcontractors. Measuring work progress involves mainly calculating or estimating the percent complete for each activity. It may also include estimating the percent complete for the entire project. This subject is broad. In this chapter, it is covered only briefly.

#### *Methods for Determining Percent Complete for Individual Activities*

As discussed in Chapter 4 (in the "Steps Required to Schedule a Project" section), the project manager or superintendent can more easily objectively assign a percent complete to a small, simple activity than to a large, complex activity. Several methods for measuring work progress are suggested. There are no correct and incorrect methods; there are only more or less suitable methods for the specific type of activity

under consideration. Six of these methods are as follows (Construction Industry Institute, 1987b):

1. *Units completed:* In the **units completed** method, Percent complete = Units completed/Total units. This method works well for activities with small, identical, repetitive components, such as laying bricks or CMUs (concrete masonry units), excavating, fishing electric wire, installing tile or carpet, and so forth. In these activities, the type of work and pace are the same throughout the activity. Percent complete can be calculated simply by dividing units completed by the total quantity. For example, in an activity involving installing 4,000 concrete blocks, 1,200 have been installed. Percent complete = $1,200/4,000 * 100 = 30\%$. In some cases, errors may arise despite the similarity in units because of the effect of learning curves or differing conditions. An example of the second case is when a mason is installing block or brick to an 8-ft high wall. The blocks on the high courses take more time than those in lower courses. When the error is small, it is ignored.
2. *Cost or time ratio:* This method applies to those activities that are continuous and uniform throughout the project, such as Safety Inspection and project management–type activities. Percent complete is calculated by dividing time elapsed by total duration (if a **time ratio**) or cost to date by total budget (if a **cost ratio**). For example, a project management activity is scheduled for 12 months with a budget of $80,000. After 2 months, it is $2/12 * 100 = 16.7\%$ complete, or if $20,000 is already spent, it is $20,000/80,000 * 100 = 25\%$ complete. Another alternative is the **man-hour ratio** (actual man-hours consumed divided by total man-hours budgeted). The time ratio method for individual activities is similar to the duration percent complete and baseline duration percent complete methods for calculating the project percent complete. These methods are discussed in the next section.
3. *Start-finish:* This method works best for small activities or those with no duration or a short duration. The project manager may assign one of three stages: have not started yet (0%), started but not yet finished (an arbitrary amount, say, 40% or 50%), or finished (100%). Errors usually balance each other. When these activities become too small, we can look at them as "almost events," either 0% or 100% complete.
4. *Supervisor's opinion:* The most subjective method is the supervisor's opinion method. It is used when no other method can be suitably applied, such as in an engine tune-up or dewatering operation. This method relies totally on the foreman or superintendent's judgment. The contractor may use this method to exaggerate the percent complete for early payment. Because it does not require actual measurements, it is considered the quickest (and dirtiest) and "most convenient" method. The scheduler must be careful not to overuse this method.
5. *Incremental milestones:* The incremental milestones method is more suitable for large and complex or multistage activities. Each stage of a given activity is assigned a "weight" that is approximately equal to its percentage share of effort in the total activity. Then, each stage is treated as "all or nothing." For

example, a contractor is installing 25 doors. Four doors that have not yet been started are 0% complete. Eight doors have had their frames erected. They are considered 30% complete. Another six doors have been hung. They are said to be 50% complete. Four more doors have been painted, making them 75% complete. The last three doors have had the hardware installed. They are now 100% complete. Each door goes through the stages for installation, shown in the following chart:

| Task | Weight (%) | Cumulative Weight (%) | No. Units | % Complete Weight |
|---|---|---|---|---|
| Not yet started | 0% | 0% | 4 | 4 * 0%/25 = 0.0 |
| Erect door frame | 30% | 30% | 8 | 8 * 30%/25 = 0.096 |
| Hang door | 20% | 50% | 6 | 6 * 50%/25 = 0.120 |
| Paint door | 25% | 75% | 4 | 4 * 75%/25 = 0.120 |
| Install hardware | 25% | 100% | 3 | 3 * 100%/25 = 0.120 |
| | | | 25 | Total = 0.456 = 45.6% |

6. *Weighted or equivalent units:* The weighted or equivalent units method is used for large and complicated activities that usually comprise several consecutive or overlapping subactivities. The method involves the following five steps:

   a. Assign a weight to each subactivity so that total weight = 100%.
   b. Multiply the weight of each subactivity by the quantity of the total activity. This is the "equivalent weight" in units for each subactivity.
   c. Determine the percent complete for each subactivity by using one of the previously discussed methods.
   d. Multiply the percent complete for each subactivity by its equivalent weight. The result is the "earned quantity."
   e. Add earned quantities for all activities and divide by total quantity.

   This is the percent complete for the total activity. For example, for a wall-framing activity, with a total quantity of 3.5 MBF (1,000 board-feet), the information shown in the chart may be true:

| Assigned Weight | Subactivity | Unit[a] | Total Quantity | Equivalent MBF | Completed Quantity | Earned MBF |
|---|---|---|---|---|---|---|
| 0.04 | Bottom Plates | EA | 20 | 0.14 | 20 | 0.14 |
| 0.40 | Studs | EA | 320 | 1.40 | 210 | 0.92 |
| 0.08 | Corners | EA | 12 | 0.28 | 8 | 0.19 |
| 0.12 | Blocking | EA | 160 | 0.42 | 92 | 0.24 |
| 0.14 | Door Openings | EA | 10 | 0.49 | 5 | 0.25 |
| 0.16 | Window Openings | EA | 12 | 0.56 | 5 | 0.23 |
| 0.06 | Top Plates | EA | 40 | 0.21 | 0 | 0.00 |
| 1.00 | Total | MBF | | 3.50 | | 1.97 |

[a]EA = each.

$$\text{Percent complete} = 197/3.50 = 56.3\%$$

Only the weights (in the first column) are subjectively assigned. All other columns are either measured or calculated. Following is a sample calculation for the studs:

$$\text{Equivalent MBF} = \text{Assigned weight} * \text{Total MBF}$$
$$= 0.40 * 3.50 = 1.40$$

and

$$\text{Earned MBF} = \text{Equivalent MBF} * \text{Completed quantity/Total quantity}$$
$$= 1.40 * 210/320 = 0.92$$

The weighted or equivalent units method and the incremental milestones method are similar. Both are used for relatively large and complex activities that comprise several subactivities. The main difference is that subactivities in the incremental milestones method must occur in chronological sequence. So, when you assign a percent complete to a subactivity, you use the cumulative percent complete, which includes the percent complete for the preceding steps (subactivities). In the weighted or equivalent units method, subactivities may be somewhat independent. Each subactivity has its own percent complete regardless of the percent complete for other subactivities.

You may wonder what the wisdom is for considering a wall-framing "activity" as a single activity with seven "subactivities" rather than simply having seven individual activities. One minor advantage that you are able to tell the percent complete for the entire wall-framing activity. This author prefers to treat the situation as a number of individual activities. Many scheduling software programs can calculate the percent complete of a number of activities, grouped under certain criteria. Oracle Primavera P6 can do so in one of two ways: (a) you identify the wall-framing activities, for example, with an activity code (e.g., Step = Framing) and then group activities by step, or (b) you create a "level of effort[7] " activity (call it *Framing*) that encompasses all wall-framing activities. Another alternative is to use the work breakdown structure (WBS) (an example of a WBS is provided in Figure 4.1) and then summarize the WBS at a certain level. In Microsoft Project, you can "indent" activities to make them subactivities. If the major activity has a WBS code of 5, its subactivities will have WBS codes of 5.1, 5.2, 5.3, and so forth.

#### *Methods for Determining Percent Complete for the Entire Project*

We have shown how to estimate the percent complete for individual activities. The next question is, "What is the percent complete for the entire project?" The answer is not clear. In fact, there might be several answers—all substantially different—yet none is the "right" one and none is "wrong."

[7] Used to be called *Hammock* activity. The author prefers the old name.

Most of the methods that are applied to find out the percent complete of an entire project are the same as those explained earlier for calculating the percent complete for individual activities:

1. *Units completed:* This method may work for the percent complete of an activity, but it is difficult to apply to the entire project because there is no single unit in common to measure. An exception to this statement is a project with simple and identifiable units of measure, such as earthwork, road pavement, and sidewalk construction. We can say, for example, that 82 miles of a total 250 miles are completed. Then, the percent complete is 82/250, or 32.8%. In this case, we are assuming that "a mile is a mile" in the project (i.e., all paving effort takes the same amount of effort and duration throughout the project). We may still have a problem with "partially finished" units, but the project manager can make an assumption with a small error or apply the incremental milestones method.

   Other types of projects, such as residential, commercial, and industrial projects, do not have a common unit of production. Do not confuse this "unit" (a unit of measurement, such as a cubic yard of concrete, a linear foot of electric wiring, or a square yard or foot of flooring) with "functional units" (finished usable units, used mostly for design and estimating, such as a room in a hotel; a bed in a hospital; a pupil in a school; millions of gallons of water per day, or MGD, in a water project; and the like). Functional units must go through multistage activities to get into their final form, and they are not appropriate, in most cases, as a measure of work progress or project percent complete.
2. *Cost/budget:* The cost method is actually two methods, and it is a good idea to combine them for comparison:

   2.1 Baseline Cost/Budget Method: Percent complete = Budgeted cost to date/Baseline budget

   2.2 Actual Cost/Budget Method: Percent complete = Actual cost to date/Estimated cost at completion

   Baseline ratio represents percent complete that is supposed to be achieved at this point.
3. *Man-hours:* This method is similar to the previous one except that we use man-hours in the equation. Obviously, this method produces a number that is focused on labor man-hours (directly related to productivity), while the cost method calculates percent complete based on total cost including labor, materials, and other things.

   3.1 Baseline Man-Hour Method: Percent complete = Budgeted man-hours to date/Baseline man-hours

   3.2 Actual Man-Hour Method: Percent complete = Actual man-hours to date/Estimated man-hours at completion

It is important to note that the "man-hours" unit is not a time-measuring unit. It is, rather, a measure of effort or consumption of a labor resource. Eight man-hours can be produced by one person during an 8-hour period, by two persons during 4 hours, by four persons during 2 hours, and so forth.

4. *Duration:* Again, this method is indeed two methods—one based on baseline and one on actual duration.

   4.1 Baseline Duration:

   $$\text{Percent Complete} = (\text{Data Date} - \text{BL Start Date})/\text{Total BL Duration}$$

   Where BL Start Date is the baseline start date, that is, when the project was *planned* to start.

   4.2 Actual Duration:

   $$\text{Percent Complete} = \text{Actual Duration}/\text{At Completion Duration}$$

   Where At Completion Duration = Actual Duration + Remaining Duration

   In Figure 7.15, the project is represented by one summary bar. There are two bars, one representing the baseline project and the other representing the updated project. The project started 3 days late and is expected to take 1 more day than originally planned; that is, it is expected to finish 4 days past its baseline finish date.

   $$\text{Baseline Duration Percent Complete} = 19/32 = 59\%$$

   $$\text{Actual Duration Percent Complete} = 16/33 = 48\%$$

   Whether the scheduler is using baseline or actual duration, the scheduler has to make sure that he or she is counting workdays or calendar days. Both are okay as long as the scheduler knows what he or she is measuring and is consistent.

5. *Workday unit:* The workday unit method is based on the assumption that activities have weights that are proportional to their durations. As a simple example, let's contemplate a project made up of three activities (A, B, and C); each one

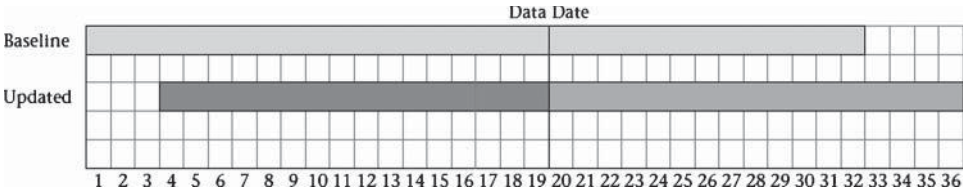



**Figure 7.15 Percent complete based on duration**

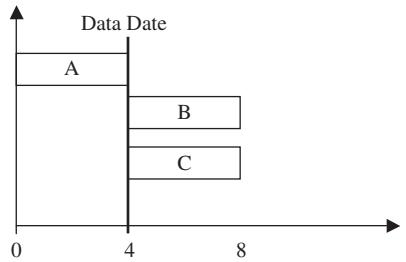



**Figure 7.16 Workday unit percent complete**

takes 4 days. Activity A is the predecessor to both B and C. Now, 4 days after the project has started, activity A is complete and activities B and C have not started yet (see Figure 7.16). In this case, each activity has a weight of 4 units. The project has a total of 12 units. Actual (or completed) units are 4.

Percent complete = Actual Units/Total Units = 4/12 = 33%

| Activity | IPA | Original Duration | Actual Duration | Remaining Duration |
|---|---|---|---|---|
| A | — | 7 | 7 | 0 |
| B | A | 12 | 9 | 3 |
| C | A | 6 | 4 | 2 |
| D | B, C | 5 | 0 | 5 |
| E | D | 9 | 0 | 9 |
| Total | | 39 | 20 | 19 |

This method is used in software scheduling programs such as Oracle Primavera P6. Another example is the project shown in the table.According to this method, the percent complete for this project is 20/39, or 51.3%. Two simplifying—but not necessarily realistic—assumptions underlie this method:

1. All activities have the same "weight per day."
2. Weight within the activity is distributed linearly. Some programs give the user the ability to change this assumption by dividing the activity into "steps" with different weights (similar to the weighted or equivalent units method). This division does not change the first assumption, that activities have weight proportional to their duration.

This method is simple and can be used by contractors who do not cost-load or resource-load their schedules. It has also an advantage that lags do not count in the percent complete because this method is based on "work-unit" and not just

duration. Its main pitfall is that activities such as procurement or obtaining permits, for example, may have much more weight than they deserve. Obtaining a permit may be a 60-day activity.[8] There may not be any work occurring for that activity during these 60 days and few or no resources allocated to it (not to underestimate the importance of the activity). It will have 30 times the weight of another activity with 300 CY of concrete placement that takes only 2 days. However, with hundreds or even thousands of activities in the schedule, the errors on both sides tend to cancel each other out.

#### *Discussion of the Methods*

So, which method—of the five (or, practically speaking, eight)—is better? Again, there is no unique answer; it depends on what you are looking for and what data are available. It is important for the project manager to know the options and then to select the appropriate percent complete method(s). Once the management team picks one (or more) method for measuring the percent complete for the activity or project, it should be used consistently throughout the life cycle of the project for project control. The contractor may use more than one percent complete measure at the same time, each for a different purpose.

In reality, the project percent complete may not be very important. It can be used for a general idea about the current status of the project, but it is not normally used for project control or progress payments. The percent complete of individual activities is more important because it provides the basis for progress payments. However, project percent complete may be used to calculate overhead cost as it is directly related to duration.

The cost and man-hours completed methods have their proponents, who believe such methods are the best way to control a project. They may be, if used with the proper understanding of what they mean. Whenever the cost, man-hour, or duration method is used, it is a good idea to calculate both the actual and baseline percent complete for comparison. The earned value analysis (explained later in this chapter) builds on this concept.

The duration method (both actual and baseline) and the workday method both measure time one way or the other. The duration percent complete method does not look at how much work is being done at certain intervals, while the workday method does. In the duration method, work on the project is treated as a linear variable (i.e., each day is the same).

The most important recommendations are: know what you (or the computer software) measures and be consistent with it.

[8] Some schedulers, including this author, prefer to assign a 1-day duration to such an activity, with 59 days lag, or even make it a milestone with a 60-day lag. Note also that this method, like the three preceding methods, can also be applied to the baseline or actual performance.

### *Percent Complete and the Computer Software*

Computer software packages define their own types of percent complete types. Some of them are simple and self-explanatory; others are not or are given a peculiar or misleading title by the software manufacturer. Even worse, some computer software packages do not give the equations or basis for calculations for such percent complete types. For example, this author had an interesting experience when third-party reporting software was used, pulling the raw data out of the scheduling software database. Some activities had percent complete exceeding 100%, although they were still incomplete. Other activities had negative percent complete! What was interesting was that such numbers showed as 100% and 0% in the reports of the scheduling software; that is, they were artificially "corrected." After investigating and contacting the scheduling software's technical support, the author discovered that equations and even terminology were used differently in the software. These three equations were presented earlier:

$$\text{Percent Complete} = \text{Actual Duration}/\text{Total Duration} \quad \text{(A)}$$

$$\text{Percent Complete} = (\text{Total Duration} - \text{Remaining Duration})/\text{Total Duration} \quad \text{(B)}$$

$$\text{Percent Complete} = (\text{Data Date} - \text{Actual Start Date})/\text{Total Duration} \quad \text{(C)}$$

The definition of *Total Duration* was pivotal: while the software used Original Duration as Total Duration, the author believes Total Duration = Updated Duration = Actual Duration + Remaining Duration.

To dramatize this point, suppose that an activity was originally estimated as taking10 days. For some reason, work has taken much more time than estimated. After 13 days of actual work, it was found that Remaining Duration = 12 days. If we keep the total duration as the original duration, which is 10 days, we will get the following results:

With equations A and C, the percent complete is 13/10, or 130%

With equation B, the percent complete is (10 – 12)/10, or – 20%.

The real percent complete is 13/(13 + 12), or 52%.

**Tip Box 7.8**

Define type(s) of percent complete to be used in the project, explain them well to the project stakeholders, and be consistent with using them.

**Example 7.2**

Assume that you have a "project" with three activities: the first two activities are identical and can be performed simultaneously. Each activity requires the installation of an interior, hollow-core wood door, each of which costs $200 (including hardware). Installation of these doors requires one laborer for 2 hours for each door. The third activity requires the installing of a hand-carved, decorative exterior door that costs $2,200 and takes three laborers 3 hours to install. Assume a man-hour costs $40.

$$\text{Total cost of first or second activities} = 200 + 2 * 40 = \$280 \text{ each}$$

$$\text{Total cost of third activity} = 2,200 + 3 * 3 * 40 = \$2,560$$

$$\text{Total cost for project} = 2 * 280 + 2,560 = \$3,120$$

$$\text{Total man} - \text{hours for project} = 2 + 2 + 3 * 3 = 13 \text{ man-hours}$$

$$\text{Total duration for project} = 2 + 3 = 5 \text{ hours}$$

Now, assuming that the first and second activities are completed and the third one has not started yet (see Figure 7.17), what is the percent complete of the "project"? Use all applicable percent complete methods. Assuming that the project is on budget and on schedule.

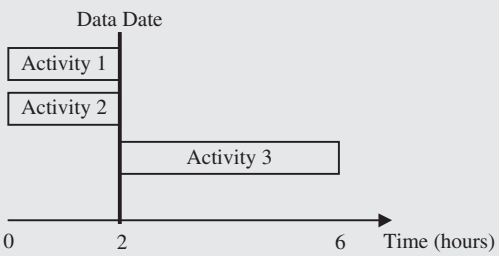



**Figure 7.17 Example 7.2: Installing three doors**

1. *Units completed:* This method assumes that a door is a door; that is, each door is a "unit," and all units have the same weight in the calculation of the percent complete.

$$\text{Percent complete} = \text{Units completed}/\text{Total units} = 2 \text{ door}/3 \text{ door}$$

$$= 66.7\% \text{ complete}$$

2. *Cost/Budget:* Percent complete = Actual Cost/Total budget = \$560/\$3,120 = 17.9% complete
3. *Man-hours:* Percent complete = Actual man-hours/Total man-hours = 4/13 = 30.8% complete
4. *Duration:* Percent complete = Actual duration/Total duration = 2 hours/5 hours = 40% complete
5. *Workday Unit (becomes here work-hour unit):* Percent complete = Actual Units/Total Units = 4/7 = 57% complete

   Methods 2 through 5 are calculated based on baseline (budget, man-hours, duration). They are correct based on actual work only if everything went as planned (on budget and on schedule).

   Now, to make things a little more complicated, let's assume that the hollow-core doors actually cost the contractor \$230 and that each one took an extra hour for installation (each). Also assume that the expectation for the third activity did not change.

$$\text{Actual cost for first two activities} = 230 + 3 * 40 = \$350 \text{ each}$$

$$\text{At Completion-cost for project} = 2 * 350 + 2,560 = \$3,260$$

$$\text{At Completion man} - \text{hours for project} = 3 + 3 + 3 * 3$$

$$= 15 \text{ man} - \text{hours}$$

$$\text{At Completion duration for project} = 3 + 3 = 6 \text{ hours}$$

   New percent complete estimates will emerge based on methods 2 through 5:

6. *Actual Cost/Budget:* Percent complete = \$700/\$3,260 = 21.5% complete
7. *Actual Man-Hours:* Percent complete = 6/15 = 40% complete
8. *Actual Duration:* Percent Complete = 3/6 = 50% complete
9. *Actual Work-hour Unit:* Percent complete = Actual units/Total units = 6/9 = 66.7% complete

If this is not confusing enough, let's say that the foreman "believes" the project is about 35% complete! These percentages can be rearranged as:

1. Units % Completed = 2/3 = 66.7%
2. Cost % Complete:

$$\text{Baseline \% Complete} = \$560/\$3,120 = 17.9\%$$

$$\text{Actual \% Complete} = \$700/\$3,260 = 21.5\%$$

3. Man-hours % Complete:

Baseline % Complete = 4/13 = 30.8%

Actual % Complete = 6/15 = 40%

4. Duration % Complete:

Baseline % Complete = 2/5 = 40%

Actual % Complete = 3/6 = 50%

5. Work-hour Unit % Complete:

Baseline % Complete = 4/7 = 57%

Actual % Complete = 6/9 = 66.7%

6. Supervisor's opinion = 35%

This example dramatizes the concept of percent complete for a reason: a percent complete is not just a percent complete! Make sure that you know exactly what you are measuring.

**Percent Complete for a Work Package** A work package (or assembly) is somewhere between an activity and a project. It is made up of a collection of related items. A continuous footing work package may include excavation, formwork, reinforcement, and concrete mix placement for that footing. A wall work package may include framing, electrical wiring, insulation, drywall, and painting. The percent complete for a work package can be obtained by selecting an appropriate method among those explained earlier, both for an activity or the project.

#### *Progress Payments and Percent Complete*

Payment requests depend completely on the percent complete for each activity and the unit prices submitted and approved in the schedule of values.[9] The five standard steps for progress payment requests are as follows:

1. The project contract usually specifies the frequency of progress payments, often monthly, and the closeout date for each period. This closeout date—say, the 25th of the month—is set for the general contractor to bill the owner. The

[9] In the British system, schedule of values is referred to as *bill of quantities (BOQ)*.

general contractor sets another date, usually 2 or 3 days earlier, for the subcontractors to bill him or her. All charges that miss the closeout date must wait until the next billing cycle (i.e., next pay request).

2. The general contractor lists all activities that were worked on. Each activity will have information such as actual start, actual finish (if completed), percent complete (if >0 but <100%), original budget, cost this period, cost to date, and cost to complete. The owner may have other stipulations in the contract, such as retainage. The general contractor must include work performed either by his or her own workforce or subcontractors.

   Materials purchased but not yet installed may or may not be included in the pay request, depending on the contractual agreement between the owner and the general contractor.

3. This report goes to the owner, who usually verifies its information. The owner's representative must verify the completed quantities, unit prices, and totals in the payment requests. Contractors sometimes front-end load the cost, which means they get their money earlier than normal. This is done by two means: first, contractors increase the unit prices of early items and decrease the unit prices of late items in a way that retains the same total (in lump-sum contracts). This is usually done in the schedule of values that the general contractor submits to the owner and is called *bid unbalancing*. The other method of front-end loading the cost is by exaggerating the percent complete for certain activities while they are in progress. Most owners do not like, and may not approve of, such practices. Thus, the owner's verification of the numbers in the contractor's payment request is important.

4. The payment request can be approved as is or rejected with certain numbers disapproved. Once the owner approves the payment request, it is processed and a check is issued payable to the general contractor for the total amount of the payment request minus any retainage, materials already paid, and/or penalties. The owner's verification of the pay request and the issuance of the check usually takes 2 to 4 weeks. When the owner pays the general contractor, the general contractor then pays the subcontractors.

   The owner requests a lien waiver from the general contractor and all subcontractors and vendors before issuing the payment.

5. The schedule of values must be updated with the cost items in any change order.

   Standard forms for pay requests, such as AIA G702 (Application and Certification for Payment) and G703 (continuation to form G702), are used in the industry. In Europe and some other parts of the world, FIDIC (International Federation of Consulting Engineers) and NEC (New Engineering Contract) forms are used.

**Tip Box 7.9**

Store and organize updates of the project in a manner that is easy to search and retrieve. You don't know when you're going to need them! This applies to completed projects, too, but they must be separated in a different "Archives Folder."

### Earned Value Analysis

**Earned value analysis** (**EVA**) is an integrated cost-schedule approach that is used to monitor and analyze the progress of a project. Popescu and Charoenngam (1995) defined it as "the performance measurement to report the status of a project in terms of both cost and time at a given data date" (p. 252).

**Earned value management** (**EVM**), started in the 1960s as a method for integrated project cost and schedule control, was designed by the U.S. Air Force and was named the *cost/schedule planning and control system*. In 1967, it became Department of Defense (DoD) policy and was renamed the **cost/schedule control systems criteria (C/SCSC)**, a formal planning and control reporting system developed by the Department of Defense in the 1960s for its contractors to use. It is used for reporting project schedule and financial information. This system was later simplified and modified to what is currently known as *earned value management*. The objectives of the C/SCSC policy were (1) for contractors to use effective internal cost and schedule management control systems, and (2) for the government to be able to rely on timely data produced by these systems for determining product-oriented contract status. C/SCSC implementation was governed by DoD Instruction 7000.2, "Performance Measurement for Selected Acquisitions," issued by the comptroller in 1967 in the financial management regulatory series. The C/SCSC and DoD Instruction 7000.2 had several implementation problems and went through several cycles of research and redefining. The name changed several times, from cost/schedule planning and control system to cost/schedule control systems criteria, or C/SCSC, and then to earned value management.[10]

The concept of **earned value** (**EV**) is simple; at any given point, take the following five steps:

1. Determine how much work you have accomplished and how much you should have accomplished according to the plan.

[10] For more information, see the Earned Value Management Web site (http://www.acq.osd.mil/pm) and the papers "Earned Value Management and Acquisition Reform." (http://www.acq.osd.mil/pm/paperpres/standown.html) and "Earned Value Management Rediscovered" (http://www.acq.osd.mil/pm/newpolicy/misc/abba_art.html), both by Wayne Abba.

2. Determine how much money you have earned[11] and how much money you have spent.
3. Calculate the time (schedule) and money (budget) variances so far.
4. Analyze the causes for the major variances and determine possible remedies.
5. Extrapolate these variances to the end of the entire project.

To understand the math involved in EV analysis, consider the following simplistic example.

**Example 7.3**

A contractor has agreed to build 30 dog houses in 90 days at a price of $800 per unit. Twenty days later, the contractor has finished 8 dog houses with an actual total cost (that includes overhead and profit) of $6,800. What is the status of the project?

**Solution**

The following analysis applies only if the work is sequential and not parallel (that is, the contractor works on one unit until it is finished and then starts the next unit, and so on). Linearity of production and no learning curve effect are also assumed.

$$\begin{aligned}\text{Total planned budget (TB)} &= 30 \text{ units} * \$800 \text{ each} = \$24,000,\\ \text{Daily planned production} &= 30 \text{ units}/90 \text{ days}\\ &= 0.33 \text{ units/day (or 3 days per unit)},\\ \text{Daily planned budget} &= \$24,000/90 \text{ days} = \$266.67\\ &= 0.33 \text{ units/day} * \$800 \text{ each} = 266.67,\end{aligned}$$

and

$$\text{Percent complete} = 8/30 = 26.7\%.$$

After 20 days, the contractor's plan calls for 0.33 units/day $*$ 20 days = 6.67 units to be finished, with a total cost of $6.67 * \$800 = \$5,333$. We call this amount the **budgeted cost for work scheduled** (**BCWS**). In other words, if everything (schedule and budget) work according to plan, in 20 days the contractor will have finished 6.67 units and earned $5,333.

The contract price was $800, and the contractor actually finished 8 units, so the contractor earned $8 * \$800 = \$6,400$ from the owner (disregarding

[11] Money earned = actual work quantity × contract unit prices

what it actually cost the contractor). This is called the *earned value (EV),* or **budgeted cost for work performed** (**BCWP**).

However, the contractor's actual cost was $6,800. This is called **actual cost for work performed** (**ACWP**).

$$\textbf{\textit{Cost Variance}} \ (\textbf{\textit{CV}}) = \text{BCWP} - \text{ACWP} = 6{,}400 - 6{,}800$$

$$= -\$400$$

$$\textbf{\textit{Schedule variance}} \ (\textbf{\textit{SV}}) = \text{BCWP} - \text{BCWS} = 6{,}400 - 5{,}333$$

$$= \$1{,}067$$

$$\textbf{\textit{Schedule variance}} \text{ in days (SV, days)} = \text{SV (\$)/Daily planned budget}$$

$$= \$1{,}067/\$266.67 = 4 \text{ days}$$

$$\textbf{\textit{Cost performance index}} \ (\textbf{\textit{CPI}}) = \text{BCWP/ACWP} = 6{,}400/6{,}800 = 0.94$$

$$\textbf{\textit{Schedule performance index}} \ (\textbf{\textit{SPI}}) = \text{BCWP/BCWS} = 6{,}400/5{,}333 = 1.20$$

$$\textbf{\textit{Forecasted cost variance}} \ (\textbf{\textit{FCV}}) = \text{CV}/\% \text{ Complete} = \$400/26.7\%$$

$$= -\$1{,}500$$

$$\textbf{\textit{Forecasted schedule variance}} \ (\textbf{\textit{FSV}}) = \text{SV}/\%\text{Complete} = 4/26.7\% = 15 \text{ days}$$

The results are tabulated as follows:

| Activity | Doghouses |
|---|---|
| TOTAL BUDGET ($) | 24,000 |
| % COMPLETE | 26.7 |
| ACWP ($) | 6,800 |
| BCWP ($) | 6,400 |
| BCWS ($) | 5,333 |
| CV ($) | 400 |
| SV ($) | 1,067 |
| SV (DAYS) | 4 |
| CPI | 0.94 |
| SPI | 1.20 |
| FCV ($) | 1,500 |
| FSV (DAYS) | 15 |

From simple observation, we can tell the following:

The project is 26.7% complete.

The project is ahead of schedule by 4 days (planned to finish 6.67 units in 20 days but finished 8 units).

The project is over budget by \$400 (earned \$6,400 but spent[12] \$6,800). If work continues at the same pace and pattern, the contractor will finish this project 15 days ahead of schedule but with a budget deficit of \$1,500.

Several factors must be taken into consideration when interpreting the preceding numbers. Most importantly, we don't have enough information to explain the variances. It is possible that the contractor is deliberately expediting work and that this is the cause of the cost overrun. It is possible that this extra cost is justifiable to the contractor.

The BCWS represents the baseline schedule and budget. The BCWP represents the "earned value" (i.e., the contractor's earning for work performed, based on the contract price). The ACWP represents the actual costs spent so far.

Both the variances and performance indexes are measures of variances from the baseline. The variances are absolute measures in units of dollars and days. The performance indexes are relative measures in percentages. To "dramatize" the difference between absolute and relative measures, let us consider two activities: the first with a \$100 budget and the second with a \$10,000 budget. If we have a **cost variance (CV)** of −\$25 in *each* activity, the **cost performance index (CPI** for the first is 0.75 (seriously low) and 0.998 for the other (consider it perfect). Contractors strive for a nonnegative cost and schedule variances, and cost and schedule performance indexes at or exceeding 1.0.

In most cases, the forecasted amounts are used to raise a red (or yellow) flag rather than to accurately predict future amounts. For example, in the previous example, the contractor can tell his crew, "We are running \$400 over budget and we are just 27% complete. If we don't do anything about it, we will end up with a \$1,500 deficit." In projects in which a penalty is imposed for finishing late and/or a bonus for finishing early, forecasting can be a key tool for making a decision to accelerate the project.[13] Analysis of the causes for variance is beyond the scope of this book. However, it is important to point out four issues:

1. Minor variances are usually expected and tolerated (although discouraged when negative). Major variances should be investigated.
2. For a negative variance (schedule or cost), it could be an indication of underperformance or unrealistic baseline. For example, labor productivity may have been lower than expected. This could be due to uncontrolled circumstances (whether forgivable or not) or due to underestimation in the baseline. Material prices could have risen unexpectedly, or waste may have

[12] The contractor's overhead and profit are part of the "expenses."

[13] For example, see the see the topic on contractor-created float discussed previously in this chapter.

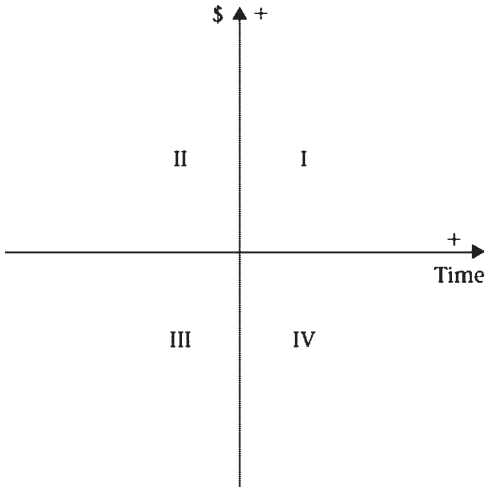



**Figure 7.18 Schedule performance versus budget performance: quadrant I, ahead of schedule and under budget; quadrant II, behind schedule and under budget; quadrant III, behind schedule and over budget; quadrant IV, ahead of schedule but over budget**

taken a larger-than-expected percentage. This causes major concern, especially in fixed-price contracts.

3. A large positive variance may not be a reason for celebration. It may indicate an error or an overestimation in the baseline budget and/or schedule.
4. Schedule performance and budget performance are independent of each other. The contractor may find that he or she is operating under the conditions found in one of the four quadrants shown in Figure 7.18. Quadrant I means the project is ahead of schedule and under budget (where you want to be). Quadrant II gives you bad news (you are behind schedule) and good news (and under budget). Quadrant III is the worst: you are behind schedule and over budget. Quadrant IV is the opposite of quadrant II: you are ahead of schedule but over budget.

Another parameter that was suggested is the cost-schedule index (CSI), which is the product of the cost performance index (CPI) and the schedule performance index (SPI). The main problem with this parameter is the possibility that good performance in one area masks substandard performance in the other. For example, in our previous sample project, the CSI was $0.94 * 1.20 = 1.13$, which is good but misleading.

**Tip Box 7.10**

Earned value can be a valuable tool; however, it is a tool that may or may not be the most suitable for the situation.

### *Earned Value versus CPM*

It is important to note that EV analysis and schedule updating may yield conflicting results. The schedule variance (SV) may be positive, but the schedule update shows that the project is behind, or vice versa. This situation occurs mainly because the EV analysis is cost-driven even for calculating schedule variance, whereas schedule updating focuses on the critical path, without regard to monetary issues. For example, the contractor may get a positive schedule variance in earned value analysis by completing noncritical activities ahead of schedule while the critical path may be behind. CPM still gives the most accurate readings on whether the project is ahead of or behind schedule. Several authors have suggested schedule variance (SV) that is time-based with several approaches[14] Such suggestions are beyond the scope of this book.

### *S Curves*

Earned value (BCWP) and actual cost (ACWP) may be plotted against the baseline (BCWS), as shown in Figure 7.19. Both curves, representing the ACWP and the BCWP, are usually extrapolated to forecast the **estimate at completion** (EAC) and the date of completion.

**EV Analysis at Different Levels** When using the WBS, project managers may look at work at different summary levels.

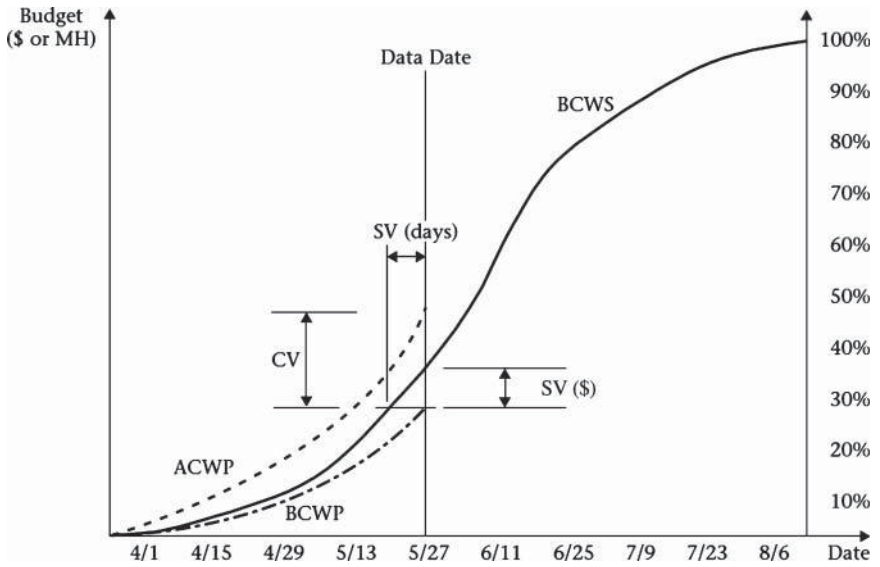



**Figure 7.19 Earned value (budgeted cost for work performed, or BCWP) and actual cost (actual cost for work performed, or ACWP) plotted against the baseline (budgeted cost for work scheduled, or BCWS)**

[14] Warburton and Kanabar (2008), Anbari (2003).

### Example 7.4

The total estimated duration of the mass excavation activities in an office building project is 40 days. After 15 days, the project manager receives the following information:

| Type of Excavation | Task No. | Total Quantity (CY) | Unit Price ($) | Total Budget ($) | Actual CY | Actual Cost ($) |
|---|---|---|---|---|---|---|
| Mass Excavation | TOB11110 | 39,000 | — | 176,500 | 13,200 | 59,700 |
| Common Earth | TOB11111 | 20,000 | 2.50 | 50,000 | 7,800 | 17,950 |
| Clay | TOB11112 | 8,000 | 5.50 | 44,000 | 1,200 | 5,850 |
| Rock | TOB11113 | 11,000 | 7.50 | 82,500 | 4,200 | 35,900 |

Perform an EV analysis. Note that the "Mass Excavation" line is a summary of the 3 lines below.

### Solution

The solution, using the equations given in example 7.2, is tabulated as follows:

| Activity | TOB11110 | TOB11111 | TOB11112 | TOB11113 |
|---|---|---|---|---|
| TOTAL BUDGET ($) | 176,500 | 50,000 | 44,000 | 82,500 |
| % COMPLETE | 32.63 | 39.00 | 15.00 | 38.18 |
| ACWP ($) | 59,700 | 17,950 | 5,850 | 35,900 |
| BCWP ($) | 57,600 | 19,500 | 6,600 | 31,500 |
| BCWS ($) | 66,188 | 18,750 | 16,500 | 30,938 |
| CV ($) | –2,100 | 1,550 | 750 | –4,400 |
| SV ($) | –8,588 | 750 | –9,900 | 562 |
| SV (DAYS) | –1.95 | 0.17 | –2.24 | 0.13 |
| CPI | 0.96 | 1.09 | 1.13 | 0.88 |
| SPI | 0.87 | 1.04 | 0.40 | 1.02 |
| FCV ($) | –6,436 | 3,974 | 5,000 | –11,524 |
| FSV (DAYS) | –5.96 | 0.44 | –14.96 | 0.33 |

In the analysis of the results, we can make the following six comments:

1. Looking at the overall budget, we find that the Mass Excavation operation is slightly ($2,100) over budget. With further investigation, we find that the main reason for this budget overrun is the Rock Excavation, which is $4,400 over budget. In fact the other two excavation activities, Common Earth and Clay, are slightly under budget. This is an example of when above-standard performance masks below-standard

performance. The CPI for Rock Excavation is 0.88 (substantially low), whereas it is 0.96 for the entire operation.

2. When we look at the schedule, the only meaningful number is the overall schedule variance, which tells us that the Mass Excavation operation is almost 2 days behind schedule. Looking at individual schedule variances may be misleading. It is possible that the contractor planned to focus effort on one area at the expense of other areas. In this case, both Common Earth and Rock are on schedule; Clay is behind.
3. Let us consider the Mass Excavation activity as part of the total excavation operation, TOB11100, which includes, in addition to TOB11110 Mass Excavation, TOB11120 Special Excavation, as shown next:

| Work Breakdown Element | Level |
|---|---|
| TOB10000 Tampa Office Building | 1 |
| TOB11000 Substructures | 2 |
| TOB11100 Excavation | 3 |
| TOB11110 Mass Excavation | 4 |
| TOB11111 Common Earth Excavation | 5 |
| TOB11112 Clay Excavation | 5 |
| TOB11113 Rock Excavation | 5 |
| TOB11120 Special Excavation | 4 |
| TOB11121 Confined Areas Excavation | 5 |
| TOB11122 Other Special Excavation | 5 |

If the same subcontractor is in charge of the TOB11120 Special Excavation operation, he may also be concentrating the effort on one operation at the expense of the other (Mass Excavation and Special Excavation). In this case, we will not be able to tell how much the contractor is ahead or behind schedule until we look at the entire excavation operation, TOB11100. In contrast, the cost variance is activity specific and is a true indicator at any level.

4. Looking at forecasted variances indicates that, if work continues at the same pace and in the same pattern, the Mass Excavation operation will finish 6 days behind schedule and with a $6,436 deficit. This situation is certainly a reason for concern for the project management team. The project manager must try to mitigate this outcome.
5. In the WBS shown in comment 3, we have five "levels of control." A typical superintendent or project manager may want to look at earned value at level 4 or even level 5. Someone in upper management may look at level 2 or 3, but if an unsatisfactory number is spotted, he or she may want to go to a lower level, such as level 4 or 5, for the specific

activity with unsatisfactory numbers to pinpoint the trouble source. It is very important to look at EV numbers as part of, but not the entire, picture. They are only indicators and possibly red flags. Once a flag is raised, more information must be collected to explain the substandard results. Once that analysis is done and the source of the problem is identified, a remedy must be prescribed.

6. We can describe activities with negative variance as "substandard performance" as compared with "above-standard performance" for those with positive variances. We do not use the term *bad* or *good* performance because the analysis may show—for an activity with negative cost variance—that the performance was satisfactory but another reason caused the negative variance. The reason could be an unexpected work problem (not caused by the field crew in charge of the activity), an error or unrealistic assumption in the original estimate, or something else. The possibility of poor performance also exists.

## CHAPTER 7 EXERCISES

1. Define *schedule updating*.
2. Why is schedule updating needed for construction projects?
3. Define *project control* and discuss the roles of schedule updating as part of project control.
4. Are the terms *project monitoring* and *project tracking* equivalent to project control? Explain.
5. Why is project control needed in construction projects?
6. What is a baseline schedule? Discuss how to adopt a balanced baseline schedule—one that is not too optimistic and not too pessimistic.
7. What is an updated schedule? What does schedule updating mean?
8. What is the data date? What other names are used for it? Which are inaccurate? Why?
9. What kind of information is needed for updating schedules?
10. How frequent should schedule updating be performed?
11. Why is schedule updating important for progress payments?
12. What does the term *degressing a schedule* mean?
13. When you are updating a project, an activity may be added or deleted. What are the mishaps that may occur, and how do you avoid them?
14. What are the steps involved in updating a schedule?

15. Refer to exercise 4 in Chapter 4. Ten days after the start of the project, the following information is received:

| | |
|---|---|
| Activities A and B | Completed on time |
| Activity C | Started; 3 days left |
| Activity D | Started; 2 days left |
| Activity E | Has not started yet but duration adjusted to 5 days |

Draw the updated network. Calculate the new project completion date. Check if there are changes to the completion date and/or to the critical path. Mention the causes for such changes, if any.

16. Refer to exercise 5 in Chapter 4. Fifteen days after the start of the project, the following information is received:

| | |
|---|---|
| Activity A | Completed 2 days later than planned |
| Activity B | Completed on time |
| Activity C | Started; 4 days left |
| Activity D | Completed; took 5 days to finish |
| Activity E | Completed |
| Activity F | Canceled |
| Activity G | Started 3 days late; project manager hopes to cut 1 day of its duration |
| Activity K | Added: Duration = 4 days. IPA = C |
| Activity L | Added: Duration = 3 days. IPA = K, G |
| Activity I | Adjusted: IPA = L |

Draw the updated network. Calculate the new project completion date. Check if there are changes to the completion date and/or to the critical path. Mention the causes for such changes, if any.

17. Refer to exercise 6 in Chapter 4. Twelve days[15] after the start of the project, the following information is received:

| | |
|---|---|
| Activities A and D | Completed on time |
| Activity B | Completed by end of day 11 |
| Activity C | Started on time; finished 1 day late |
| Activity E | Not started yet |
| Activity F | Duration changed to 7 days |
| Activity G | Canceled |
| Activity I | Started; 1 day left |

A change order was issued with three new activities:

| | |
|---|---|
| Activity N | Duration = 4 days; IPA = None |
| Activity O | Duration = 3 days; IPA = N, H |
| Activity P | Duration = 5 days; IPA = O, L; No successor |

[15] Assume this project is updated biweekly and the crews are working 6 days per week.

Draw the updated network. Calculate the new project completion date. Check if there are changes to the completion date and/or to the critical path. Mention the causes for such changes, if any.

18. "If the logic used in creating this schedule was accurate, there should be no difference between the Retained Logic and Progress Override options." How much do you agree with this statement? Explain.
19. How is project updating tied to pay requests?
20. Explain what is meant by the term *contractor-created float*.
21. Explain the steps usually taken in a monthly update of a schedule.
22. Does the scheduler have to "explain" the results of the update to the project manager? When? Why or why not?
23. During the life of a project, the scheduler receives a lot of feedback on the schedule from different parties, such as the architect, the engineer, the owner, the subcontractors, and others. As a scheduler, how would you take and implement or reject such feedback?
24. Can the critical path in a project change during the life of the project? How can such a thing happen? Give an example.
25. Management must pay attention not only to critical activities but also to near-critical activities. Explain this statement from a practical point of view.
26. List each of the six methods for measuring the work progress of a certain activity. Under what conditions would each be recommended? Give an example for each method.
27. A roofer is working to cover a 2,500-square-foot roof. He must first install rafters, then sheathing, then felt, and finally shingles. He assumes the previous tasks compose 35%, 20%, 15%, and 30% of the total roofing activity, respectively. At a certain point, the roofer gets the following information on the subtasks:

| Subtask | Unit[a] | Total Quantity | Installed Quantity |
|---|---|---|---|
| Rafters | EA | 150 | 102 |
| Sheathing | SF | 2,720 | 1,200 |
| Felt | SQ | 27.2 | 10 |
| Shingles | SQ | 27.2 | 5 |

[a]EA = each; SF = square feet. SQ (square), is 100 square feet; a unit used mostly in roofing jobs.

Calculate the estimated percent complete for the roofing activity.

28. Which method of measuring work progress is suitable for each of the following activities?

    a. Laying bricks for an exterior wall
    b. Safety inspection

c. Installation of a furnace
d. Project supervision
e. Multiple reinforced concrete footings
f. Setting up a patented formwork system for a wall
g. Hydration of a concrete slab on a grade (assume a small slab)
h. Fishing[16] an electric wire for an entire floor
i. Excavation of earth (assume one type of soil)
j. Excavation of earth (assume several types of soil)
k. Dewatering
l. Installing ceramic tile for a large area (involves a few subactivities)

29. When you are calculating the percent complete for an entire project, more than one answer might be possible. The project manager says the percent complete is about 60%, the cost engineer says it is 65%, the computer program says it is 57%, and the owner says it should be 50% (according to her representative's feedback). You calculate it on the basis of how much time has elapsed and how much time is given in the contract; your result is 70%. Can you explain these confusing and "conflicting" numbers?
30. On the basis of the information given in the previous exercise, do you think the project is in trouble (with regard to the budget and the schedule)? How did you conclude this?
31. Explain the procedure for initiating and processing pay requests.
32. This exercise is for persons who use Oracle Primavera P6 software: you created a project without feeding the program any budget or resources information. After the first update, the scheduling report says the project is 16.7% complete. Do you know how the program determined this number? How accurate is this number?
33. The EV analysis involves comparing what happened with what should have happened. Explain this statement with regard to both the budget and the schedule.
34. A mason contracted with a general contractor to build an exterior wall from 8-inch CMUs. The wall is 82 feet long and 8 feet high.[17] The mason must finish the wall in 3 days and gets paid $4 per block. At the end of day 1, the mason has installed 220 blocks. Her actual cost (including overhead and profit) is $836. Analyze the situation with regard to both the budget and the schedule.
35. Draw the S curve for the masonry job in the previous exercise.

[16] To run an electric wire through a conduit by using resilient "fish tape" or a "snake."

[17] Do not forget the CMU face dimension (including the mortar joint): 8 inches by 16 inches.

36. A flooring subcontractor must install three types of flooring in an existing building:

| Type | Quantity (SF)[a] | Unit Price ($/SF) | Total Price ($) |
|---|---|---|---|
| Carpet | 2,600 | 2.30 | 5,980 |
| Vinyl tile | 1,200 | 2.95 | 3,540 |
| Ceramic tile | 3,330 | 4.95 | 16,484 |
| Total | 7,130 | | 26,004 |

[a]Carpet is usually sold and installed by the square yard. We used square foot (SF) here for conformity with the other flooring types.

The subcontractor is given 10 days to finish all the work. Assume he has crews to start all three jobs concurrently. Four days after the start of the work, he discovers the following:

| Type | Quantity Installed (SF) | Actual Cost ($) |
|---|---|---|
| Carpet | 1,500 | 3,150 |
| Vinyl tile | 800 | 2,488 |
| Ceramic tile | 750 | 3,638 |

Perform an EV analysis of the preceding task:

a. Analyze each subtask (carpet, vinyl tile, ceramic tile) individually; determine its status with regard to the budget and the schedule.
b. Analyze the entire flooring activity as one unit; determine its status with regard to the budget and the schedule.
c. How do you combine the answers for parts A and B?
d. On the basis of performance so far, do you believe the subcontractor will finish the job on time? Within budget? Justify your answer.
e. Draw the S curve for the entire task.

Chapter 8

# Schedule Compression and Time-Cost Trade-Off



West Orange High School, Winter Garden, Florida

*On January 17, 1994, a 6.7-magnitude earthquake caused heavy damage and many casualties in Northridge, California. The immediate major concern for Caltrans (the California Department of Transportation) was reopening the public highways in one of the busiest areas in the United States.*[1] *Part of the damaged highways was two sections of Interstate 10 in Santa Monica. C. C. Meyers, Inc., of Rancho Cordova, California, was awarded the contract to repair these sections. C. C. Meyers' bid of $14.7 million was significantly less than the Caltrans engineer's $22.3 million estimate. The contract gave the contractor 140 days to finish the project and included a* ***liquidated damages***[2] *clause of $200,000 for each day of delay and a similar bonus amount for each day finished early. The contractor finished the project in only 66 days, 74 days ahead of the stipulated deadline. This early finish was possible because the project was fast-tracked. In addition, C. C. Meyers worked around the clock, putting large amounts of resources into the project, making this project the focus of the company. Excellent cooperation between Caltrans and the contractor also helped. Caltrans did its part to help push the project, assigning 10 engineers on the day shift and 4 on call at night to inspect work and answer questions.*

*In the process of expediting the schedule, C. C. Meyers may have gone over the original budget, but with about a $14.8 million bonus, the company was certainly ahead of the game. Despite the large bonus paid, Caltrans seemed pleased with the results. The public's convenience was well worth the effort and the money. Caltrans and C. C. Meyers both believe that despite the schedule compression, work quality was not compromised.*

## INTRODUCTION

Construction projects almost always have finish deadlines assigned by the owner and stipulated in the contract. Some of these projects have strict deadlines that do not allow for any slippage. An example of such a project is the facilities built for the Olympic Games or international exhibits or conferences. Any slippage in the schedule in such a case could literally mean a disaster: an international embarrassment and a loss of large sums of money. Other, mostly public, projects have strict deadlines because of the interest of, or convenience to, the general public. An example is a highway, a school, or a water treatment plant. Any delay in such a project might not be assessed by a monetary amount; however, the consequences would still be severe. Other projects might have deadlines that are rigid, but a slippage would not result in such disastrous outcomes. An example of such projects is a hotel or a shopping center for a certain tourist or shopping season. Finishing late in this case would mean a loss of revenue for the season. Still other projects, not tied to a specific event or season, might have "normal" finish dates, which would mean that the contractor could work at a "normal" pace. In most cases, a normal schedule means 5 days per week, 8 hours a day, but the schedule depends on the contract. Slipping a few days or weeks in this case may be acceptable to the owner and may not cause serious consequences.

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[1] The next major concern for Caltrans was retrofitting bridges and other structures to be earthquake resistant.

[2] *Liquidated damages* are a stipulation in a contract of a monetary amount that must be paid by the contractor if the contractor fails to satisfactorily complete the project by the contract finish date. They are discussed in more detail in Chapter 13.

For all of these types of projects, the contract may or may not contain a liquidated damages clause. The damages usually include an estimated loss of revenue as a result of a delay and may include **punitive damages**. Punitive damages are difficult to recover in court, especially in the case of a mere breach of contract. To recover punitive damages (also called **exemplary damages**), the owner must prove that the breach was committed maliciously or that an intentional tort or another illegal or wrongful act, such as fraud, was committed (Wickwire, Driscoll, and Hurlbut, 2009, §11.19).

## SETTING PRIORITIES

Finishing on—or ahead of—schedule is an important objective of the contractor and the owner. Finishing on—or under—budget is another important objective. Achieving these two objectives simultaneously is desirable and usually possible, but often the contractor must rank them in order of importance: one above the other. As is shown later in this chapter, the project manager may, at a certain point, be faced with a situation in which shortening the duration costs more money. At this point, a decision must be made between two alternatives:

1. Do not shorten the duration further and keep the cost to a minimum.
2. Keep compressing the schedule, even though the cost will continue to rise.

**Tip Box 8.1**

It is true that time and cost are very important; however, one must be more important than the other. You make the decision!

## ACCELERATING A PROJECT

### What Is "Accelerating" a Project?

**Accelerating a project** means shortening the normal duration of the project schedule without reducing the original scope of work (also called **schedule compression**). It does not necessarily mean aiming for the shortest possible duration. The term *compressing the schedule* is synonymous and is used throughout this book. The term **schedule crashing** is generally used to indicate maximum acceleration, although it is sometimes used in lieu of accelerating.

### Why Accelerate a Project?

A contractor may want to accelerate a schedule for one or more of several reasons, such as the following:

1. The contractor's "normal" calculated finish date in the planned schedule does not meet the imposed finish date in the contract. The contractor usually knows this situation before starting construction or, sometimes, even before bidding. In many cases, the owner requires the contractor to submit a construction (critical path method, or CPM) schedule that shows a satisfactory finish date. Many government agencies even require the contractor to use a specific scheduling software program.
2. After starting construction and completing a certain percentage of the project, the contractor realizes that the project is behind schedule. He or she needs to accelerate the remainder of the schedule in order to make up for lost time and to avoid finishing late (referred to as **recovery schedule**). In many contracts, penalties (mostly liquidated damages) may be levied on the contractor for a late finish. In some cases, this acceleration is requested by the owner even though the delay was not caused by the contractor. In such case, the owner may be responsible for the extra cost of the acceleration.
3. In some cases, the contractor may have a contractual monetary incentive to finish ahead of schedule. The case study mentioned at the beginning of this chapter is an example.
4. Sometimes, especially when the economy is doing well, finishing early means, to the contractor, starting another project earlier and, thus, making more profit. In many cases, the contractor knows the date when he or she is supposed to mobilize to the next project. This may require the contractor to compress the current project in order to free certain resources so that they can be reallocated to the new project.
5. To a certain extent, accelerating a project may prove profitable to the contractor, as is discussed subsequently.

Acceleration can be planned before the start of a project, as in points 1 and 3 and possibly 4 and 5. In other cases, it is not planned, but at some point during construction, the work situation necessitates it.

#### How Can the Duration of a Project Be Shortened?

Construction projects may take more or less time than planned (usually more rather than less) for reasons that may be within or beyond the contractor's control. Reasons beyond the contractor's control, such as *force majeure*, differing site conditions, and change orders, draw time extensions from the owner in most cases. These situations are not discussed in this chapter. Instead, our discussion is restricted to the ways in which the contractor can influence the duration of the project. The Construction Industry Institute (1988a) has suggested more than 90 techniques for schedule compression. It further has classified them by project phase or function:

I. Ideas applicable to all phases of a project
II. Engineering phase

III. Contractual approach
IV. Scheduling
V. Materials management
VI. Construction work management
VII. Field labor management
VIII. Start-up phase

A review of these techniques underscores the importance of early planning. For some projects, the decision to compress the schedule may be made during the construction phase. Other projects, such as the Northridge case study, are carefully planned from the moment the project is conceived through completion.

The author suggests 10 techniques (not in any particular order):

1. *Revisit or study the schedule thoroughly to find any errors or unnecessary logic or constraints*: The most common pitfall is using the finish-to-start (FS) relationship when a start-to-start (SS) relationship with a reasonable lag can work. For example, suppose that the logic is that activity B in Figure 8.1a cannot start until activity A is finished (i.e., day 10). After checking the situation, we find that activity B can start only after a certain portion of activity A is finished (e.g., 40%). In this case (Figure 8.1b), activity B can start as early as day 4, which saves 6 days. If you prefer to use only FS relationships, then split the predecessor into two or more activities (a detailed discussion can be found in Chapter 5).
2. *Fast-track the project (as mentioned in Chapter 5)*: *Fast-tracking* means starting construction before the design is completely finished. Conceptual design must first be done; the detailed design follows in stages. The construction of each phase (or component) follows the detailed design of the phase while the next phase is being designed (see Figure 8.2). The decision for this option has to be made very early during the project's conception and requires a special agreement/contract between the owner, the designer, and the contractor. There is a good possibility that with this option, the contract is design/build, which means that the owner signs a contract with only one entity for both design and construction services. Fast-tracking has its disadvantages as well, especially when it is not well planned.

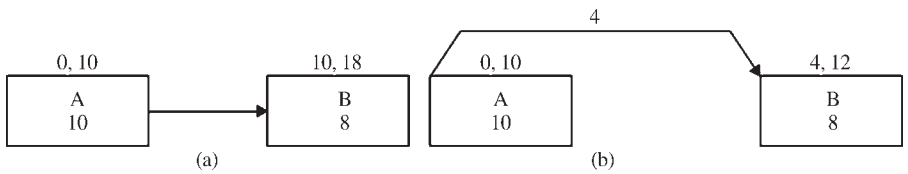



**Figure 8.1 Time savings difference between (a) finish-to-start (FS) and (b) start-to-start (SS) relationships**

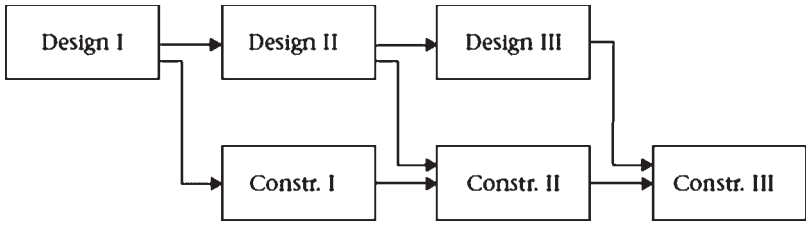



**Figure 8.2 Fast-tracking**

3. *Conduct value engineering and constructability studies*: **value engineering (VE)** has been defined as "an analysis and comparison of cost versus value of building materials, equipment, and systems. VE considers the initial cost of construction, coupled with the estimated cost of maintenance, energy use, life expectancy, and replacement cost." (RSMeans, 2010a). In the bigger context, SAVE International defines *value management (VM)* as "a systematic and structured approach to improve projects, products, and processes. VM is used to analyze manufacturing products and processes, design and construction projects, and business and administrative processes. VM helps to achieve a balance between required functions, performance, quality, safety, and scope with the cost and other resources necessary to accomplish those requirements. The proper balance results in the maximum value for the project, where Value = Function/Cost."[3]

   **Constructability** has been defined as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (Construction Industry Institute 1986a, p. 2)[4]. The *Means Illustrated Construction Dictionary* (RSMeans, 2010a) defines *constructability review* as "the practice of peer reviewing the plans and specifications prior to issuing for bid with the intent of correcting errors, omissions, inconsistencies or discrepancies." The Institution of Professional Engineers New Zealand (IPENZ) defines it as project management technique to review construction processes from start to finish during the preconstruction phase. It helps to identify obstacles before a project is actually built in order to reduce or prevent errors, delays, and cost overruns.[5] It is also called *buildability*.

   Although there is an overlap between value engineering and constructability, there are two main differences between them. First, VE is considered an

[3] http://www.value-eng.org/value_engineering.php

[4] *Wikipedia* online defines it as "a project management technique to review construction processes from start to finish during preconstruction phase. It is to identify obstacles before a project is actually built to reduce or prevent error, delays, and cost overrun."

[5] http://www.ipenz.org.nz/ipenz/forms/pdfs/PN13_Constructability.pdf

optimization study, answering the question, "Is it fit or overfit?" whereas constructability is mostly a feasibility study, identifying obstacles and clashes during the construction process. Second, VE covers the entire life cycle of the facility, whereas constructability focuses on the construction phase only. In both, the participation of all involved parties is encouraged, and the earlier the study is conducted, the better results should be expected. VE and constructability can coexist and even complement each other (Construction Industry Institute, 1993).[6]

Contracts often include a reward clause for contractors who submit creative suggestions. In such clauses, the savings are usually split between the owner and the contractor.

Detecting and removing/managing obstacles and clashes, and improving the design and construction efficiency will most likely help the acceleration effort.

4. *Utilizing **Building Information Modeling (BIM)***: The use of BIM in construction projects with lean construction principles has proven to be effective in saving time and money, improving efficiency and safety, and helping to achieve better results in general. BIM helps "simulate" and visualize the building process before construction takes place, to detect clashes and help improve cost, time, productivity, safety, and other aspects of the project (see Chapter 15 for more details), and lean construction principles increase value, minimize waste, enhance profitability and quality, and ensure client satisfaction.

5. *Work overtime—more hours per day and/or more days per week*: The results of some studies suggest that productivity declines with more hours worked per week than the basic 40 hours. The Business Roundtable[7] (1980) suggested an immediate, significant drop (week 1, as a result of the initial pattern change), followed by a partial recovery (weeks 2 and 3, when the person starts to adapt to the overtime schedule), and then a gradual, slight decline (weeks 4 through 9, as a result of work fatigue), and finally a leveling off (after weeks 9 or 10) (see Figure 8.3). *RSMeans Building Construction Cost Data* (RSMeans, 2010b) showed a more "linear" approach. It gave declining productivity numbers from week 1 to week 4. For example, for 6 days per week and 10 hours per day, productivity was assumed to be 95%, 90%, 85%, and 80% for weeks 1 through 4, respectively. Some researchers (Larew, 1998) questioned the reliability of these overtime studies.

   As far as cost, overtime pay is almost always more than regular pay. If the workers have a union contract, overtime is compensated according to the collective bargaining agreement between the contractor and the labor union. In most construction contracts, hours exceeding 40 per week and any hours on Saturday are compensated at 1.5 times the regular rate. Other hours, possibly

[6] You may also want to refer to the summary in two Construction Industry Institute reports (1986, 1987).

[7] Now The Construction Users Roundtable (CURT).

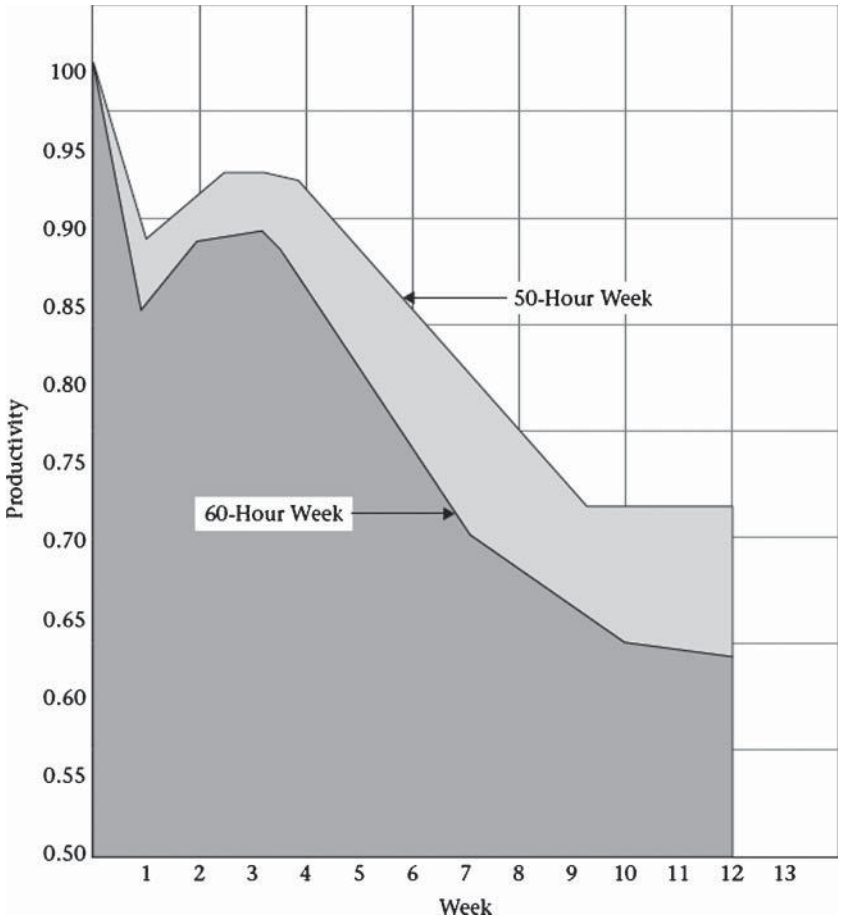



**Figure 8.3 Cumulative effect of overtime on productivity (50- and 60-hour workweeks). (From The Business Roundtable, *Scheduled Overtime Effect on Construction Projects* [New York: The Business Roundtable, November 1980], Report C-2, p. 10. Reproduced by permission from The Construction Users Roundtable [CURT; formerly the Construction Committee of The Business Roundtable]**

Sunday and night hours, may be compensated at double the regular rate. If the project involves open-shop labor, overtime pay depends on the contractor's company policy but is always subject to government regulations. For hourly workers, hours in excess of 40 per week almost always cost more than regular hours. In contrast, salaried employees may not receive overtime compensation.

The Business Roundtable (1980) studied the combined effects of reduced productivity and increased costs resulting from overtime. The curves in Figure 8.4 show these effects. In general, the author does not recommend overtime as a long-term policy.

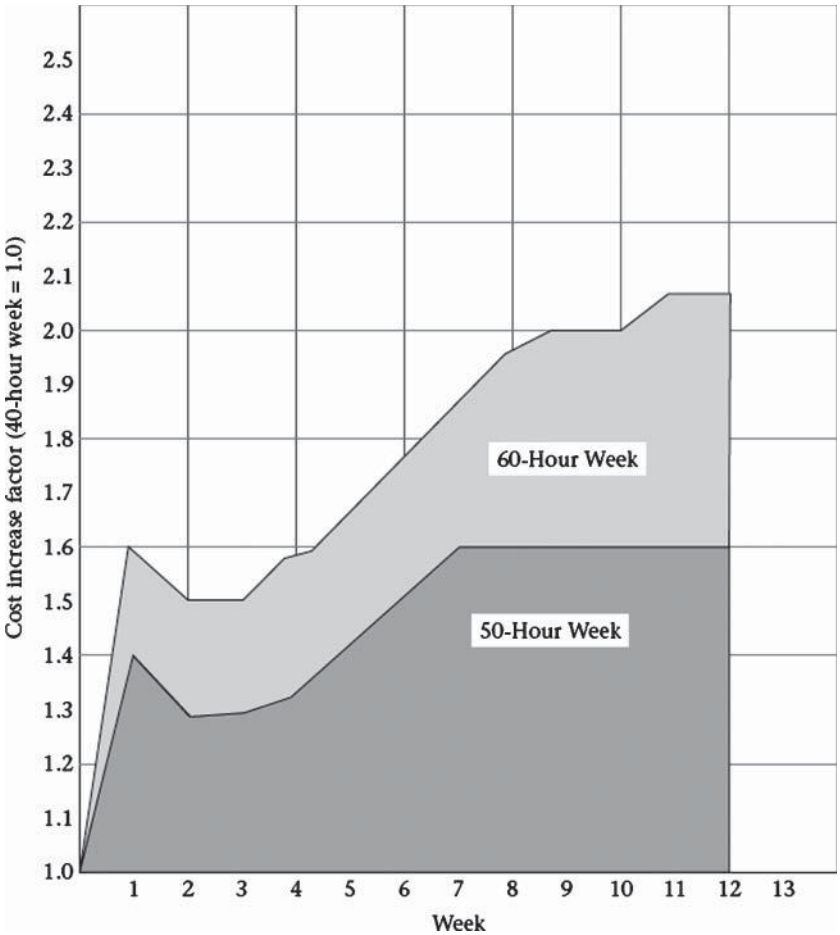



**Figure 8.4 Cumulative cost of overtime successive weeks' productivity loss overtime premiums. (From The Business Roundtable, *Scheduled Overtime Effect on Construction Projects* [New York: The Business Roundtable, November 1980], Report C-2, p. 11. Reproduced by permission from The Construction Users Roundtable [CURT; formerly the Construction Committee of The Business Roundtable]**

6. *Offer incentives to workers or crews for improving productivity*: The contractor usually has an incentive to compress the schedule, such as avoiding a penalty or earning a bonus. Workers do not directly pay the fine or get the contract bonus. The contractor must offer them an "internal" incentive, which could be more symbolic (a plaque, certificate, party, baseball cap, bomber jacket, T-shirt, coffee mug, etc.), monetary compensation, paid vacation, or a combination of these.
7. *Acquire more workers*: This may mean adding more workers to the current workforce and/or hiring workers for a second and possibly a third shift.

Usually, the number of workers and the amount of equipment allowed on-site are limited. Saturating the job site may lead to site congestion that could adversely affect productivity and safety, which would defeat the purpose of acquiring more workers and equipment. When hiring additional workers for more shifts, a turnover time will have to be taken into consideration. If workers are working on multiple shifts, the worker will need some time to identify the work elements and status when starting. Supervisors must ensure work consistency and that all shifts conform to the same standards. Several factors must be balanced in this regard: the cost of the "extra" resources, the cost of not having these resources when needed, and the consideration of what to do with the extra resources after the peak need ends.

8. *Acquire special materials and/or equipment that help speed up the work process*: This may be as simple as adding accelerating agents to the concrete mix or as major as adding a tower crane. Difficult decisions may have to be made in this regard—mainly, justifying the cost of such materials and equipment. In some instances, automation and/or using preengineered or manufactured assemblies results in a reduction in the number of workers as well as an increase in production (see the next section, "Construction versus Manufacturing").
9. *Improve project management or supervision*: In some cases, the contractor may recognize a problem with the project team. There could be an "authority battle" between the project manager (leaning toward pure project organization) and the main office (preferring functional organization). Having everyone on the same page is extremely vital for the success of the project. Replacing the project manager or superintendent in the middle of the job is not an easy decision. However, under certain circumstances, doing so may be less of an evil than keeping the status quo.
10. *Improve communications among parties, particularly during the submittal process*: Sometimes a structural subcontractor may have an inquiry about a structural detail. The contract stipulates a chain of command requiring the subcontractor to submit his **request for information (RFI)** to the general contractor, who sends it to the architect, who in turn forwards it to the structural engineer. The response then must come back in reverse order across the same chain. Many contracts allow the subcontractor to send an RFI directly to the structural engineer (or whoever the responsible party is) but requires the subcontractor to send copies to the contractual parties (the general contractor and the architect). The structural engineer, in turn, can answer the structural subcontractor directly but must also copy the architect and the general contractor.

    With advances in technology, the process of reviewing and approving drawings has become faster than before. Some companies handle the process online by uploading their drawings to a (usually exclusive) private Web site. All parties are informed by e-mail about the new drawings and/or documents. In many cases, the review can take place online as well. The entire process can

be completed in a few hours rather than several days with a high accompanying delivery cost. Management software also speeds up the RFI process if all parties have immediate access to the software.[8]

The author also suggests using *optimum scheduling* (discussed later in this chapter), a concept that, when applicable, can result is time saving, among other potential benefits.

The earlier the need to accelerate the schedule is known, the more options the contractor will have and the lower the cost may be.

## CONSTRUCTION VERSUS MANUFACTURING

The term *construction* has more to do with the process than the final product. For example, making mobile homes and trailers falls technically under the manufacturing industry, not the construction industry. Construction is a process that takes place primarily on the project site where the final product will reside, even if there are parts of the project that are premanufactured or preassembled somewhere else. Manufacturing takes place in a plant, and then products are shipped to where they will be permanently installed. However, the combination of construction and manufacturing is possible and often done. For example, modular units and precast concrete members are manufactured products that are frequently used in construction.

The extent of use of such manufactured products depends on many factors, such as feasibility, economics, quality, and logistics. For example, a floating platform for an oil rig may be completely manufactured on land and then transported and installed in the desired location. Modular units are used sometimes either for economics or for speed of construction in areas of extreme weather. The manufactured products are prepared in advance and are then delivered and installed (constructed) during the limited period of good weather.

Manufactured products have a number of advantages by working under controlled conditions. Control of adverse weather conditions allows work to continue indoors without concern about weather. Use of assembly line techniques speeds up the construction of components by allowing safe, efficient processes to be performed repeatedly with less knowledgeable labor. Jigs and templates allow for the construction of components to be achieved in the most advantageous conditions, such as building walls on a convenient platform with carpenters on each end. Lighting conditions and convenient power and power tools allow the workers to work with increased safety and improved efficiency. The advantages improve the efficiency of the overall manufacturing operation, reduce the costs, and shorten the time to completion.

The use of manufactured products also poses some challenges, mainly, transportation and installation. These products have to be designed to withstand not only service

[8] Most project management software packages provide access to users on the company's server, with the possibility of providing limited access through the Internet.

loads but also transportation and installation loads. Their size and weight may also make the transportation, handling, and delivery a challenge. Overall, the designer has to weigh all factors to balance the objective with all constraints (time, cost, quality, etc.).

When projects have to be accelerated, it may make more sense to use manufactured or preassembled products, especially in the case of multiple items. Such items (e.g., modular units) are manufactured under plant automation, allowing faster and better production, while quality is better controlled and they are transported to the project location and installed professionally. The extent of use of such manufactured products is a matter of balance of time and cost, and this varies from one project to another.

### How Does Accelerating a Project Work?

The duration of the entire project is equal to the duration of the critical path. Thus, to shorten the duration of the entire project, we must shorten the duration of the critical path. Let us consider a project that has eight paths (whether dependent—for example, they share some activities—or independent), as shown in Figure 8.5. Path 4 is the critical path, with a duration of 27 days. To accelerate the project, we would do the following:

1. We start accelerating the project by shortening the longest (critical) path (i.e., path 4).
2. To shorten the duration of a path, we cut the duration of one or more activities on the path. As a rule of thumb, we choose the activity with the least acceleration cost.

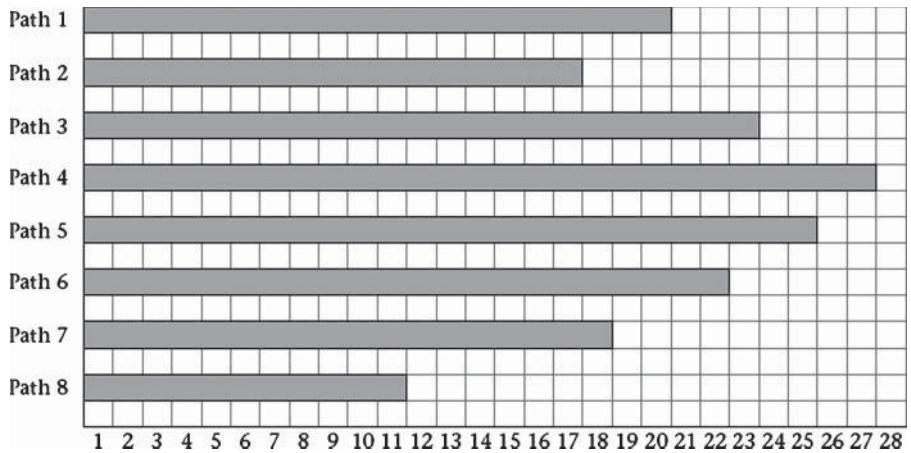



**Figure 8.5 Project with eight paths**

3. We accelerate path 4 by 2 days (we may have to do so in two steps—one day at a time—or we may be able to do so in one step; this point is explained later). Now, the duration of the project is 25 days.
4. If the shortened activity falls on more than one path, all of the paths with the activity will also be shortened.
5. Assuming that the shortened activity is not on path 5, we now have two paths with 25 days' duration: paths 4 and path 5. To accelerate the project further, we must shorten *both* paths. If the two paths share one or more activities, cutting the duration of a shared activity will shorten both paths. Otherwise, we must cut the duration of an activity on *each* path. We cut 2 days from each path. Now, the duration of the project is 23 days.
6. Three paths are now tied as the longest: paths 3, 4, and 5. We repeat step 5 for these paths in order to cut 1 day from each path and subsequently cut 1 day from the duration of the project. The duration is now 22 days.
7. Note again that when we cut the duration of an activity, several paths may be affected. For example, if we cut an activity that is on both paths 4 and 2, path 2 is now cut unintentionally from 17 days to 16 days.
8. Path 6 has now "joined the club" and become critical. We repeat step 6.
9. Clearly, the further we accelerate the project, the more paths must be shortened and the more activities must be involved. Consequently, we may need to compress six or seven activities to cut only 1 day from the project duration. This fact is why the direct cost of accelerating is not linear (although it may be linear for short intervals).

It is interesting to note that an increase in the duration of the critical path by $x$ days will result in an increase in the duration of the project by $x$ days as well. However, the reverse is not necessarily true. A decrease in the duration of the critical path by $x$ days will result in a decrease in the duration of the project by $y$ days, where

$$0 > y \leq x$$

So, if we have a project with the critical (longest) path = 150 days and we cut this path to 144 days ($x = 6$ days) but we find that the project duration = 146 days (then $y = 4$ days), the explanation for this is that there is another path with duration = 146 days, and it has become the new critical path. We need to:

a. Keep what we did to the original critical path but also cut the new critical path by two days, or
b. Reverse what we did and cut the original critical path by only 4 days and then deal with the new situation (two critical paths) on the basis of the steps discussed earlier. We may find an activity that both paths share, and it may be easier and less costly to crash this activity.

## DIRECT AND INDIRECT COSTS

A contractor's main expenses are as follows:

I. **Direct costs**

A. *Labor*, particularly hourly workers, for whom a labor expense can be directly linked to a particular work item

B. *Materials*, such as concrete, rebar, bricks, lumber, nails, paint, drywall, carpet, structural steel, and *installed equipment*, such as elevators, air-conditioning units, and kitchen equipment

C. *Equipment*, mainly construction equipment (bulldozers, excavators, cranes, concrete pumps, etc.)[9]

D. *Subcontractors* (even though subcontractors' charges comprise labor, materials, equipment, overhead, and possibly sub-subcontractors, the general contractor treats these charges as a direct cost)

E. *Other costs*, such as government permits and fees, and fees for lawyers and consultants hired for a specific task in a project

II. **Indirect costs**

A. Project overhead (or **job overhead**), such as the following:

1. Project staff (project manager, project superintendent, project engineer, receptionist or secretary, clerk, etc.)
2. Office trailer and other temporary structures
3. Cars and trucks assigned to the project team
4. Office equipment (copying machine, fax machine, computers, etc.)
5. Temporary utilities (electricity, water, drinking water and ice, telephones, cell phones, gas, portable toilets, etc.)
6. Other indirect project-related expenses, such as power generators and projectors used to provide light during night working hours.

B. **General overhead**, such as the following:

1. Main office expenses (rent, lease, maintenance, utilities, etc.)
2. Main office personnel

[9] If a power generator was installed as a permanent part of the building, it counts as materials. If a power generator was used to provide power for construction work only, such as night lighting, it counts as equipment. Construction professionals in the United Kingdom call all equipment used in the construction *plant* to make a clear distinction from installed equipment.

3. Main office equipment and vehicles
4. Main office services, such as lawyers and accountants (not working exclusively for a specific project)
5. Other main office expenses, such as advertising and charity contributions

C. *Profit* (usually estimated by the contractor before he or she takes on the project; it usually ranges between 5 and 10%, although it can and does occur outside this range; the profit percentage depends on many project-specific factors, prevailing economic conditions, and the contractor's financial status). The term *profit* has been given many definitions, but this author's preferred definition is "return for taking risk"; thus, the profit amount (or percentage) is usually proportional to the risk taken.

D. **Contingency fees** (an additional sum of money allocated for the unknown events that will most likely occur during the life of the project; they are directly proportional to the risk taken in the project)

The main criterion for differentiating between direct and indirect expenses is that a direct-expense item must be directly linked to a specific work item. For example, if you pay someone to set up concrete forms for a shear wall, the expense is direct. If you pay a security guard to look after the project, the expense is indirect because it is not related to a specific work item. The same simple rule applies to differentiating between project overhead and general overhead. Any overhead expense directly linked to one specific project (or several but not all) is project (job) overhead; otherwise, it is general overhead. General overhead is usually distributed among all projects in proportion to their cost and duration. In some cases, certain overhead expenses are shared by multiple, but not all, projects that are undertaken by a specific contractor. For example, a scheduler or a safety officer in a company may be assigned to two or three projects of the many projects on which the company is working. This cost must be treated as job overhead and divided between the two or three projects.

### Cost Concepts as They Relate to Schedule Compression

As the schedule is compressed, the direct and indirect costs will be impacted in a different and opposite manner. Let us start with what we define as the normal duration and the normal cost for a project. Although the term *normal* may be vague and may be interpreted differently by different people, we define **normal duration** as *the amount of time required to finish the project under ordinary circumstances without any deliberate acceleration or deceleration*. **Normal cost** is *the cost of a project that is performed within the normal duration*. These definitions also apply to individual activities.

### How to Choose the Best Method for Project Acceleration

Using accelerating methods that incur minimal cost (or have the lowest cost-benefit ratio) generally makes sense. Let us consider some of the different methods.

Overtime costs more per hour and, according to the studies mentioned previously, might contribute to lower productivity. This fact does not automatically disqualify overtime as a means of accelerating projects. However, all of the pros and cons should be considered before a decision is made to use this method.

Acquiring more workers and equipment may lead to site congestion and less efficiency. In addition, it may create a problem for the human resources and equipment departments: what to do with excess resources after the peak need ends.Hiring a second and possibly a third shift may lead to more turnover time, result in more communication problems, and require more careful management coordination. Extended work hours, because of the second and possibly the third shifts, may require artificial lighting or special nighttime arrangements (e.g., services and security). In addition, second and third shifts may also create a problem for the human resources department: again, what to do with them after the peak need ends.

Acquiring special materials or more efficient equipment must be evaluated on its merits on a case-by-case basis. Such acquisition almost always costs more, but the contractor must look at the cost-benefit ratio and other related factors (e.g., public relations, customer satisfaction, and long-term impact). A classic case is when the contractor owns expensive equipment (e.g., an excavator) that is not the most efficient for the job. He or she is faced with the decision to use it, even though it is not the most efficient for the job, or to acquire a more efficient piece of equipment at an extra cost. The market is full of materials, equipment, tools, software, and other gadgets that supposedly make work simpler, faster, or more efficient. All of these products come with a cost that may or may not be justified.

**Tip Box 8.2**

Project acceleration is a science. It is *not* the random accumulation of resources on the job site!

#### Effect of Acceleration on Direct Costs

As explained previously, direct costs almost always increase during project acceleration. However, the more we accelerate, the more the cost of accelerating per day increases. There are two reasons for this phenomenon:

1. At the activity level, accelerating becomes more difficult and may require different and more expensive techniques. Consider a CIP (cast-in-place) concrete suspended slab activity. Its normal duration is 12 days, but we want to compress it to 6 days. Assume that this activity includes setting up the formwork, placing the rebar, placing (pouring) the concrete, finishing the slab, stripping down the forms and reshoring, and removing the reshores. Compressing the schedule from 12 days to 11 days may be achieved with a simple and inexpensive adjustment, such as having a special concrete mix (with accelerators)

or having the laborers work 10 hours per day (but no work on Saturdays and Sundays). If overtime hours are compensated at 1.5 times the regular rate, workers will work 10 hours per day but get paid for 8 * 1 (straight time) + 2 * 1.5 (overtime) hours, or 11 hours. The increase in labor cost will be 10% (we ignored the effect of overtime on productivity). Going from 11 days to 10 days may require working on Saturdays (at 1.5 times the regular pay). The increase in labor cost will be 17%[10] (we again ignore the effect of overtime on productivity). To accelerate the schedule more, we may have to change the method of placement (pumping in lieu of using a crane and bucket) or acquire a different formwork system. In other words, when we start accelerating, we may have many options, and we select those that are the least expensive. As we accelerate, we run out of inexpensive options, and we may be left with only those that are expensive. At the entire project level (or, rather, the critical path level), we may have many activities from which to choose. We always choose the activity that has the least cost for crashing. As accelerating progresses, we may have fewer and more expensive choices. Also, as demonstrated previously, in the early stages of acceleration, the compression of one activity may result in the compression of the entire project. In later stages, when multiple paths are tied as critical, we may need to compress several activities (each on a different path) to reduce the project duration by only one day.

For the preceding two reasons, direct costs usually increase nonlinearly (at an increasing rate), as shown by the curve in Figure 8.6. Note that the *x*-axis represents the total duration of the project in days. For this reason, as we accelerate the project, we move from right to left on the *x*-axis.

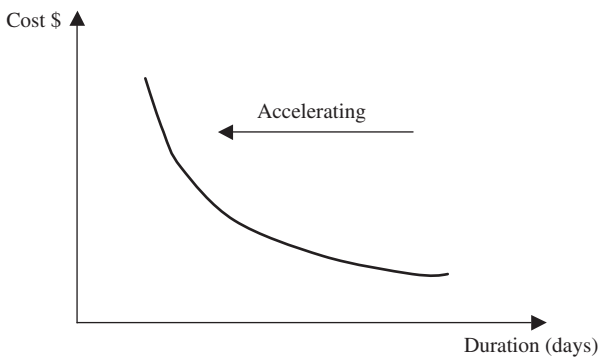



**Figure 8.6 Nonlinear increase in direct costs with project acceleration**

[10] In a typical 10-hours-per-day, 6-days-per-week situation, the worker works 60 hours, 20 of which are overtime. If overtime is compensated at 1.5 times the normal rate, the worker will receive 70 hours' worth of pay for the 60 hours' work. The additional pay ratio is 70/60 * 100% = 116.7%.2.

### Effect of Acceleration on Indirect Costs

Indirect costs include mainly overhead items, such as the job trailer, equipment in the trailer (copier, fax, etc.), utilities, staff members (salaried employees, not hourly workers), and insurance. These expenses are directly and linearly proportional to the duration, so when the project is being accelerated, they decrease at a constant rate, as shown in Figure 8.7.

This constancy is true with minor acceleration techniques; however, it may not stay constant with more aggressive acceleration techniques. With significantly more workers and/or a second shift, the office may need more staff and equipment, its utilities bills will increase, and there may be a need for night lighting. For simplicity, the scheduler can either keep the assumption of constancy with minor negligible error or assume that the overhead expenses will stay constant to a point and then increase to a certain amount (per day) but remain constant from that point to end of the project. This can divide the duration into two or more periods of constant overhead expenses per day; for example, if the normal duration is 225 days:

- $200/day from 225–215 days
- $250/day from 214–200 days
- $300/day if duration is less than 200 days

### Effect of Acceleration on Total Cost

Depending on the shape, slope, and real values, when we combine the curves for direct and indirect costs, we obtain a curve like that shown in Figure 8.8.

We begin with the normal duration and the normal cost. Then we start accelerating. At the beginning, the total cost starts decreasing at a decreasing rate (because the increase in direct cost starts smaller than the savings in indirect cost per day). However, as we accelerate more, the direct cost increase per day will reach a certain point and then exceed the constant savings from indirect cost. At that point, when the two amounts (increase of direct cost and decrease in indirect cost) are equal, we have the **least cost (LC)**, with a corresponding **least-cost duration (LCD)**. If cost is our priority, we must stop at this point. As we accelerate further, the total cost

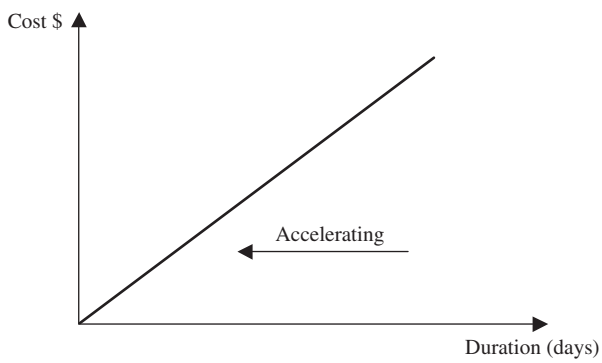



**Figure 8.7 Linear decrease in indirect costs with project acceleration**

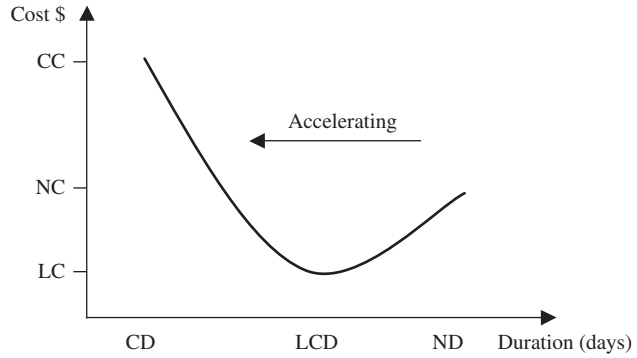



**Figure 8.8 Effect of project acceleration on total cost: the general case, in which total cost decreases with acceleration until a certain point and then starts increasing—CC, crash cost; NC, normal cost; LC, least cost; CD, crash duration; LCD, least-cost duration; ND, normal duration**

increases at an increasing rate, until we either reach our desired duration/end date or stop at the absolutely least possible duration, called **crash duration (CD)**, which has an associated **crash cost (CC)**.

As mentioned previously, the shape and slope of the curve differ from one case to another. In some cases, the curve may start going up immediately (i.e., total cost starts increasing as soon as we start accelerating), as shown in Figure 8.9.

In other cases, the curve goes down and then stops at the crash duration point, without going up anymore (see Figure 8.10). In this case, the crash duration point coincides with the least-cost duration point.

### Issues to Be Considered When Accelerating a Project

Accelerating a project affects many aspects in the project other than time. Failing to consider these aspects may lead to undesired adverse results. The project manager must consider issues such as the following:

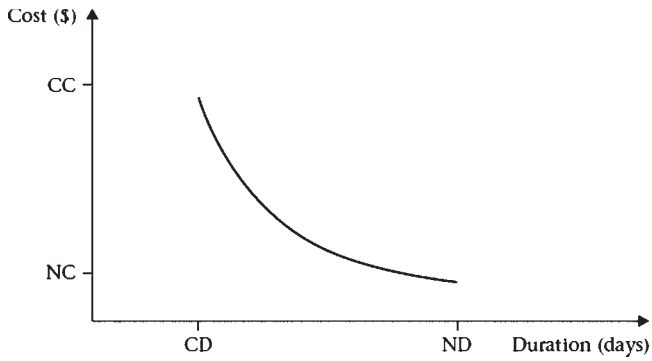



**Figure 8.9 Effect of project acceleration on total cost: a special case, in which total cost starts increasing as soon as acceleration starts—CC, crash cost; NC, normal cost; CD, crash duration; ; ND, normal duration. Least cost duration, LCD, coincides here with normal duration, ND**

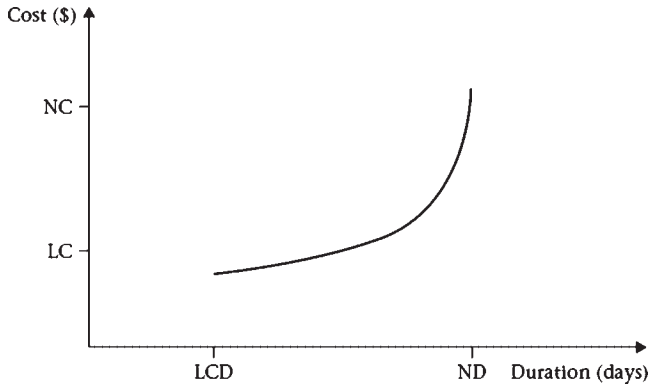



**Figure 8.10 Effect of project acceleration on total cost: a special case, in which total cost keeps decreasing until the project is completely crashed—NC, normal cost; LC, least cost; LCD, least-cost duration; ND, normal duration. Crash duration, CD, coincides here with least cost duration, LCD**

1. If the acceleration is decided early enough, perhaps in the conceptual phase, the owner should consider this when choosing the contract type and delivery method. Adding incentives to the contract and fast-tracking the project may also be considered.
2. The effect of acceleration on cash flow for both the owner and the contractor should be considered. Since the overall project cost will likely increase but its duration will decrease, it is expected that monthly expenses and payments will be much higher.
3. The schedule may need to be updated more frequently. Also, the importance of information accuracy is more stressed, as the impact of errors may be more severe than in a normal situation. Missing one day for severe weather or other reason means missing a large amount of work.
4. When increasing the number of work crews (workers and/or equipment), the contractor must consider the following issues:
   a. Space and logistics for safe and efficient operations, including materials and equipment storage.
   b. Shift turnover, as there is usually a loss of time and productivity when one shift picks up after another shift.
   c. Fatigue, long-term exhaustion, and stress on staff and laborers may lead to lower productivity and morale, and perhaps an increase in accidents and absenteeism.

   d. Equipment maintenance may require more attention, as equipment will be used at a higher rate per day, and the contractor cannot afford taking the equipment off work for a long time for maintenance.
   e. Managing subcontractors so that they are on the same page with the GC while accelerating work is a matter with high importance.
5. Procurement of resources will be more important, and the project manager may look for methods to expedite delivery, including alternative ways to transport materials.
6. Government permits and regulations on work hours and road restriction should be considered. If the contractor needs a government permit as a precondition for a certain type of work, there may not be any point in accelerating the work if the permit cannot be accelerated. If the project is located in an urban area, there might be government regulations on noise after certain hours that prevent the contractor from operating certain equipment after those hours.
7. What should be done with the extra staff, workers, and equipment after the completion of the project? This is an important question that the contractor needs to keep in mind when making the accelerating decision.

**Tip Box 8.3**

When accelerating a project, many aspects of the schedule get higher intensify: resources, cash flow, and so forth. Don't forget procurement!

## RECOVERY SCHEDULES

In real-life projects, schedules may slip. This situation may concern the owner, especially if the project deadline is critical. The owner may demand that the contractor adjust the work plan to enable him or her to finish on schedule. The owner must be convinced that the contractor can feasibly do so, or the owner may terminate the contractor and hire another contractor to ensure a timely finish. When the contractor adjusts the schedule, the result is a **recovery schedule**. It can be defined as a schedule prepared during construction, after the project has fallen behind (because either the interim target has not been met or serious signs of failure to meet the deadline can be seen), with adjustments made by the contractor that will expedite the remainder of the project and ensure a timely finish. The recovery schedule may incorporate one or more of the techniques mentioned previously.

### Example 8.1

Calculate the normal, least-cost, and crash durations for the following project. Calculate the cost associated with each duration. Indirect (overhead) costs are $120 per day.

| | | Duration (days) | | Cost ($) | |
|---|---|---|---|---|---|
| Activity | IPA | Normal | Crash | Normal | Crash |
| A | – | 5 | 4 | 500 | 600 |
| B | A | 7 | 5 | 350 | 500 |
| C | A | 8 | 5 | 800 | 920 |
| D | A | 11 | 7 | 1,200 | 1,400 |
| E | B, C | 6 | 4 | 600 | 700 |
| F | C | 4 | 4 | 500 | 500 |
| G | D, F | 7 | 5 | 700 | 1,000 |
| H | E, F | 6 | 5 | 300 | 420 |

### Solution

This simple project has five paths (see Figure 8.11). They are listed next, along with their lengths in days:

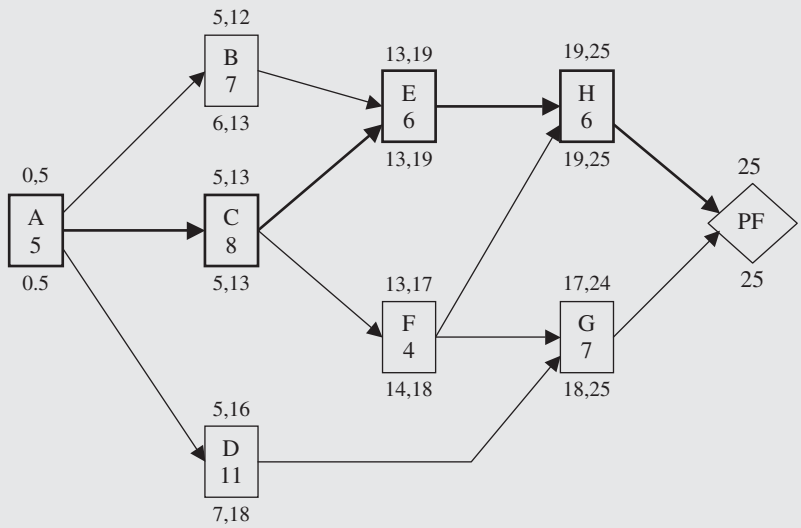



**Figure 8.11 Precedence network for project in example 8.1—PF, project finish**

**Cycle 0 (before crashing)**

| Path[a] | Duration (days) |
|---|---|
| ABEH | 24 |
| ACEH | 25 |
| ACFH | 23 |
| ACFG | 24 |
| ADG | 23 |

[a] When the letter representing an activity is crossed, e.g., F, it means this activity cannot be crashed (such as activity F) or has reached its minimum/crash duration

Let us prepare the time-cost trade-off calculation table (Figure 8.12). We have to start with the critical (longest) path: ACEH. We choose activity C because it costs the least to crash, $40 per day. We cut the duration of C from 8 days to 7. This action affects three paths: Cycle 1

**Linear Project Crashing** Overhead per day = $120

| Activity | Duration (days) | | Cost | | Δ | Δ | Δ cost | Days Shortened / Cycle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Normal | Crash | Normal | Crash | Days | Cost | Δ days | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| A | 5 | 4 | $500 | $600 | 1 | $100 | $100 | | | 1 | | | | |
| B | 7 | 5 | $350 | $500 | 2 | $150 | $75 | | | | | 1 | 1 | |
| C | 8 | 5 | $800 | $920 | 3 | $120 | $40 | 1 | | | 1 | 1 | | |
| D | 11 | 7 | $1,200 | $1,400 | 4 | $200 | $50 | | | | 1 | 1 | | |
| E | 6 | 4 | $600 | $700 | 2 | $100 | $50 | | 1 | | 1 | | | |
| F | 4 | 4 | $500 | $500 | 0 | $0 | | | | | | | | |
| G | 7 | 5 | $700 | $1,000 | 2 | $300 | $150 | | | | | | 1 | 1 |
| H | 6 | 5 | $300 | $420 | 1 | $120 | $120 | | | | | | | 1 |
| | | | | | | | | | | | | | | |
| | | | | | Days Cut | | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | | | | | Project Duration | | **25** | 24 | 23 | **22** | 21 | 20 | 19 | **18** |
| | | | | | Increased cost $ | | $0 | $40 | $50 | $100 | $140 | $165 | $225 | $270 |
| | | | | | Direct Cost $ | | $4,950 | $4,990 | $5,040 | $5,140 | $5,280 | $5,445 | $5,670 | $5,940 |
| | | | | | Overhead Cost $ | | $3,000 | $2,880 | $2,760 | $2,640 | $2,520 | $2,400 | $2,280 | $2,160 |
| | | | | | Total Cost $ | | **$7,950** | $7,870 | $7,800 | **$7,780** | $7,800 | $7,845 | $7,950 | **$8,100** |

**Figure 8.12 Time-cost trade-off calculation table for example 8.1**

**Cycle 1**

| Path | | Duration (days) |
|---|---|---|
| ABEH | 24 | 24 |
| ACEH | ~~25~~ | 24 |
| AC~~F~~H | ~~23~~ | 22 |
| AC~~F~~G | ~~24~~ | 23 |
| ADG | 23 | 23 |

This action increased the direct costs by $40 and decreased the indirect costs by $120. The total impact on the cost is a net savings of $80.

We now have two paths that tie at 24 days' duration: ABEH and ACEH. We can compress a shared activity (A, E, or H) or a combination of unshared activities (B and C). We choose activity E and compress it from 6 days to 5 days at a cost of $50.

**Cycle 2**

| Path | Duration (days) | | |
|---|---|---|---|
| ABEH | 24 | ~~24~~ | 23 |
| ACEH | ~~25~~ | ~~24~~ | 23 |
| ACFH | ~~23~~ | 22 | 22 |
| ACFG | ~~24~~ | 23 | 23 |
| ADG | 23 | 23 | 23 |

The direct costs increase by $50, and the indirect costs decrease by $120. This results in a net decrease of $70 in the total cost.

Now we have four paths that tie at 23 days' duration: all but ACFH. We can compress a shared activity (A) or a combination of unshared activities (plenty of options exist). We choose activity A and compress it from 5 days to 4 at a cost of $100[11]. Activity A is now completely crashed.

**Cycle 3**

| Path | Duration (days) | | | |
|---|---|---|---|---|
| ABEH | 24 | ~~24~~ | ~~23~~ | 22 |
| ACEH | ~~25~~ | ~~24~~ | ~~23~~ | 22 |
| ACFH | ~~23~~ | 22 | ~~22~~ | 21 |
| ACFG | ~~24~~ | 23 | ~~23~~ | 22 |
| ADG | 23 | 23 | ~~23~~ | 22 |

With this action, we spent an extra $100 in direct costs and saved $120 in indirect costs. The total cost decreased by $20 (we are still saving money, but the rate is decreasing).

Now we need to compress the same four paths using the least-cost combination. After a simple mathematical inspection of the table, we find the best combination to be C, D, and E, with a total combined cost of $140.

[11] If activity A could be crashed by more than 1 day, we could have crashed it to the limit, since it is part of any path on the network. This means any day cut from activity A would automatically mean a day cut from the entire schedule.

We compress *each* of these activities by 1 day to shorten the project duration from 22 days to 21 days.

**Cycle 4**

| Path | Duration (days) | | | | |
|---|---|---|---|---|---|
| ~~ABEH~~ | 24 | ~~24~~ | ~~23~~ | ~~22~~ | 21 |
| ~~ACEH~~ | ~~25~~ | ~~24~~ | ~~23~~ | ~~22~~ | 20 |
| ~~ACFH~~ | ~~23~~ | 22 | ~~22~~ | ~~21~~ | 20 |
| ~~ACFG~~ | ~~24~~ | 23 | ~~23~~ | ~~22~~ | 21 |
| ~~A~~DG | 23 | 23 | ~~23~~ | ~~22~~ | 21 |

Note that path ACEH was cut by 2 days because it contains both C and E. Now the total cost has increased by $20 ($140 increase in direct costs and $120 decrease in indirect costs). The next step is to find an alternative to activity E because it is completely crashed. The next least-cost combination is B, C, and D, at a total cost of $165. In this case, the total cost has increased by $45.

**Cycle 5**

| Path | Duration (days) | | | | | |
|---|---|---|---|---|---|---|
| ~~ABEH~~ | 24 | ~~24~~ | ~~23~~ | ~~22~~ | ~~21~~ | 20 |
| ~~ACEH~~ | ~~25~~ | ~~24~~ | ~~23~~ | ~~22~~ | ~~20~~ | 19 |
| ~~ACFH~~ | ~~23~~ | 22 | ~~22~~ | ~~21~~ | ~~20~~ | 19 |
| ~~ACFG~~ | ~~24~~ | 23 | ~~23~~ | ~~22~~ | ~~21~~ | 20 |
| ~~A~~DG | 23 | 23 | ~~23~~ | ~~22~~ | ~~21~~ | 20 |

Note that the critical paths may change in every round. Now, activity C is also completely crashed. Our next choice is the combination of B and G at a combined cost of $225, with a net increase of $105 in the total cost.

**Cycle 6**

| Path | Duration (days) | | | | | | |
|---|---|---|---|---|---|---|---|
| ~~ABEH~~ | 24 | ~~24~~ | ~~23~~ | ~~22~~ | ~~21~~ | ~~20~~ | 19 |
| ~~ACEH~~ | ~~25~~ | ~~24~~ | ~~23~~ | ~~22~~ | ~~20~~ | 19 | 19 |
| ~~ACFH~~ | ~~23~~ | 22 | ~~22~~ | ~~21~~ | ~~20~~ | 19 | 19 |
| ~~ACFG~~ | ~~24~~ | 23 | ~~23~~ | ~~22~~ | ~~21~~ | ~~20~~ | 19 |
| ~~A~~DG | 23 | 23 | ~~23~~ | ~~22~~ | ~~21~~ | ~~20~~ | 19 |

Activity B is now completely crashed. All paths are tied at 19 days. The only remaining option is to combine activities G and H at a cost of $270, with an increase of $150 in the total cost.

**Cycle 7**

| Path | Duration (days) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ~~ABEH~~ | 24 | ~~24~~ | ~~23~~ | ~~22~~ | ~~21~~ | ~~20~~ | ~~19~~ | 18 |
| ~~ACEH~~ | ~~25~~ | ~~24~~ | ~~23~~ | ~~22~~ | ~~20~~ | 19 | ~~19~~ | 18 |
| ~~ACFH~~ | ~~23~~ | 22 | ~~22~~ | ~~21~~ | ~~20~~ | 19 | ~~19~~ | 18 |
| ~~ACFG~~ | ~~24~~ | 23 | ~~23~~ | ~~22~~ | ~~21~~ | ~~20~~ | ~~19~~ | 18 |
| ~~ADG~~ | 23 | 23 | ~~23~~ | ~~22~~ | ~~21~~ | ~~20~~ | ~~19~~ | 18 |

Now the entire project is completely crashed, with a duration of 18 days. The results may be summarized as follows:

- The normal duration is 25 days, at a total cost of $7,950.
- The least-cost is $7,780, at a duration of 22 days.
- The crash duration is 18 days, with a crash cost of $8,100.

**Notes**

1. Accelerating can become complicated even in a small network. For larger projects, we use computers, as explained in the next section.
2. Activity D is not completely crashed, which demonstrates an important point: to accelerate a project, we do not need to compress all activities. If we did, we would be wasting money with no benefit to the schedule.
3. We assume linearity within each activity (e.g., it costs the same amount of money to compress activity C from 8 days to 7, from 7 days to 6, or from 6 days to 5). However, we see that the change in total cost for the project is not linear.
4. The project manager may choose a project duration between 22 days and 18 days to meet the contract-required finish date (22 days for least cost and 18 days for least duration).

## ACCELERATING PROJECTS USING COMPUTERS

Real-life projects usually contain hundreds or thousands of activities. There may be tens or even hundreds of paths, each with 50, 60, or more than 100 activities. Performing calculations such as those done in example 8.1 would be too cumbersome. The practical approach is to use trial and error. However, nine guidelines follow:

1. Always make a backup copy of the schedule before you make any changes.
2. Focus on the critical path. A good idea is to sort activities by total float (first criterion) and start date (second criterion), in ascending order. You may also

apply a filter to show only critical activities (be careful of the software's definition of *critical activities*).

3. For every activity that may be accelerated, prepare a list of accelerating methods in an ascending order of cost. When the activity has to be accelerated, start with the least expensive method till this method is exhausted then cross it and use the next method, if you need to keep accelerating.
4. Pick an activity on the critical path and reduce its duration by one day. Schedule the project (perform CPM calculations) and examine the impact on the project's finish date. If the finish date is now 1 day earlier, move to step 6. If you are applying a filter, you may have to refresh the view.
5. If the project finish date has not changed, at least one other critical path must exist, and you reduced only one. Go back to the list of critical activities (those with least total float), pick one, and repeat step 4. Looking at the different paths on either a bar chart or a logic diagram can be helpful.
6. You have reduced the project duration by 1 day; you now need to reduce it by another day. Repeat step 4. You may find more activities that are critical now. This fact does not mean there will be more options for you. On the contrary, you may have to compress several activities simultaneously to reduce the project duration by one day.
7. Repeat the same steps until you achieve the desired duration.
8. Avoid compressing any path by multiple days in one step unless you know the critical path is longer than the next one by at least the same number of days or the compressed activity is shared between/among the longest paths. For example, if you compress a path by 10 days, but the project's duration decreases by only 3 days, you have achieved nothing from the last 7 accelerated days. Only the first 3 days of acceleration were effective. In this case, go back and replace the 10-day compression with 3 days (or the correct effective number).
9. If you are determining the least-cost duration, you may want to do the calculations manually (for every step, you calculate the total net savings by subtracting the increase in direct costs from the decrease in indirect costs). You may also create a simple spreadsheet that performs the calculations.
10. The project manager should give the scheduler the crash duration and crash cost information for the activities. The scheduler must then experiment with the accelerated schedule and submit the results to the project manager. After the project manager approves the results, the scheduler may implement the accelerated schedule.

## POTENTIAL ISSUES WITH UNCOORDINATED PROJECT ACCELERATION

As explained earlier, the contractor may accelerate the project schedule, responding to instructions from the owner, or the contractor may do so for his or her own interest.

In the latter case, the contractor must discuss such acceleration with the owner to make sure that the owner knows and approves such action. This may sound trivial or unnecessary, as finishing early is generally perceived as a positive achievement. Generally, this is true, but not always. Some problems may arise from an uncoordinated early finish, such as the following:

1. *The owner may have a cash-flow problem*: Even when the contractor is not asking for extra money, acceleration will result in front-end loading of charges. The owner may receive higher than expected pay requests because more work is being done per pay period than originally planned. If the owner was not consulted on this matter and did not formally approve such acceleration, this may cause a delay in payment to the contractor.
2. *The owner may not be ready to take over the facility*: The project may be a hotel, an office building, a factory, an oil refinery, or other facility. Owners always plan for operating the facility when the project is completed and turned over to them by the contractor. Such planning includes, but is not limited to, staffing and budgeting. If the contractor surprises the owner by finishing the project 2 or 3 months early, the owner may not have the staff and/or budget to run the facility. In addition, such early operation may not go well with the strategic plans for the organization. This may also create a problem with when the warranty on the project and major equipment in it starts.

For the preceding reasons, it is highly recommended that, if the contractor is planning a project schedule acceleration for his or her own reasons, the contractor should consult with the owner and get the owner's written consent.

**Tip Box 8.4**

Project acceleration must be coordinated among all parties: owner, general contractors, and subcontractors.

#### Optimum Project Scheduling

Traditional CPM scheduling mainly aims at completing the project in the shortest *normal* manner, which is identified and defined by the critical path. In certain cases, this schedule is accelerated, as discussed earlier, because of time constraints or to minimize costs and/or maximize profit. The project's starting point is usually defined by the contract, based on the owner's objective and requirements. Amazingly, this starting point is rarely calculated scientifically (along with activities' durations) to produce an optimum plan (including and focusing on the schedule) in order to meet the owner's objectives of cost, time, and scope/quality.

#### Project Scheduling and Prevailing Economic Conditions

Construction projects are subject to a myriad of uncertainties, such as availability and price fluctuations in labor, materials, and equipment; weather; availability of funds;

political changes; wars; and natural and man-made disasters. Some of the fluctuations can be predicted fairly accurately, such as those induced by seasonal and climatic changes. Other effects are less predictable, such as from wars, natural disasters, political turbulence, economic recessions, and other local and global events, although some of them have "warning signs" that experts can sense.

Naturally, many developers and investors react to the market conditions and follow the trends. However, the reaction in the construction industry needs a relatively long lead time to deliver the product to the market. By that time, the market conditions may have changed. Let's assume that the market demand is represented by the curve in Figure 8.13.

It took some time to convince an investor that market conditions are encouraging to build a project (say, a housing development) and then to get ready to start the project. The investor started at point "A," when the market was moving favorably (for investors) and demand exceeded supply. It took the investor 2 years to finance, acquire the land, obtain the permits, design and build the houses, and make them ready for sale. Even though, in most cases, the developer may start selling before construction work has finished, he still has to complete and secure a certain portion of the project before he can sell anything. This portion can take 1 year or more. By the time the developer can start selling houses (completed or not), the market has hit a saturation point and started to slow down (point B). At this point, the developer's options are limited. He is "damned if he continues and damned if he does not." He may have huge financial obligations to banks or financiers, and he has to make payments for contracts already signed with the designer, contractor, and other parties. A few houses have been sold, and even for those houses sold, he has received only a small down payment that buyers in such situations may simply forfeit in order to escape a worse financial loss. The survival of the developer depends on his financial strength and resilience (mostly how much cash and other liquid assets he has on hand) and how long he can hold on. The developer may scope down the project or pause it. For example, he can complete a portion of the entire development and hold the rest until the market starts improving. Another option is to continue but slow down the work progress, using fewer resources and delaying the delivery of the product. If he cannot

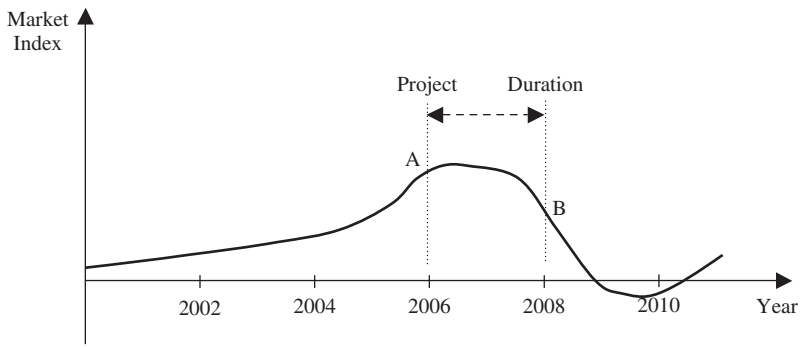



**Figure 8.13 Market conditions. This curve does not accurately reflect past market index, nor does it accurately forecast conditions. It is for illustrative purposes only**

do this, he may sell the project as is (perhaps by auction) and use the proceeds to pay off his debts. All of these options come with some negative consequences, but the developer/owner may have to choose the lesser of several evils. Unfortunately, many investors stretch themselves too much—mostly motivated by greed in a situation exacerbated by miscalculations—and these options may be unfeasible or insufficient for them. Their only option then is to declare bankruptcy, which does not help in the long run. In other types of projects, where the project is one entity that cannot be partially built (e.g., a high-rise building, factory, or shopping center), completing a portion of the project may not be a viable option.

To minimize the risks of such a situation, there are several recommended measures. Since this is *not* a book on economics or risk management, we will focus only on scheduling issues. In brief, when the economy is booming, the response to the market demand must be quick. This can be achieved by having a ready plan and accelerated/optimum project schedule. When the economy is slumping, it may be a good idea to slow down the pace of the project or even "hibernate" until conditions improve.

In this context, we will discuss the selection of the starting point of the project and its activities' durations and timing, which that determine the optimum duration of the project, coupled with the optimum (least) cost. Such a discussion applies not only to recessions and slow economic times but also to all conditions. However, the application of the principle must be adjusted to suit the market and the owner's conditions.

#### Project Scheduling in Extreme Weather Regions

In regions where there are harsh weather conditions (extreme cold/heat, excessive rain, sand storms, hurricanes and floods), it is desirable to have the construction—or at least the first portion of it (that is performed under no roof, for building projects)—occur during the preferred season. This can be achieved by applying the idea of optimum scheduling: choosing the starting point of the project and activities' durations and timing that result in optimum schedule and/or cost.

#### Optimum Scheduling

*Optimum scheduling* is defined as selecting the project's starting point and the composition of the durations and timing of its activities, within logic constraints, which results in an optimum schedule and least cost while maintaining the project's scope and quality.

Optimum scheduling is explained here just as a concept. The concept is open to more research, in terms of both theory and application.

Any activity needs resources, mainly labor, materials, and equipment. Each type of resource is subject to a group of influencing factors:

1. *Supply and demand*: All resources are subject to the supply and demand rule, which usually has both predictable and unpredictable consequences. For example, many locales have a high season for construction (usually when the weather is mild), and demand is heavy at that time. Also, demand may become unexpectedly high following a disaster (war, earthquake, flood, etc.) or economic boom, or as the result of other factors. Demand for special trades may spike following a governmental regulation, such as the American with

Disabilities Act (ADA) or a new building code. Along with the increase in demand, there is usually a price increase. This increase may slowly go back to normal after the demand tapers off and/or the supply increases to match the demand. Avoiding demand spikes, if the owner has such a luxury, results in lower prices and, in some instances, better quality.

2. *Productivity fluctuation*: Labor productivity is subject to a host of factors. Weather is one of the most influencing factors, particularly for outdoor activities. During extreme weather conditions, workers' productivity is usually impaired. In addition, they may work reduced hours.[12] Working overtime (extra hours per day or extra days per week) may result in a reduction in productivity (as discussed earlier). There are several studies on the effects of overtime, but they do not necessarily agree on the conclusion. However, the author recommends against using overtime for extended periods of time.

   Since the construction industry is not fully automated, equipment's productivity is directly linked to labor's productivity.

3. *Weather and climate*: In addition to its effect on productivity, weather may also affect the behavior of certain materials. Concrete, for example, takes more time to cure in cold weather and may require heating and/or insulating formwork. In extremely hot weather, concrete has a different problem. It hardens quickly, unless retarding agents are added to the mix, and then needs special curing. Extreme weather affects other materials, too, such as asphalt and adhesives. Other materials may become brittle in extremely cold weather, which makes them less workable and more subject to breakage. Excessive rain hampers outdoor activities. Rain may also come with lightning, which poses a danger during outdoor activities, particularly to those workers using cranes and tall equipment. Moisture may slow down the curing of concrete or the behavior of adhesives, and it also may adversely affect stored materials such as wood. You may want to avoid outdoor construction in areas where seasonal monsoon rains, hurricanes, tornados, floods, and other forms of extreme weather occur during such seasons. While scientists may use various methods, such as simulation, to forecast the timing and severity of such disasters, they cannot make accurate predictions.

   Weather also may affect logistics and materials storage. Extreme weather poses difficulties and sometimes hazardous conditions on roads. Stored materials under extreme weather conditions have to be protected with special methods that may be expensive. The time of year may have an impact on work hours, which differ between summer and winter. Depending on the latitude, there may be fewer daylight hours in the winter than in the summer. This may require the contractor to use artificial lighting.

4. *Locale*: This factor encompasses other factors that are not included above, such as local culture and government regulations.

[12] In some countries in the Arabian/Persian Gulf, government regulations forbid outdoor work during certain daytime hours in the summer. In extremely cold regions, local law may prohibit outdoor work if the temperature dips below a certain limit.

These factors impact both productivity and cost. The impact on productivity will affect duration of the activity and the cost of labor and equipment resources.

### Productivity and Cost Multipliers

The scheduler can divide the year, in a certain location, into time segments (intervals of 10 days, or months, for simplicity in this discussion), assigning productivity and cost multipliers for each segment. The base productivity and cost can be "normal," "average," or "optimum." It does not matter, as long as the multipliers are estimated with respect to the base numbers. For example, if we consider January as base for productivity and cost in location $X$ (100%), then we compile productivity and cost multipliers for other months (or time periods) based on past records and future expectations. Let's suppose that we compiled this table:

| Month | Productivity Multiplier (PM) | Cost Multiplier[a] (CM) |
|---|---|---|
| January | 1.00 | 1.00 |
| February | 1.00 | 1.00 |
| March | 1.10 | 0.90 |
| April | 1.05 | 0.90 |
| May | 0.95 | 0.95 |
| June | 0.85 | 1.05 |
| July | 0.75 | 1.10 |
| August | 0.70 | 1.20 |
| September | 0.85 | 1.10 |
| October | 1.00 | 1.00 |
| November | 1.10 | 0.90 |
| December | 1.00 | 0.95 |

[a]The cost impact from the productivity change is included under the productivity multiplier only. For more accurate results, the cost multiplier should be broken into three multipliers—for labor, equipment, and materials—but for the sake of simplicity and to demonstrate the concept, we will keep it as one multiplier.

Now, when a schedule is created based on base productivity and cost, it has to be recalculated:

$$\text{Adjusted duration} = \sum \text{Dur}_i/\text{PM}_i \tag{8.1}$$

$$\text{Adjusted cost} = \sum \text{Cost}_i * \text{CM}_i \tag{8.2}$$

For example, if an activity is scheduled to start on May 27 and it has 12 days' duration (with base productivity), the adjusted duration will be distributed between May and June. We don't know exactly how long this activity will take, but based on Productivity multipliers <1.00, we expect the total duration to be >12 days. The portion in May will be 5 days (May 27 through 31), but we need to calculate the portion in June, $X$:

From equation 8.1:

$$\text{Base Duration} = \text{Adjusted Duration} * \text{Productivity Multiplier}$$

Then,

$$12 = 5 * 0.95 + X * 0.85 \rightarrow X = 8.53 \text{ days}$$

$$\text{Total adjusted duration} = 5 + 8.53 = 13.53 \text{ days}$$

In other words, this activity, when started on May 27, would be expected to take 1.53 days more than it would if it were performed in January. This is not as bad as performing it in July (12/0.75 = 16 days) or August (12/0.70 = 17.14 days). On the other hand, it would take less than 12 days if it were performed in March or November (12/1.1 = 10.91 days).

Keep in mind that unit price is inversely proportioned to duration:

$$\textit{Unit price}\,(\$\,\textit{per unit}) = \frac{\textit{Crew cost}\,(\$\,\textit{per day})}{\textit{Crew production}\,(\textit{units per day})}$$

Ideally, we would like to do this activity when productivity is at its maximum (i.e., duration is at its minimum) and cost is at its minimum. This may be possible and simple if we are talking about one activity. But in the panoramic view of project scheduling, with hundreds or thousands of activities spread over several months or years, we should not focus on the local optimal (activity) solution but, rather, on the global optimal (project) solution. It will take several iterations because, in each iteration, activities' durations change when productivity multipliers are applied. This will trigger shifts in the start and finish dates of succeeding activities, which may push them into different productivity multiplier zones, and so on. For more details, see papers coauthored by the author in the reference section[13].

After finding the "optimum" schedule, it is a good idea for the scheduler to conduct a sensitivity analysis: if the project start is delayed or moved earlier by 1 day or one unit of time, what would be the impact on the completion date and cost? Such an analysis is important because it will help the project management assess different scenarios, including the possibility of change orders, weather delays, and other factors. It is like many of us who experiment with the optimum time to leave home in the morning and arrive at our workplace, in order to have the shortest driving time. A delay of 10 minutes in departure may mean arriving 30 minutes later.

**Tip Box 8.5**

It may amaze you to find out the cost savings from optimizing the project's start point and activities' durations. It is the responsibility of the general contractor to explore the optimum schedule and inform the owner of that schedule and the alternatives.

[13] Four papers written by Dr. Ahmed Senouci and Dr. Saleh Mubarak (2012, 2013), listed in the reference section.

As discussed earlier in this chapter, even though we tend to like completing projects with the least duration and least cost, the user has to set the project's priorities: time versus cost. Then the scheduler can optimize the schedule using one criterion (time or cost) as the primary objective function and the other criterion as the secondary objective function.

## CHAPTER 8 EXERCISES

1. What does the term *accelerating a project* mean?
2. Why would a contractor accelerate a project?
3. Why would an owner accelerate a project?
4. An owner finds that the 18 months that are needed to complete her proposed shopping center project is not acceptable, so she decides to scale it down by 20%, which allows the contractor to finish it in 15 months. Is this considered project acceleration? Explain your answer?
5. A project manager may shorten the duration of a project in many ways. Mention six of these ways. Discuss each one of them briefly, mentioning its pros and cons.
6. The decision to accelerate a project may be made early, before the project starts, or in the middle of it. The timing may limit your options for accelerating the schedule. Discuss this statement. Mention any example that comes to mind.
7. Discuss the pros and cons of fast-tracking construction projects and using this concept as a means for accelerating projects.
8. Explain how accelerating a project works.
9. Would you advocate using overtime always, sometimes, or never? Explain your answer.
10. Give an example of accelerating a project by improving the communication among the parties involved in the construction activities.
11. Your critical path is 128 days long. The next longest path is 122 days long.
    a. If you extend the longest path by 5 days, the entire project duration will increase by 5 days. True or false?
    b. If you reduce the longest path by 5 days, the entire project duration will decrease by 5 days. True or false?
    c. If you reduce the longest path by 10 days, the entire project duration will decrease by 10 days. True or false?
12. You are the project manager of a construction project. Your project is falling behind schedule. You meet with your team (including the scheduler) and discover that accelerating the schedule to bring it back on track will cost you an additional $20,000. Would you do it? (*Hint*: You do not know enough to give a definite answer.)

13. You are the scheduler for a large commercial building project. The schedule that you prepared (based on feedback from the project manager) falls 15 days short of the owner's deadline. The project manager decides to write a memo to all of the subcontractors, requiring them to work 6 days per week, 10 hours per day. You ask the project manager to wait until you determine the most efficient way to crash the project. Outline your argument to convince the project manager to go with a certain accelerating plan that focuses on the critical path and not all activities.
14. In general, what is the effect of accelerating an activity on the direct costs of a project? Why?
15. What is the effect of accelerating an activity on the indirect costs of a project? Why?
16. In general, what happens to the total cost of a project when you start accelerating and keep accelerating the scheduleuntil you reach the least possible duration?
17. Explain your answer to the previous question graphically. Make sure you show the points of normal duration (ND), normal cost (NC), least cost (LC), least-cost duration (LCD), crash duration (CD), and crash cost (CC).
18. Visit a construction site and meet with the project manager. Ask the project manager what it would take to reduce the project's duration by 5 days. Try to quantify the extra cost and benefits for such an acceleration. Ask the project manager about the means he or she would use to achieve such an acceleration.
19. What is a *recovery schedule*?
20. Calculate the normal, least-cost, and crash durations for the following project. Calculate the cost associated with each duration. Indirect (overhead) costs are $100 per day.

| | | Duration (days) | | Cost ($) | |
|---|---|---|---|---|---|
| Activity | IPA | Normal | Crash | Normal | Crash |
| A | – | 7 | 5 | 500 | 640 |
| B | A | 6 | 5 | 550 | 630 |
| C | A | 8 | 5 | 800 | 935 |
| D | B | 10 | 7 | 1,200 | 1,440 |
| E | B, C | 6 | 4 | 600 | 700 |
| F | C | 4 | 3 | 500 | 590 |
| G | D, F | 4 | 2 | 700 | 1,000 |
| H | E, F | 7 | 4 | 650 | 950 |
| I | G, H | 2 | 2 | 300 | 300 |

21. Calculate the normal, least-cost, and crash durations for the following project. Calculate the cost associated with each duration. Indirect (overhead) costs are $120 per day.

| | | Duration (days) | | Cost ($) | |
|---|---|---|---|---|---|
| Activity | IPA | Normal | Crash | Normal | Crash |
| A | – | 5 | 4 | 770 | 900 |
| B | – | 3 | 2 | 660 | 700 |
| C | A | 7 | 4 | 800 | 1,070 |
| D | A, B | 4 | 3 | 1,000 | 1,110 |
| E | B | 6 | 4 | 800 | 920 |
| F | C, D | 6 | 5 | 560 | 630 |
| G | D | 5 | 3 | 700 | 810 |
| H | F | 8 | 4 | 1,000 | 1,260 |
| I | E, G | 4 | 3 | 500 | 580 |
| J | H, I | 3 | 2 | 400 | 600 |

22. Calculate the normal, least-cost, and crash durations for the following project. Calculate the cost associated with each duration. Indirect (overhead) costs are $200 per day.

| | | Duration (days) | | Cost ($) | |
|---|---|---|---|---|---|
| Activity | IPA | Normal | Crash | Normal | Crash |
| A | – | 1 | 1 | 800 | 800 |
| B | A | 7 | 4 | 1,000 | 1,600 |
| C | A | 6 | 4 | 300 | 500 |
| D | A | 3 | 2 | 400 | 800 |
| E | B | 3 | 1 | 100 | 200 |
| F | B, C | 7 | 5 | 500 | 800 |
| G | D | 8 | 4 | 1,200 | 1,400 |
| H | E | 7 | 6 | 350 | 600 |
| I | F | 5 | 3 | 700 | 850 |
| J | F, G | 3 | 2 | 500 | 1,000 |
| K | H, I, J | 5 | 4 | 450 | 800 |

23. When you accelerate projects by using a computer, what steps do you follow?
24. Using *ENR* magazine and other resources, prepare a case study on the Northridge earthquake and the C. C. Meyers' project. Determine how the contractor achieved these results (mention them as itemized factors).
25. Arrange a meeting with a project manager and discuss the concept of optimum scheduling. In particular, discuss the choice of the starting point and whether the project could have benefited from shifting the starting point.
26. Pick a few types of materials and prepare a table with productivity and cost multipliers for your locale. You may need to consult contractors and materials suppliers.
27. Finishing the project early is always a reason for a contractor to be happy. Are there exceptions or precautions? Elaborate.

Chapter 9

# Reports and Presentations



Dubai Mall, Dubai, United Arab Emirates

*Little John was excited about his new pair of pants, but they were a bit too long for him. He asked his oldest sister, Dorothy, "Would you please take 4 inches off my new pants?" "I would, but I have to go out now," she said. He asked his middle sister, Terry, "My beloved sister, would you please take 4 inches off my new pants?" With a sad smile, she replied, "I am so sorry, I can't. I am too busy with house chores." He thought he would never ask his little sister, Lisa, but he had no choice. "I am really sorry, Johnny. I have tons of homework to do," she said. Little John went to bed, upset that he would not be able to wear his new pants to school the next day. Dorothy came back home early that evening. She wanted to surprise her little brother. She quietly went to his room and took the pants to her room. She was good at alterations. She altered them in no time and put them back in their place. Terry finished her house chores and still had some energy. "I feel so guilty letting my little brother down," she thought. Not knowing what her sister just did, she took 4 more inches off the pants. Lisa was sitting in her room doing homework and studying for an exam the next day. She was thinking of little John's disappointment at not being able to wear his new pants to school. Despite her not-so-friendly relationship with him, she closed her book and went to his room, took the new pants, and shortened them by yet 4 more inches. Next morning, the family was having an early breakfast when angry John came in with his new pants reaching barely below his knees and asked, "Who is the idiot who took a foot off my new pants?"*

## INTRODUCTION

Without a doubt, good communication is an essential component of successful management. This means conveying the right (or proper) information to the right party at the right time and in the right form. There are 12 characteristics of good communication, which are as follows:

1. *Clarity*: The information must be clear to the receiver. Such ambiguous and subjective terms as "as soon as possible," "good performance," and "the changes must be authorized by a responsible person in the architect's organization" should be avoided. Acronyms and abbreviations must not be used in the contract unless they are identified in the contract or they are standard in the industry. Terms to designate future time, such as "tomorrow," "next Tuesday," or "4 days later," should be accompanied by a date. The speaker or writer must make sure that the listener or reader understands exactly what is meant. Technical terms can be used only with people who have a compatible technical background and can understand them.

   In communication, a clear title is important, especially when e-mail is used. E-mail has its own protocol and etiquette; in this context, when a business e-mail is sent, it must have a clear title, indicating the subject of the e-mail.
2. *Simplicity*: Simplicity helps to improve understanding. If the information can be efficiently conveyed in one sentence, two sentences or a paragraph should not be used. The contract may contain phrases that may not be easy for a layperson to understand because of their legal nature. That is why

it is important for each organization (e.g., owner, contractor) to have an employee or a department that is proficient in reading and interpreting legal language. Project team members should use simple language in their daily communications. Technical terms should not be used, unless they are known in the profession, and to the least possible extent absolutely necessary.

3. *Accuracy*: Professional communication must be accurate, objective, and up to date. Personal opinion and subjective statements should be limited and clearly labeled as such. For example, the project manager *should not* say, "I don't think the project is behind schedule, although we have a negative float of 20 days on the critical path." However, the project manager may say, "Despite the fact that the project is behind schedule by 20 days, I believe we can finish on time with a recovery plan."

   When you are quoting information, such as prices and professional opinion, you should include all relevant information (specific description, quantity, name of salesperson, date, length of validity of quote, etc.). Information that is taken from the Internet and then quoted may not be accurate or reliable. It depends on the specific source, which should always be mentioned.

   Communications must be up to date in today's business world. For example, "general conditions" of a company's contracts may have been written years earlier, and its technical specifications may have become obsolete.

4. *Timeliness*: Although accuracy is important, timeliness is equally important in internal communications. Many issues have deadlines and/or a critical schedule. If such information is not communicated in a timely manner, it will lose its value and may lead to negative consequences.

5. *Preciseness and relevance to the subject*: Providing too much or irrelevant information may be confusing and counterproductive. An example of this is what this author calls *lazy designer syndrome*: some architects and engineers copy and paste information from the drawings and specifications of previous projects or boilerplates, although many sections, details, or paragraphs may not pertain to the current project. For instance, a contract may be written in New York or Chicago that contains a clause about the frost line, which would never apply in Miami or the Caribbean. Such information will only confuse and aggravate the contractor when the contractor is trying to link it to the studied project. People who write contracts may do the same: they may use forms that belong to previous cases with many clauses that don't relate to the present contract. This only adds more pages, wasted time, confusion, and frustration.

6. *Legibility*: Some people have handwriting that is illegible or difficult to read. Sometimes only a person's secretary can read that person's handwriting. Such people should either type their communications using a computer or have someone on their staff type it for them. Legibility also includes "readability," whether on paper, on the computer screen, or on the projection screen. One

of the frequent pitfalls for speakers using PowerPoint slides is packing slides with a lot of text that viewers cannot read.

7. *Proper support tools (pictures, tables, charts, statistics, etc.)*: The old saying, "A picture is worth a thousand words," proves to be true when we perform a simple task like assembling a bookshelf. Not only are pictures more helpful, but they also are unilingual: anyone can understand them. Tables, flowcharts, bar charts, organizational charts, and so forth are also helpful in conveying information. Current e-mail systems allow users to attach files, pictures, audio clips, video clips, and so forth to activities in a schedule or to an issue in project management software. When you are sending a file by e-mail, you must be aware of two issues (other than the possibility of computer viruses): the size of the attachment and software compatibility. Some users send e-mails with huge attachments that may clog or slow down the recipient's e-mail system. Instead, they can upload the attachment to an FTP site, or a virtual location from which the recipient can download the files. Also, some users send file attachments that are not compatible with the recipient's software and cannot be opened. Some file types are universal (e.g., .doc, .xls, .ppt, .mdb, .txt, .rtf, .pdf, .jpg, .gif, .exe), and almost any computer can open them. You should always check with the recipient when the size of an attachment is large or when the file type is uncommon.
8. *Proper level of detail*: The communicator must balance the amount of information being given in an intelligent way. Giving insufficient information or information that is too abstract may not convey the whole picture clearly, in which case, one of two situations results: either the information recipient must contact the source to clarify the information, which takes time and perhaps causes aggravation, or the recipient must make assumptions to "fill in the blanks," which may lead to wrong conclusions. In contrast, providing too much information may overwhelm and confuse the recipient. With strict time limitations and the fact that we receive a multitude of mail, e-mail, fax, and telephone messages every day, we often discard information that does not seem important. The more concise the information is, the better the chance the recipient will read it. A message containing too much information may be overlooked, delayed, or trashed.[1] When communication must include a large amount of information, one good idea is to include an abstract or a brief summary paragraph about the issue (the downside is that the recipient may feel content to read only the summary and not read the details).
9. *Good organization and formality*: Good organization implies sorting and organizing the information so that it is easy for the viewer to read, follow, and retrieve. Formality means following the company's procedures, including the use of standard forms. It aims at facilitating reading, searching, storing,

[1] An example of this is a contract for buying and financing a new car or for applying for a credit card. Contracts are often long and written in complex legal language. Most people sign such a contract without reading it.

and retrieving information. For example, when a chief estimator needs to find the amount of contingency that one of his estimators assessed in an estimate (say, in Excel format), he should know exactly where to find it. Such facilitation is important in large companies, especially those with high employee turnover rates. Several software packages, such as Primavera Contract Manager[2] (Oracle Primavera Systems, Inc., Bala Cynwyd, Pennsylvania), Prolog Manager (Meridian Project Systems, Folsom, California), and Project Management (Timberline, Beaverton, Oregon), were developed to help organize project documentation and communication.

On a related subject, the author believes that much of the problem of "weak memory" that many people complain of is actually a problem of "unorganized memory." Lack of organization, in all aspects of life, results in wasted time, frustration, high stress, loss of business and profit, and even deterioration in human relations. It is a good idea for each person, particularly professionals, to be organized in every aspect of their lives.

10. *Conformance to industry standards*: As the world grows smaller, the construction industry is trying to find a common language. Many specifications were written years ago with descriptions of products and services that no longer are available or supported. The International Organization for Standardization (ISO)[3] is a worldwide federation of national standards bodies, one from each of more than 140 countries. ISO is a nongovernmental organization that was established in 1947. ISO's mission is to promote the development of standardization and related activities in the world with a view toward facilitating the international exchange of goods and services and toward developing cooperation in the spheres of intellectual, scientific, technological, and economic activity. ISO's work results in international agreements that are published as international standards.

    Whether or not the construction or design firm follows ISO 9000, or other standards, it must make sure that it conforms to the client's specifications, the local codes, federal standards, other components of the project, and general industry guidelines. For example, U.S. companies that do international work often have to convert their measuring units to the metric system and the date convention, month/day/year, to the world standard, day/month/year.[4]

11. *Retrievable and transformable (from one form to another)*: We are no longer in the age of basements full of boxes and file cabinets that contain information

[2] Formerly known as *Expedition*.

[3] The term *ISO* is not an acronym for the name of the organization; it is derived from the Greek *isos*, meaning "equal," which is the root of the prefix *iso* that occurs in a number of terms, such as *isometric*. For more details, go to http://www.iso.ch/iso/en/ISOOnline.frontpage.

[4] A safe practice in this regard is to spell the month's name, or at least the first three letters, for example, Jun 15.

on archived projects. Fortunately, we can store, on a single compact disc (CD) or similar media, more than an entire file cabinet can hold. Not only is this possible, but also the ease of searching and retrieving the information is incomparable. Retrieving information for live (current) projects can be performed easily by using computer search commands. Retrieval also includes resurrecting information on closed-out projects that were archived, which may be important in some legal cases. One common practice these days is to store information on a computer accessed remotely via an Internet Web site (or in the "cloud") so that it can be retrieved from anywhere. This can be done either by "renting" a memory space or storing the information on one's own Web site. Ownership of data is an important issue that must be addressed by users.

Transferring information from one program to another may not be as smooth as we would like. Information may get distorted or "chopped" when we go from one program to another or even from an old version to a new version of the same program. Although software vendors make claims about the compatibility of their products with Microsoft (MS) Project, Primavera, and other products, glitches and discrepancies should be expected. The problem may not be in the compatibility per se but in the different functions of, and terminology used in, the programs. For example, Primavera products allow combination relationships (start to start plus finish to finish). MS Project limits logic relationship between two activities to only one. So, if you transfer a project from Primavera P3/P6 format to MS Project format, some relationships may be dropped. In addition, products are frequently updated, so their compatibility may not remain intact. You must be careful with any transformation.

The ability to convert and open electronic files and to read the information is extremely important. For this reason, the author advises against using unknown software packages unless you are certain that such products communicate with more common products without problems.

12. *Secure*: An organization's information must be secure against loss, damage, or theft. This requires that the information be handled by professionals, since risks have increased due to the failure of technology to prevent hacking and vandalism.

## THE DIFFERENCE BETWEEN REPORTS AND PRESENTATIONS

Although reports and presentations both are types of communication that aim at conveying information, one major difference exists between them. The printed materials of a report are the only vehicle for conveying information between the person preparing the report and the person receiving it. For this reason, the report should be clear and complete. In contrast, a presentation focuses on a speaker's persuasive skills, although a printed report (partial or complete, detailed or summarized) is sometimes provided to the audience. The speaker focuses on certain points, using oral, visual,

and written or printed tools. In addition, audiences usually have the opportunity to ask the speaker to elaborate on or to explain any point that is unclear to them.

Presentations are used for a variety of purposes, both within an organization and for outside parties. They may carry a lot of weight in influencing an audience's decision to buy a product or service. Four types of presentations are as follows:

1. *Contract candidate presentations*: Many owners require a presentation as part of the selection process for design, construction, or construction management professionals. The main focus of the presentation is to convince the owner (or the decision maker) that the presenter not only can do the job but also can do it better than other candidates can. This type of presentation should simply answer the owner's explicit or implicit question: "Why should I (we) hire you?" In many cases, contractors and consultants win contracts from owners with the help of a brilliant presentation, even though they may not be the lowest bidders.
2. *Sales and demonstration presentations*: A representative of a manufacturer or a vendor may give a presentation to demonstrate a product (e.g., computer software, an office machine, specialized equipment).
3. *Project status presentations*: A project manager or a team member may give a presentation to upper management on a particular project and its status. Such a presentation may be conducted both periodically and on an as-needed basis.
4. *Management presentations*: The management of a company may conduct a presentation to its staff in order to inform them about a new work plan, a new system, a new organization, or something else.

A sales presentation and an educational presentation are significantly different, although they have several characteristics in common. The first two types of presentations described earlier are mostly the sales type, even though they may have some educational content. A presentation on computer software does not aim at teaching its use to the audience. Rather, such a presentation focuses on the features and points of strength in the software; it attempts to impress and influence rather than to educate. It can be biased and subjective for the purpose of making a successful sale. The last two types of presentations described are mostly educational or informative. We can argue that they are also "sales" presentations. In project status presentations, the project manager may try to impress the management for self-promotional purposes. In management presentations, the management is "selling" a new work plan or a new system to the employees. Still, the main difference is that the last two types do not usually lead to a direct sale.

Another key difference between presentations and reports is the time constraint. Reports are submitted to a party who can read and review them at his or her own pace (within deadline restrictions). Presentations are time constrained. The information flows at the presenter's pace (within time-limit restrictions), not the receiver's. A large amount of information could be included in the presentation, but the presenter's challenge is to prioritize this information and focus on important issues that

have more influence on the audience, particularly the decision maker. In many cases, the presenter refers the audience to a detailed report (which may be available with the presentation) or to an external source (e.g., an Internet Web site or an article in a journal or a magazine).

One advantage of electronic reports is the ability to hyperlink certain information. For example, an executive summary may be only one page long, but certain words may be hyperlinked and can take the reader to more details inside or outside the report.

Scientific seminars and short courses are not relevant to this discussion, although they are still subject to "good communication criteria." Thus, they are not covered.

## SKILLS NECESSARY FOR GIVING GOOD PRESENTATIONS

In addition to learning the characteristics of good communication described previously, presenters should develop eight skills for giving good presentations:

1. *Focus on the client's needs*: The presenter should present his or her product or service in the best way that serves the client (audience). The product or service may have great features that are not relevant to the client's line of work. Elaborating on such features would be a waste of time. The presenter's main focus must be on how to meet the client's needs.
2. *Be honest*: Even though the presenter's ultimate goal—in most cases—is to sell a product or a service, the presenter should be honest and objective at all times, especially with regard to facts and numbers. For instance, making a statement such as "Our product is the best on the market" is easy to do, but backing up this statement with numbers, such as the sales volume, the number of clients served, and the results of a customer satisfaction poll, would make a better statement. It may be difficult for the salesperson but ethically required to admit to the client that his or her product does not meet the client's needs or that there is another product in the market that meets those needs better.
3. *Ensure that materials are visible*: The presenter must make sure that the materials displayed on the screen are comfortably viewable and legible from all sides of the room. If possible, the presenter should test the display from several positions in the room before giving the presentation. During the presentation, the presenter should stand in a position that does not block the audience's line of sight.
4. *Speak clearly*: The presenter should speak clearly and with authority, occasionally interacting with the audience and sometimes using humor. The tone of the speaker should change occasionally based on the context of the presentation.
5. *Make eye contact*: The presenter should speak to the audience and not to him- or herself or to his or her notes. Eye contact with the audience is extremely important. Eye contact should be made with not just those in the front row or closest to the presenter but with everyone in the audience.

6. *Watch your body language*: Body language and hand and arm gestures are important. General advice on this topic and special advice about body language in certain cultures can be found in many articles and books that have been written on this subject.
7. *Manage time wisely*: Presentations almost always have time limits. Besides, human beings have a limited attention span. It is easy to become side-tracked and lose track of time, sometimes because of an audience's questions and comments. A good presenter sets "milestones," for example, that when the presenter reaches half-time, the presentation will have reached a certain point or slide. Putting a watch or a small clock on the podium—preferably unseen by the audience—may be a good idea (but should not be a distraction to the speaker).
8. *Have a backup plan*: Some precautions should be taken in case something goes wrong before or during the presentation. Items to have on hand include an electrical extension cord, a signal cord, an electronic copy of the presentation on a USB flash drive, an electrical adaptor, and a printout of the presentation. Using a remote control to move through the slides is a must that gives the speaker the freedom to move around the room. If the presenter is not using a personal computer, he or she must make sure the necessary software (e.g., Microsoft PowerPoint) is installed on the computer that will be used. It is important to test everything before the presentation.

In addition to the preceding points, there are many hints on how to improve a PowerPoint presentation and/or handouts. Recently, Prezi software has been gaining grounds as a competitor to MS PowerPoint. Such hints plus more hints on good speaking and delivering good presentations can be found in specialized references. The author recommends Toastmasters International[5] for those who would like to improve their speaking skills and self-confidence.

## THE POWER OF PRESENTATIONS

Current technology gives us powerful tools with which to create, manage, manipulate, present, disseminate, and store data. When producing reports or presentations, we typically have many options for organizing and displaying information. Any cost estimating, scheduling, project management, or other software has tens if not hundreds of standard reports. Users can also create and customize their own reports. Third-party software packages can provide even more reporting templates. Each report has its own settings, rules, and options. Many features in these reports can be adjusted or turned

[5] Toastmasters International is a nonprofit organization that was established in 1924 to train people to have better communication and leadership skills. It has local clubs in almost every U.S. city and in many other locations worldwide. For more information about this organization, visit http://www.toastmasters.org/.

on and off. Many users use these reports "as is,"without paying careful attention to the default settings and consequently the output.

To create a good report, you should ask yourself the following questions:

- Does the report include all of the information that the report user needs?
- Does the report include any unneeded information?
- Is the information clear and well organized?
- Is the information presented in the required format?
- Can the look of the report be enhanced?

The report must address the specific needs of the recipient. For example, if the report is for an upper-level manager who is responsible for tens or hundreds of projects, it should be brief and precise, containing a powerful summary that is not overly detailed. If the manager needs more information, then he or she can request more details on a specific topic (electronic reports may contain hyperlinks that lead to more details if needed.)

A progress payment report may not need to show bar charts or technical details, such as total float, constraints, and so forth. Likewise, a report issued by the general contractor to a subcontractor may not show details of other subcontractors' activities that will not affect this subcontractor's work. The general contractor may not want to reveal the total float to subcontractors and, similarly, may not want to reveal certain information, such as the actual cost, when presenting a report to the owner.

The report should focus on one main issue or area. For example, the look-ahead schedule shows the contractor what is supposed to happen in the next 2 weeks or month. Selecting activities with a total float of less than 3 days, for example, allows the contractor to focus on the critical path. When the project is large, it is divided into several areas, departments, or phases. The scheduler can then produce reports that cover a relatively small group of activities, grouped by building, floor, phase, and so on, one group at a time. In some reports, the scheduler can show all areas, departments, and the like, summarized by a single bar per code. Use of software filters[6] and the organize function helps in choosing, sorting, and grouping activities efficiently.

The information in a report is composed of text and graphics. Graphics are an excellent tool if they are used properly. Graphics include bar charts, logic diagrams, flowcharts, pictures, video clips, and other items. Graphics are best used to support a result, a finding, or a recommendation or to explain a situation (e.g., a bar chart for a project schedule). However, overuse or misuse of graphics may be counterproductive. Text should also be organized. Using tables, bullets, and short paragraphs helps the reader separate and focus on specific issues in the report.

Careful use of vivid colors can help the report user understand the report more easily. For example, red is customarily used for critical activities. Bars representing

[6] A *filter* is a function in some computer scheduling programs, such as Primavera products. Its main function is to pick certain activities on the basis of specified criteria.

activities that are under way or completed should be clearly identified. Black-and-white graphic reports, even with varying grades of shading and/or patterns, may not be as powerful as reports presented in color.

The size of report pages may be specified by the owner (the party that will receive the report). Many schedulers print the schedule on regular letter-size, 8 1/2-by-11-inch) paper, which will fit in a folder or a binder with other project documents. It is also customary to print the schedule on 11-by-17-inch paper and then fold it to fit an 8 1/2-by-11 size. However, project managers like to print a complete schedule on a large piece of paper (size D or E) and post it on the wall inside the project trailer. Regular inkjet and laser printers can handle paper as large as 11 by 17 inches. Plotters can handle larger sizes of paper.

Any report—text or graphic—should contain the following information:

- Name of the company and department or division; address of the company, especially if multiple offices; company logo
- Name of the person preparing the report and supervisor's approval (initials), if needed
- Name and location of the project
- Date
- Title of the report
- Attachments, if any
- Page numbers (if multiple pages) in a format such as "Page 2/6" so that missing pages can be placed where they belong
- Legends to explain any graphics and colors in graphic reports
- Definitions of terms and acronyms or abbreviations that may not be known

In some cases, hiring a professional to prepare a report makes sense if the company does not have the expertise or time to produce a high-quality professional report. Always remember:

- The human being behind the computer is more important in making judgments than the computer itself. The computer (including software and printer) is a wonderful tool, but it is still just a tool.
- In reports, there is no "one size fits all." Reports must be customized for different parties in different occasions.

## REVIEWING REPORTS BEFORE AND AFTER PRINTING

Since reports often comprise many pages and color printers may be slow, a report should be reviewed on the computer screen (in Print Preview) to make sure that it looks fine. If the report comprises many pages, the author recommends printing a

sample page: review and approve it and then print the entire report. Remember that, in many cases, what you see on the computer screen may not be what you get.

An error may occur in any report. It may be caused by the software, the hardware (computer or printer), or the user. Thus, the scheduler should review the report after printing it but *before* submitting it, because errors may be found in a report even after it has been successfully reviewed on the computer screen. Many printers in professional offices are shared, and people may pick up their printout only to discover later on that the printout contains pages that don't belong to them. Some companies with multiple offices enable employees to send printouts to any printer, in any of their offices. This is a great convenience; however, the software usually retains the last used printer as the default printer until the application is turned off. So the user may decide to print another report, hit the Print icon (or button), thinking that the report will go to the original default printer around the corner, but, instead, the report goes to a printer in another office!

## GENERAL TIPS ON PRINTING REPORTS

In many cases, the scheduler must repeat the printing process several times because of errors, missing data, or instructions from the supervisor or other clients. The result is multiple printouts of the same report. Although some reports indicate the time and date the report was printed, the scheduler may become confused by the similar printouts and submit an incorrect copy of the report. For this reason, invalid copies of any report should be destroyed or recycled as soon as an error or omission is detected and the decision to reprint is made.

For some projects, certain reports must be printed with every update. Primavera software gives the user the opportunity to combine all of these reports in a "series." In this case, the scheduler chooses one series rather than several individual reports.

While organizing the report, the person preparing the report may want to separate issues, areas, phases, and so forth, and perhaps print each on a page. However, the scheduler must be careful not to waste paper unnecessarily. Several ways to condense a report and save paper are as follows:

- Make sure that only the needed activities and information are included in the report. Use the software filter to help exclude unwanted information.
- Margins may be slightly reduced to allow more information per page.
- The choice between Portrait and Landscape may make a difference as to how many pages the report comprises.
- Using a smaller or a different (narrower) font may help. However, make sure that the report is comfortably legible.
- Use the Fit to One Page function in the Print menu (but keep in mind that it doesn't always give good results).
- In limited cases, you may print on both sides of the paper.

- Most importantly, many reports and other types of communication may remain in electronic form and need not be printed. The most common format across organizations is the PDF (Adobe Acrobat) format. A report in PDF format may be produced directly by the software in this format or can be converted through other software.

## SUMMARY REPORTS

The scheduler must relate the schedule information to the project manager not only as computer-generated colorful charts but also in clear language. For example, after a periodic update, the scheduler will likely produce standard Primavera or MS Project reports, including bar charts, cost tables, and so forth. Along with the reports, a document (written in plain text) summarizing the situation should be included. This summary report should contain the following information:

- The overall situation of the project: the total float for the critical path and the updated expected completion date.
- The preceding information as compared with that in the last update: did we gain or lose any days?
- The new critical path, if it has changed: what is delaying the project?
- Cost information (if applicable): cost this period, cost to date, cost to complete, cost variance, cost at completion, and forecast cost variance.
- Any other information that may help the project manager identify or anticipate trouble spots or make up for any lost time, as well as any suggestion to resolve troubled situations.
- No unnecessary details, such as routine progress per activity or a slight delay in activities that have sufficient float.

The summary report should not exceed one page or two pages. It should be written in the form of a memorandum as a simple word-processed document.

## PAPER OR ELECTRONIC REPORTS?

Computers have become an essential part of our lives and businesses, including project management. Many documents are now sent electronically. Electronic signatures are even legally accepted in many situations. Nevertheless, some documents still must be printed on paper. Either way, the contractor, the design professional, the construction management consultant, and the owner must be able to store, manage, and retrieve information efficiently. The software industry has developed several software packages for this purpose, such as Primavera Contract Manager, Meridian's Prolog Manager, and Timberline's Project Management. These software packages help organize the "paperwork": transmittals, submittals, purchase orders, payment requisitions,

telephone logs, RFIs (requests for information), requests for proposals (RFPs), proposals, change orders, memos, invoices, notices, general correspondence, meeting minutes, daily reports, and any other documents that relate to project management. Such software also helps speed up communications, including the review and approval processes. There are also many document management software programs that go beyond the objective and capabilities of those software programs mentioned earlier. Such software packages are becoming more and more powerful:

- They are continuously being expanded, and more modules are being added to them to circumvent all facets of project management.
- They can be integrated with other programs (CAD, BIM, estimating, accounting, scheduling, etc.).
- They include many standard forms, including some third-party forms.
- They allow the user to tap into the software through their SDKs (software development kits) and to customize certain aspects or to export data.
- They allow project team members to go on the Web (Internet and intranet) and view and respond to documents from anywhere.
- They can be linked to external devices such as cell phones (PDAs), tablets, iPads, and Blackberrys.

Users of electronic media should follow certain precautions, such as the following nine points:

1. Back up your documents periodically or even automatically. If you are on a local server and are using a shared drive, be sure to back up your documents regularly. Keeping a backup copy in a safe place away from the company's building is also a good idea. One of the options available these days is to keep a backup copy in the "cloud" such as Google Drive or Microsoft OneDrive. Doing so is a precaution against fires, floods, hurricanes, theft, and other events that can destroy the records. Having all the information in one local location only, such as the scheduler's notebook computer, is dangerous and unwise.
2. Programs such as Oracle Primavera P6 either have no Undo function or a limited Undo function. There is no Save As function. Whatever you do will likely be permanent and cannot be reversed. For this reason, if you want to experiment with some "what-if" scenarios, make a copy of the schedule and leave the original intact. Once you finish experimenting, move, delete, or archive the file so that it does not get mixed up with other files.
3. When e-mails are used for communication, print important e-mail messages or transfer them from the Inbox to a secured folder or box that is out of the e-mail system. Most e-mail systems automatically "clean up" the Inbox periodically (e.g., every 6 or 12 months).

4. For projects that require periodic updating, always make a copy of the schedule before updating the schedule. The names of the schedules must follow a pattern that represents the company's policy. The old Oracle Primavera P3 allowed only four characters for a file name. One good practice was to use two alpha characters to identify the project and two numerical characters to indicate the number of the update (starting with the baseline, 00). Oracle Primavera P6 and MS Project do not have this limitation and allow almost as many characters as the user desires. However, the scheduler must still choose a pattern for naming project schedule files and should use it consistently. All versions of a project schedule should be stored in an organized and systematic way. An example follows:

   **When limited to four characters (P3):**

   C:\Schedules\Tampa\OfficeBuilding\OB00
   . . . . . .\OB01
   . . . . . .\OB02
   . . . . . .
   C:\Schedules\Orlando\SmithBuilding\SB00
   . . . . . \SB01
   . . . . . \SB02
   . . . . . .

   **When not limited to four characters (P6 or MS Project):**

   C:\Schedules\Tampa\ShoppingCenter\TpaOfficeBldg00
   . . . . . .\TpaOfficeBldg01
   . . . . . .\TpaOfficeBldg02
   . . . . . .
   C:\Schedules\Orlando\CityGarage\OrlandoCityGarage00
   . . . . . \OrlandoCityGarage01
   . . . . . \OrlandoCityGarage02
   . . . . . .

5. Many documents are scanned and stored, mostly in PDF format. If this document is mainly text, try to scan it as a text, not image, file. This not only may reduce the storage size of the document, but more importantly enables the system users to search for keywords. Even text documents that were received as image can be converted to text using Adobe or other programs.
6. When making a copy of the schedule (or any project-related file) on a CD or DVD, label or identify it with the project name, version, and date. Don't store any unlabeled CDs/DVDs that are loaded with data.

7. Some users of simple programs, such as word processors and spreadsheets, "insert" the date format rather than typing the date itself. For example, MS Word has an Update Automatically option that can be turned on or off. Serious problems may result if this option is unintentionally turned on. The document may have originally been created on OCT 15, 2013, but the project manager may need a copy of the document on DEC 16, 2013. The date that would appear on the document would be DEC 16, 2013, not the original date, OCT 15, 2013. Note that many users do not usually pay attention to software options, which may also result in unintended consequences.
8. It has been said that your hard drive is like your garage: no matter how large it is, it will soon be full of junk. For this reason, completed projects should be archived. Thanks to new technology, what formerly occupied several file cabinets can now be stored on a single CD or DVD. Because of the fragility of CDs and other electronic media, however, making duplicate CDs or other electronic media and storing them in different locations may be wise. Make sure that the CDs are labeled properly. Having another copy stored on an Internet Web site is also a good idea. Storing old files or a separate sector of the server or online is also possible and may be more advantageous for a multiuser environment.
9. Only professionals should be in charge of company technology. Computer viruses and hackers often cause serious damage. An overlooked or a careless action by an employee may cause the computer system in a company to shut down for a period or may erase important files, which may result in huge losses and inconvenience. For this reason, large companies usually dedicate a department to taking care of information technology (IT) and safeguarding electronic correspondence.

## E-REPORTS

Reports can be e-mailed, but the sender must make sure that the receiver has the proper software with which to open them. Many computer programs offer the Save As option with several format options. Some of the formats that have become popular are the HTML and PDF formats, which allows any user to view the report. Several Primavera products call this option the *Publish* function. When the e-report has multiple files, the sender may want to "zip" them into one compressed, self-extracting file. The receiver may want to create a temporary folder in which to download the zip file, and then extract it there. Large attachments should not be sent unless the receiver approves such an action. Large files can be uploaded to an FTP site, and then the FTP address should be sent, along with the user name and password, to the receiver, who can later download the files. When sending several documents/reports, the sender should include a table of contents with a brief description of each report and then identify each report.

## COMMUNICATIONS IN THE INTERNATIONAL ENVIRONMENT

Technology has rendered the world smaller. Not only can project participants (owner, architect, structural engineer, mechanical engineer, general contractor, etc.) be located in different regions or countries, but also many companies now have a diversified workforce. Thus, making a mistake as a result of lack of knowledge about a local culture and work environment is easy, and possibly embarrassing and costly.

Many books and articles have been written and many seminars have been conducted on this subject. We cover only some scheduling-related issues:

1. In most countries, the date is written in the day/month/year format rather than in the customary U.S. date format of month/day/year. A date such as 11/8/2010 can cause a crisis if it is meant as the 11th day of August but is interpreted as the 8th day of November. For international projects, writing the name of the month, rather than its number, is recommended. The previous date can then be written as 11 August 2010. Alternatively, the month may be abbreviated by three letters, such as 11 AUG 2010.
2. Most of the Western world starts the workweek on Monday and takes Saturday and Sunday off as nonworkdays (weekend). This is not necessarily the case in other parts of the world, such as the Middle and Far East. The weekend could be Friday and Saturday. Thus, software defaults must be checked and adjusted accordingly.
3. Holidays differ from one country to another. They may have to be inserted as nonworkdays in the schedule. Even Christmas is not observed on December 25th in all Christian countries. Some people (Orthodox Church) celebrate it on a different date, January 7.
4. In the daily work schedule, the number of workdays (5 or 6), start time, finish time, lunch break, "siesta time," and other breaks may also differ. In some countries that have extremely hot summers, government regulations forbid outdoor work during certain hours of the day. Thus, productivity, and hence activity durations, may have to be recalculated.
5. Weather can have a significant impact on the schedule. The project management team must be fully aware of local weather, including seasonal floods, hurricanes, sandstorms, rain, and so forth.
6. The labor market and customs also differ from one place to another. In some countries, most of the skilled labor needed in construction projects is imported. In such countries, it is not unusual to see workers from different backgrounds (ethnicities, religions, cultures) working together. In some cases, workers on the same project do not speak a common language, and therefore communication becomes a challenge for management.
7. Availability and methods of acquisition and delivery of materials and equipment may differ significantly. In some countries, rigid or slow customs procedures may cause major delays.

8. Permits and government procedures for approval may also differ and may require special consideration.
9. Contracts also differ. Even though there are some internationally known and used forms (e.g., FIDIC), certain provisions and practices differ. For example, in some countries, a percentage (10 to 20%) of the total contract is paid to the contractor upfront and then is recovered gradually by deducting the same percentage out of progress payments. Retainage (also called *retention*) rules may also differ. Types, definitions, provisions, and cost of bonds and insurance also differ from one region or country to another.
10. Communication among different cultures, even among those who speak the same language, may result in misunderstandings. For example, in the United Kingdom, scheduling is referred to as *programming,* with the schedule called *programme*. The same word may have two different meanings to two people. There is a big discussion on what is conceptual design, preliminary design, schematic design, and design development.

    Body language and hand gestures may have different—and possibly obscene—meanings in different cultures. In fact, a person may unintentionally insult another person because of a misunderstanding or a language or cultural difference.
11. Currency exchanges may create a nightmare for management. In some international contracts, the budget may be set in U.S. dollars but the materials and labor are paid in local currency. The exchange rate may differ from day to day. It is not uncommon for the same contract to include two currencies at the same time. The management team must deal with such situations carefully.

## CHAPTER 9 EXERCISES

1. List the characteristics of good communication. Briefly explain each.
2. Why do you think communication is an important issue? Can you mention a situation in which the lack of good communication resulted in negative consequences?
3. What is the *lazy designer syndrome?*
4. You are a new scheduler for a medium-sized project. You joined the company after the project started. The project manager asks you to prepare a report that tells her "everything about the schedule." Does this statement provide sufficient instructions for you to create the report? If not, list the questions that you will ask the project manager so that you will know exactly what you need to print out.
5. You were hired by a company that does not have a formal policy for managing schedule files. Schedules are currently on the project manager's laptop (created with SureTrak Project Manager software[7]). What precautions do you recommend to ensure the uniformity and security of the schedules?

[7] Old software by Primavera Company, that was replaced later by Oracle Primavera Contractor.

6. Mention and briefly describe the various types of presentations.
7. What are the major differences between reports and presentations?
8. Indicate which type of presentation is required for each of the following situations.
   a. The owner of a large project has a short list of three contractors. They all seem qualified, but the owner wants each contractor to present the way he or she will build the project so that the best contractor will be chosen.
   b. Primavera and Meridian are competing on a bid to provide project management software to a local government. Each provider will be given a 2-hour time slot in which to show the advantages of the software. Following this, the government will make its choice.
   c. The government in exercise b chose the software. Now, it hires a consultant to teach the use of the software to its employees.
   d. A large company changes its medical insurance provider. As a result, many terms of the insurance have changed. Linda, a human resources manager, will give a presentation explaining the new terms and procedures of the new medical insurance.
   e. A construction company is in financial trouble. A new president was appointed by the board of trustees. He lays out a recovery plan for the company. He will present this plan to the employees.
   f. Before the new president presents his plan in exercise e, he requires each project manager to give a presentation on the status of his or her projects to the upper management members.
   g. A large company is hiring a chief estimator. There are three top candidates. As part of the interview process, each candidate must give a presentation simulating the estimation of a real project.
9. List some tips for giving a successful presentation.
10. "The report must focus on certain issues." Discuss this statement and mention some helpful tips.
11. In addition to the main data in the report, what type of information should a report contain?
12. Why is it important to review a report before and after printing it?
13. Provide some tips on saving paper when you are printing reports.
14. You are the scheduler for a shopping center project. You just finished an update on many activities occurring in the project. You printed the updated bar chart and cost tables, but you missed something important before submitting the report to the project manager. What was it? What kind of information must you include?
15. Your company is trying to "go electronic." It just bought new computers and a new server. You are given the task of writing a set of instructions for all project

managers and their personnel on the procedures for storing and managing the projects. Outline your plan.

16. In the previous exercise, since you are the only "computer guru" in the company, you are also given responsibility for the company's information technology. Outline your plan to back up and secure the company's files.
17. Mention some tips for a project manager who will be taking over a new project in the Middle East. Bear in mind, this is the project manager's first trip overseas.
18. Can you mention any situation in which not understanding a particular language or a culture resulted in an embarrassment or a loss to a company? This experience does not need to be personal. You may use any real story.

Chapter **10**

# Scheduling as Part of the Project Management Effort



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## INTRODUCTION

Construction project management comprises several components that are often interrelated. Typically, one person (the project manager, or PM for short) is responsible for running and managing the overall operations. Under the PM is the project management team, which may consist of a large number of professionals (assistant PM, project superintendent, project engineer, scheduler, estimator, quality manager, safety manager, procurement manager, document control manager, contract administrator, accountant, clerk, secretary, etc.) for large projects. Small projects typically have a smaller team, and some of the team members may have more than one role and/or may be working on multiple projects.

The management team typically includes field and office personnel. It may include team members who are dedicated exclusively to a particular project and others who are assigned to the project part time (they work on other projects as well) or serve on the project for only a temporary period. For example, a project scheduler may be dedicated to one large project even if he or she works in the main office. For smaller projects, the scheduler may distribute his or her time among assignments for the different projects.

Managing projects requires several skills. We must distinguish between managerial skills and technical skills. In some cases, a person who is top notch in his or her technical field may fail completely as a manager. Managerial skills are essential for a PM. An interesting statement is found in *Commentary on AIA Document A201–2007* (The American Institute of Architects, 2007, p. 14, http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aias076835.pdf): "A superintendent cannot build a project alone, but an incompetent superintendent can single-handedly ruin one." This statement applies even more so to the PM. It is outside the scope of this book to discuss the characteristics of a good project manager. With regard to technical expertise, construction is a diverse industry; within each type are many specialties, such as demolition, excavation, concrete, masonry, carpentry, structural steel, finishes, electrical, HVAC (heating, ventilation, and air conditioning), plumbing, and many others. Within each specialty might be numerous subspecialties. Rarely, if ever, a person is an expert in all fields. A typical PM may be an expert in one or a few fields, but the PM must be familiar with all of them in order to manage the project competently.[1] Each technical area is usually headed by a foreman, who must be an expert in that particular field.

Scheduling is one of the important pieces of the "project pie." It is a technical field that is concerned with time calculation and management. Scheduling interrelates with other components of the overall project management. In this chapter, we briefly discuss some of these interrelationships.

[1] The PM's expertise is generally described as "an inch deep, a mile wide."

## PROJECT OBJECTIVES

Many project management professionals use similar versions of Figure 10.1 to emphasize the "project objectives." They are considered the three most important "objectives" in project management:

1. *Scope/quality*: that is, to achieve the project scope within the specifications prescribed in the contract.[2]
2. *Cost/budget*: that is, to complete the project within (on or below) the set budget.
3. *Time/schedule*: that is, to complete the project within (on or ahead of) the schedule.

Every project has one objective and one objective only: to complete the scope of the work as described in the contract documents. There is no question that being on budget and on schedule are very important, but in the author's opinion, they are requirements and constraints. In fact, there are other project requirements and constraints, but traditionally we think of cost and schedule as the most important ones. For example, we can't say the objective of our project is to build a 10-story office building in Tampa, Florida, within certain specifications, to spend up to $12 million, and to take up to 18 months in construction. The correct way to make this statement is: "The objective of our project is to build a 10-story office building in Tampa, Florida, within the contract specifications. The most important project constraints are not to exceed the $12 million budget and to finish the project within the 18 month schedule." Figure 10.2 shows the correction of Figure 10.1. These constraints interact with the scope (the objective) and with each other.

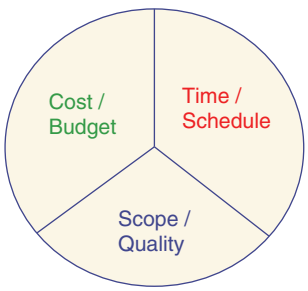



**Figure 10.1 Project objectives**

[2] Quality is not a measure of goodness. It is rather the conformance to specifications.

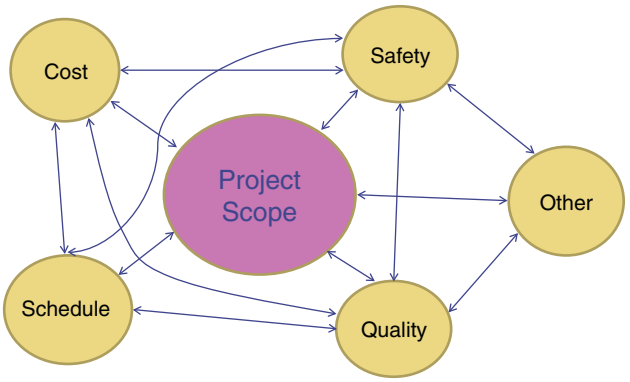



**Figure 10.2 Project objective and constraints**

## DEFINING AND MEASURING PROJECT SUCCESS

*Success* has been defined in different ways; however, what seems to be in common among all definitions is, "the achievement of something desired, planned, or attempted." So, we can define *project success* as "achieving the project objective within the defined constraints." What is interesting about project success are two things:

1. Success can be seen from different perspectives: the owner, the designer (architect or engineer, A/E), the contractor, the construction management consultant, the general public, and so forth. Success for one party may not necessarily mean success for the other parties. For example, an investor has chosen a poor location for a hotel. The designer and the contractor did a great job in designing and building the project, but due to the poor location, the hotel has not attracted many customers. In such a case, the project is successful from the designer's and contractor's perspective but not from the owner's. It would be great if all parties partnered together so that they could all succeed together. There are many models for partnering; however, each party still has strategic goals that define success for him, her, or them.
2. Project success is not a simple yes (100%) or no (0%). There are degrees of success. This author suggests using a model that lists all criteria (constraints and requirements) along with their relative weights that represent their importance to the user (see Table 10.1).

By assigning weights, the user can put more or less emphasis on certain criteria. For example, a stadium for the World Cup or the Olympic Games may have a heavy weight for the schedule. Another environmentally sensitive project may have a higher weight for its environmental friendliness. Tables 10.2a and 10.2b make the grading of the cost and schedule performance more objective. The user can create similar tables for other criteria.

**Table 10.1 Project Success Measuring Model**

| Criteria | Weight | Score (out of 10) | Weighted Score |
|---|---|---|---|
| Cost | 35 | 8 | 28 |
| Schedule | 25 | 10 | 25 |
| Safety | 8 | 9 | 7.2 |
| Environmentally friendly / Sustainable | 4 | 7 | 2.8 |
| Change orders | 8 | 6 | 4.8 |
| Claim disputes | 7 | 8 | 5.6 |
| Relationship with other parties | 5 | 8 | 4 |
| Public image | 3 | 9 | 2.7 |
| Satisfied employees/workers | 5 | 8 | 4 |
| **Total** | 100% | | 84.10% |

**Table 10.2a**

**Cost**

| Outcome | Grade |
|---|---|
| Finished on or under budget | 10 |
| Cost overrun < 1% of budget | 9 |
| Cost overrun 1–2% of budget | 8 |
| Cost overrun 2–3% of budget | 7 |
| Cost overrun 3–4% of budget | 6 |
| Cost overrun 4–5% of budget | 5 |
| Cost overrun 5–6% of budget | 4 |
| Cost overrun 6–7% of budget | 3 |
| Cost overrun 7–8% of budget | 2 |
| Cost overrun 8–9% of budget | 1 |
| Cost overrun > 9% of budget | 0 |

**Table 10.2b**

**Schedule**

| Outcome | Grade |
|---|---|
| Finished on or ahead of schedule | 10 |
| Finished late 1–3 days | 9 |
| Finished late 4–6 days | 8 |
| Finished late 7–9 days | 7 |
| Finished late 10–12 days | 6 |
| Finished late 13–15 days | 5 |
| Finished late 15–17 days | 4 |
| Finished late 18–20 days | 3 |
| Finished late 21–23 days | 2 |
| Finished late 24–26 days | 1 |
| Finished late > 26 days | 0 |

Keep in mind that the model shown is an attempt to measure project success as objectively as possible. It is not necessarily unique, and it may not always reflect the degree of success realized by all parties.

## SCHEDULING AND ESTIMATING

Scheduling and estimating are closely related, and their relationship is probably one of the most important relationships in project management. They both make predictions on future consumption: money for estimating and time for scheduling. They are both

updated and adjusted during the execution of the project, and every attempt is made to get the project completed within the baseline (estimate): money and time. These two functions intersect in many ways, such as the following eight:

1. The estimator needs to know how long the project's duration is in order to estimate certain costs, particularly overhead costs (management team, field office, utilities, etc.).
2. Estimating and scheduling departments collaborate to provide information to the procurement department. The estimating department explains what resources are needed and how much, and the scheduling department tells when they will be needed. This facilitates the procurement of labor, materials, and equipment.[3]
3. The scheduler sometimes estimates the durations of activities with help from the estimating department, since estimators usually keep track of the crews' productivities.
4. Many schedules are cost-loaded. The cost must be imported (manually or electronically) from the cost estimate.
5. In most construction companies, tracking of money and time are combined under the Project Control Department. This department typically includes cost estimators and schedulers who continuously compare the actual performance to the baseline budget and baseline schedule. Earned value management (EVM), discussed in Chapter 7, is part of the project control effort and is an integrated approach to project cost and schedule control.
6. **Progress payments** depend on the schedule of values (prepared by the estimator) and the percent complete (reported by the scheduler[4]).
7. Resource allocation and resource leveling are cost related, although they are scheduling functions.
8. Schedule compression always involves a balance between cost and time.

Both cost estimating and scheduling require breaking down the project into smaller components (activities, tasks, items, etc.) that are managed and controlled easily (usually homogeneous, measured with one unit). However, the cost estimator and the scheduler may think differently about this breakdown. The cost estimator usually divides the project into items according to their nature, with no regard to location or chronology. So, 2-by-4 wood studs can be combined in one item, even though they may be installed in different locations and with different timing. The scheduler's attitude toward the project breakdown is focused on the timing

[3] The project schedule might have an impact not only on the procurement schedule but also on the estimate, because the timing may affect the cost of labor, materials, and equipment.

[4] Percent complete is initially reported by the field crews (foremen) but collected and formalized by the scheduler.

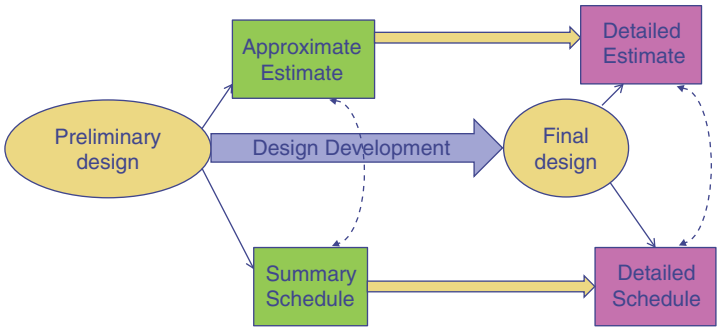



**Figure 10.3 Evolution of a schedule and cost estimate for a project**

and location of the work item, not its homogeneity. For example, many schedulers combine the formwork, rebar, and concrete placement for a reinforced concrete item (e.g., suspended slab) as "FRP Suspended Slab," even though formwork is measured by area (or contact area, to be precise), reinforcement is measured by weight, and concrete mix and placement is measured by volume. There also might be concrete curing and/or finishing along with them, which are measured differently.

Many construction and software professionals have suggested one project breakdown for both cost estimating and scheduling, and some of them have claimed success with this method. Still, this matter is far from being settled.

Other interrelationships exist between estimating and scheduling, as is shown in the following sections.

### Evolution of a Cost Estimate and a Schedule for a Project

When a contractor considers a project for bidding or negotiation, he or she needs to know the cost and the time frame.[5] (See Figure 10.3.) The owner usually specifies the required finish date of a project in the bid documents and the contract. However, the contractor must calculate his or her own estimate of the project's duration to ensure that he or she can meet the owner's stipulated finish date. If the contractor's schedule does not meet the owner's date, the contractor must either accelerate (crash/compress) the project to fit it within the given time interval or obtain the owner's approval to extend the time limit on the project.

Depending on the size and type of the project, as well as the contractual arrangement, the contractor may start with a rough estimate of the schedule (not necessarily a critical path method, or CPM, schedule, but an educated estimate of the time required to build the project). The contractor may use his or her previous experience and a "gut feeling" to estimate the duration of the major components of the project and to build

[5] Timeframe does not mean only the duration. It includes the time span during which the project will occur. For example, a project scheduled to occur during a winter season in Chicago will probably cost more than if it were built in the summer.

an initial rough schedule. After the contractor lays out an initial rough schedule, the contractor uses the duration to estimate the indirect cost items (overhead), such as the following:

- Project staff (PM, project superintendent, project engineer, receptionist or secretary, clerk, etc.)
- Office trailer
- Cars and trucks assigned to the project team
- Office equipment (copying machine, fax machine, computers, etc.)
- Temporary utilities (electricity, water, drinking water and ice, telephones, cell phones, gas, portable toilets, etc.)
- Other indirect project-related expenses

The cost of most, if not all, of these items is linearly proportional to time, although not all of them last for the entire duration of the project. This is why the estimator needs to know the duration of the project in order to assess the indirect expenses. The contractor also uses the time frame of the proposed project to study the impact on other work underway or planned and the resources required.

Schedules, like cost estimates, are created on the basis of available information. Reality (what will actually happen) is never fully known in advance. Thus, every cost estimate or schedule includes some assumptions and guessed information (some estimators like to call it a *guesstimate*). A difference exists, though, between a situation in which 90% of the information is known and 10% is assumed, and a situation in which 20% of the information is known and 80% is assumed. Estimators use one major criterion to differentiate, in principle, between approximate estimates and detailed estimates. Detailed estimates are obtained by performing quantity takeoffs from the design drawings and using the specifications. These detailed quantities are then multiplied by unit prices set by the estimator. Indirect expenses are added to the calculated direct expenses to yield the grand total.

In contrast, approximate estimates are based on comparing the project under consideration with previous similar projects (applying a unit cost, such as $140/SF) and then making adjustments according to the size, quality, location, timing, and so forth. No work breakdown or quantity takeoff is used in approximate estimates. The common factor between the two methodologies is that we start with the known information, which is supposed to be the majority for detailed estimates, and then complement it with assumptions for the unknown. With detailed estimates, we can look at the estimate and identify the cost of one particular item, such as a window, paint, or even a single footing. With approximate estimates, such identification is generally not possible.

In scheduling, no such clear distinction exists between a "rough schedule" and a "detailed schedule," but the process is similar to that for cost estimating. We start with the known information and complement it with assumptions. One frequent practice of designers is to show a construction activity as one bar without details. Once

a contractor is chosen, the contractor will submit a detailed construction schedule that should fit within the time frame of that single bar. This detailed schedule is then integrated into the original schedule created by the designer and replaces the single construction activity.

Summary schedules may also be used for speed, rather than a lack of detailed information. This approach is not generally used, and such schedules may not be used for field implementation or project control. This approach is also similar to using approximate cost estimates when the contractor needs to give the potential client a ballpark cost estimate of the project without spending much time studying the design drawings and specifications.

When the design is finalized, the detailed cost estimating and scheduling can be performed. This practice is used in the traditional delivery method, in which the project is completely designed and then a contractor is selected through the process of bidding or negotiation. In other delivery methods, a contractor may be selected[6] before the design is completed or even started, such as in design-build (D/B) or pure agency construction management (Pure CM or CM Agency) delivery methods. In this case, the design may come in stages, called **design development (DD)**. Each stage specifies a completed percentage of the design. For example, if the design is called *DD30,* it is approximately 30% complete. In this case, when the contractor estimates the cost and duration of the project, the contractor must use the available design information, and then supplement it with assumptions. Doing so is exactly like solving a 100-piece puzzle with 30 given pieces and the rest imagined. Later, the designer provides a more detailed design (e.g., DD60, DD90, etc.). The design is still incomplete but contains more information than in the previous stage. The contractor refines the cost estimate and schedule by replacing some assumptions with new design information. If the project schedule changes, the cost estimate may be affected. If the scope changes, both the cost estimate and the schedule may change. This process continues until the final design is issued. The final design[7] will be the base for the contractor's final cost estimate and schedule.

### Estimate-Generated Schedules

Some cost-estimating software programs can export such information as a project's breakdown to scheduling programs. In most cases, the result is a list of activities along with their durations but without any logical links (relationships). Before we discuss the estimate-generated schedule, let us briefly discuss how information is generated in cost-estimating programs. In short, with regard to labor and equipment costs, two methods for building the cost-estimating database are used:

[6] In some contractual arrangements, there is no prime or general contractor. Instead, subcontractors may contract directly with the owner (e.g., CM Agency which is CM not-at-risk) or with the construction management professional (e.g., CM at-risk).

[7] In the traditional delivery method, the final design is called the construction document and becomes part of the contract.

1. Provide the labor and equipment cost per unit. For example, if we are placing concrete for columns, using a pump, the cost is $25.18 per CY (cubic yard) for labor and $8.88 per CY for equipment. Although there is a basis for how we derived these numbers, the database does not contain this information or any details about how we generated these numbers.
2. For the same item, suppose that we are using Crew C-20[8] and this crew can place 90 CY per day. The cost of the crew is usually listed as part of the resource information in the database, not for each item. In our case, Crew C-20 comprises the following:

| Resource | Quantity | Cost/Hour Each ($) | Total Cost Per Day ($) |
|---|---|---|---|
| Labor foreman | 1 | 35.10 | 280.80 |
| Laborer | 5 | 33.10 | 1,324.00 |
| Cement finisher | 1 | 39.70 | 317.60 |
| Equipment operator | 1 | 42.95 | 343.60 |
| **Total Laborers** | **8** | | **2,266.00** |
| Gas engine vibrator | 2 | 3.80 | 60.80 |
| Concrete pump | 1 | 92.35 | 738.80 |
| **Total Equipment** | — | | **799.60** |
| **Total Crew C-20** | — | | **3,065.60** |

If we check the numbers,

$$\text{Cost/CY} = \text{Total daily cost/Total daily production}$$

so

$$\text{Labor cost/CY} = \$2,266/90 = \$25.18/\text{CY}$$

and

$$\text{Equipment cost/CY} = \$799.60/90 = \$8.88/\text{CY}$$

which is identical to the numbers obtained with the first method.

The second method has two advantages over the first:

1. If the labor or equipment rates change, you can make limited changes to the labor or equipment rate tables, assuming that you are using a computer. Such changes should automatically adjust the prices of all items, using these labor or equipment rates. In the first method, you must manually change every database item that uses the changed resources.
2. When you are deriving a schedule from the estimate, the first method does not indicate productivity and, thus, cannot provide the activity duration. The second method can provide the activity duration if you simply divide the total

[8] This example was taken from RSMeans Building Construction Cost Data (RSMeans 2010)

quantity by the daily production rate. For instance, in the preceding example, if we had to place 166 CY of concrete, the duration would be $166/90 \approx 2$ days. The PM might choose to use multiple crews or to adjust the productivity as a result of favorable or unfavorable conditions. Regardless, one source of productivity will feed both the estimate and the schedule.

Materials costs do not affect the productivity level, the durations, or the schedule. One important note regarding materials is how estimators apply the waste factor. A waste factor must be added to the estimate of the materials; however, good estimators differentiate between "takeoff quantity," which does not include waste allowance, and "order quantity," which does include such allowance. The problem with adding the waste allowance to the takeoff quantity is that it will apply to labor and equipment, although it shouldn't. This erroneously affects both labor productivity and cost. For example, suppose that you are taking off the number of studs for framing a building and you have calculated a total of 536 studs (2 by 4, 9' 4'' long[9]) are needed, that is, 3,335 board-feet. You want to order 600 studs (2 by 4, 10' 0'' long), that is, 4,000 board-feet. The total cost should be:

$$\text{Total cost} = \text{takeoff quantity} * [\text{unit price for labor and equipment} + \text{unit price for materials} * (1 + \text{waste factor \%})]$$

The scheduler must be extremely careful about using estimate-generated information, for three reasons. First, activities in such a schedule are defined by the estimator, not the scheduler. Second, the durations in such schedules are based on the productivity level built into the estimate items. In reality, the productivity level may need to be adjusted because of many factors, such as project size and complexity; crew size; skill level; weather conditions; site conditions; equipment size, type, and condition; overtime or the lack thereof; and management competency and experience. Formulas and adjustment tables and curves have been developed to allow productivity-level adjustments for individual factors such as weather and overtime (Oglesby, Parker, and Howell, 1989).[10] Some authors have even suggested using one formula that incorporates these factors for the productivity adjustment (Neil, 1982). Third, in some activities, two or more crews may be working simultaneously (a common occurrence in large projects), which will reduce the duration accordingly.

After the scheduler has adjusted the productivity rate, the logic (relationships and lags) must be built. The importance of such a step cannot be overemphasized.

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[9] For rough carpentry such as framing, the waste percentage is usually higher than for other items because waste allowance not only covers broken, defective, and missing pieces but also waste resulting from cutting. For example, in the studs case above, the true length may be 9' 4'' (9 feet + 4 inches) but studs are sold only in increment of 2 feet, so the estimator has to order studs 10 feet long.

[10] See also the discussion on overtime in Chapter 8.

### Cost-Loaded Schedules

A **cost-loaded schedule** is a schedule in which each activity is assigned a budgeted monetary amount. Similar to the two methods described previously for building the cost-estimate database items, two methods are used to assign a budget to activities in scheduling programs[11]:

1. Assign a lump-sum amount without providing details about how this number is sliced or which resources use it. You may still be required to supply a cost account code in some software packages to help track the cost.
2. Assign a number of units of required resources (e.g., one foreman, one equipment operator, two common laborers, one hydraulic excavator) to the activity. The schedule must contain a "resource dictionary," in which every resource is defined and priced. The program calculates the required resource quantities for the activity by multiplying the number of resources required for the activity by the duration of the activity. For example, if the activity requires three laborers and has a 4-day duration, the resource assignment is $3 * 4 = 12$ labor-days, or $3 * 4 * 8 = 96$ man-hours. The program then calculates the budget for the activity by multiplying the resource assignment by the resource unit prices in the resource dictionary. The second method has several advantages, which are discussed in Chapter 6.

## ESTIMATING AND ACCOUNTING

**Cost accounting** is defined as "the systematic recording and analysis of the costs of materials, labor, and overhead incident to production" (Merriam-Webster, 2014. Cost accounting basically is concerned with checks and balances: matching actual spending with estimated or budgeted amounts. The actual cost of every work item must not exceed the estimated (budgeted) amount. In some cases, particularly in public agencies, accounting also involves different categories of sources of money (funds). For example, a transportation project in a city may be funded by a combination of federal funds, state funds, local funds, grants, and special taxes or fees. Each fund has its limits and restrictions. Many grant funds have stipulations, such as the type of project, geographic location, type of expense, equal or greater matching funds from the owner agency, or type of subcontractor (e.g., minority, small business). The accountant must make sure that the expenses meet these stipulations.

As discussed in Chapter 8, construction project costs are classified as direct and indirect expenses. Direct expenses include labor, materials, equipment, and subcontracts. Indirect expenses include job overhead, general overhead, profit, and contingency fees. When actual expenses are incurred, the accountant must link each expense to a specific work item. The expense must be categorized (labor, materials, equipment,

[11] See "Assigning Budgets in Computer-Scheduling Programs" in Chapter 6.

overhead) and subcategorized (common labor, carpenter, concrete, crane, etc.). The accountant must make sure that actual expenses do not exceed the estimated cost.

The contractor's accounting system maintains a list of vendors, suppliers, and subcontractors. At any time, the contractor should be able to track any material ordered from any particular supplier, including the following information:

- Total quantity ordered
- When it was ordered
- Delivery status; if received, when and who signed for it.
- Total cost, how much paid, the balance, and the due date for the balance
- Any problems with the materials and the action taken

The general contractor's accounting system should also include any records of a subcontractor's monthly payments: how much was requested, approved, authorized, paid, and retained.

The payroll (for hourly workers) is done regularly (weekly or biweekly). Workers' hours (regular and overtime) are also posted against specific work items. Accountants add burden expenses and benefits, and then subtract the appropriate amounts from the payroll, such as federal and state withholding tax, FICA (Federal Insurance Contributions Act) fees, FICA medical fees, unemployment insurance contributions, union dues, medical insurance contributions, and so forth.

The general contractor collects subcontractors' pay requests, incorporates them into a **request for payment**, and submits the pay request to the owner. A pay request goes through the usual steps: verification and approval by the owner, processing, and issuance of the payment (minus any retainage and/or penalties[12]). Owners also require lien releases[13] from the general contractor, subcontractors, and vendors before releasing the payment. Accountants must also keep track of each subcontractor and vendor: total contract, payments to date, retainage to date, and balance.

Every expense must be approved by an authorized person before it is accepted into the accounting system. Checks must also be signed by an authorized person.

## SCHEDULING AND ACCOUNTING

Scheduling is related to accounting in basically one way. When the project is updated (statused), information is obtained on new work progress. The cost of this new work

[12] In certain locations in the world, contracts allow the contractor to receive an advance payment when signing the contract. It is usually around 10–20% of the contract value and it is recovered gradually by deducting the same percentage from progress payments.

[13] A lien release is a written agreement by a lien holder (general contractor, subcontractors, vendors) releasing the debtor (owner) from further obligation. Without a lien release, it is possible that the owner pays his general contractor but the general contractor does not pay a subcontractor, then the subcontractor places a mechanics lien against the building (i.e., the owner).

progress is then processed as described previously. If the schedule is cost loaded, it provides periodic information, such as the following:

- Which activities have started (along with the start dates)
- The percent complete of such activities
- Which activities are completed (along with the finish dates)
- Total budget, cost this period, cost to complete, **cost at completion**, and cost variance
- Any other activity-related financial information

This information must be reviewed and approved by the PM and is then forwarded to the accounting department.

If the project is not cost-loaded, the same procedure must take place through the accounting system. In this case, the percent complete for each activity must be entered for the pay period. The accounting system uses the schedule of values and calculates cost this period, cost to complete, cost at completion, and cost variance. After the schedule is approved, the cost this period becomes the basis for monthly progress payments, as described previously.

## SCHEDULING AND CHANGE ORDERS

The accounting, estimating, and scheduling departments also handle change orders (COs),[14] each from its own perspective. In construction, COs are usually inevitable. However, well-planned and well-managed projects may have few or no COs. Change orders may be initiated by the contractor or the owner (and are discussed in more detail in Chapter 13). In all cases, the contractor estimates the cost of the CO and the impact on the schedule, if any. The owner approves, rejects, or negotiates the contractor's request. Once the owner approves such a request, the owner issues the CO.

The contractor must then implement the CO in the estimating, scheduling, accounting, and other management/tracking systems. Managing COs may present a challenge to the contractor's staff. Change Orders may—and usually do—affect existing items. For example, two additional floors in a midrise office building may require the engineer to redesign the columns, the foundation, the main HVAC unit, the type of elevators, and possibly other items. A deletion of a swimming pool will alter the amount of excavation and landscaping. If the contractor encounters "differing site conditions," the contractor's work plan may have to be delayed or altered.

What is important to scheduling and project control is implementing the changes in the baseline schedule (and estimate) so that measuring against the baseline will be

[14] Also called variation orders, VOs.

fair and objective. The original baseline should not be deleted. Rather, it should be kept with the project records because it could be used in case of a future dispute.

## PAPERLESS PROJECT MANAGEMENT

The construction industry, as well as other industries, is increasingly managing information electronically. As a result, the traditional use of paper has been minimized.

Any project usually starts with a preliminary (or concept) and then a detailed design (architectural, civil, structural, mechanical, electrical, etc.). Many designers work with drafting or design software, such as AutoCAD (Autodesk, Inc., San Rafael, California) or MicroStation (Bentley Systems, Inc., Exton, Pennsylvania). When the design is finalized and approved, it is issued as "construction drawings" (usually on paper) and officially submitted to the contractor, along with the specifications.[15] The contractor calculates quantity takeoffs from these drawings and then prices the job. Contractors do takeoffs by using manual, electronic tools such as digitizer boards, directly from CAD drawings, or by using BIM[16] modeling. These quantities are carried over to the estimating spreadsheet or program either manually or electronically.

Project management software programs, such as Oracle Contract Manager (formerly known as Oracle Primavera Contract Management), Meridian's Prolog Manager, and Timberline's Project Management, keep records of all project administration and communication documents. In an ideal situation, they link to the schedule, the cost estimate, the accounting software, and other programs. In addition, you can host all of this information on an exclusive Web site (Internet or intranet) where project participants can obtain access to the project, review documents, and correspond with you. The Web site administrator can control who sees what. This capability can expedite communications tremendously, such as design review, submittals, RFIs, payment requests, and so forth, among project participants. Several leading companies in the construction software industry are trying to develop a "total project management suite" in which all project management and administrative components are available and are communicating with each other flawlessly.

## PROCUREMENT MANAGEMENT

**Procurement** is the process of acquiring materials, equipment, and/or services from external sources for use in a project. Procurement is a process that usually starts

[15] In some nontraditional contracts, the contractor may be involved in the project before the design is complete. In such cases, he/she may receive incomplete design documents (e.g., DD30, DD60) or complete design documents only for a portion of the project.

[16] Building Information Modeling, known as BIM.

long before the start of the construction process and ends with project completion or **project closeout**. The procurement team must work in close coordination with both the estimating and scheduling teams, all under the project management team. Depending on the company's functional hierarchy, the procurement manager or department may or may not be under the project manager. In most large companies, the PM is the highest authority within the project management team. Under this person there are a construction manager, a procurement manager, a quality manager, a safety manager, and so forth.

In management, project organization may be a *pure project organization* (in which the team becomes autonomous, almost like an independent company), a *functional* or *departmental organization* (in which everyone works under his or her functional department in the main office), or a *matrix organization* (a combination of the preceding two types of organizations, which leans more toward a pure project organization, more toward a functional organization, or somewhere in the middle)[17].

The two objectives of procurement, from the general contractor's viewpoint, are as follows:

1. *To hire the subcontractors who will actually erect and assemble the project*: Doing so can be accomplished through bidding or negotiation. Such hiring is also subject to the contractual agreement between the general contractor and the owner. The general contractor must know when each subcontractor's role starts in the project. For this reason, the general contractor focuses on subcontracts on the critical path. Some subcontractors may not be hired until after the project starts. Again, such hiring is subject to the agreement between the owner and the general contractor.
2. *To purchase the materials called for in the contract*: This task may not be easy. First, the procurement team must have a list of all of the needed materials, along with their specifications, quantities, and dates of installation. Custom and special orders as well as long-lead items must be given special attention. Often, if an ordered material does not exactly match its description in the specifications, confusion will arise on the job site and decisions will have to be made about what to do. Second, the procurement team must find the best prices for the ordered materials. Finally, the procurement team must also balance between having a conservative attitude of buying the materials early and storing them (the inventory buffer theory) and having a risky attitude of ordering the materials for installation when needed (the just-in-time theory). (Both theories are discussed in Chapter 6.)

The purchasing cycle involves the estimating, scheduling, procurement, accounting, quality assurance, and perhaps other departments. The estimating department

[17] *Project Management: A Managerial Approach* by Jack R. Meredith and Samuel J. Mantel Jr. (2008).

provides a list of the types and quantities of materials needed for a certain activity. The scheduling department predicts the date on which the activity will start. The procurement team then makes sure that the materials are ordered and are available on time. It also verifies the cost of these materials against the cost estimate and then provides the actual cost to the accounting department. The contractor's project management team is responsible for receiving and unloading the materials as well as accepting, sorting, and storing them. The quality assurance department of both the contractor's and the owner's organizations may become involved to ensure that the materials comply with the specifications.

The purchase of some materials, such as ready-mix concrete, must be carefully coordinated. This type of concrete must be installed immediately upon delivery and cannot be stored. Some materials may be flammable, explosive, poisonous, or dangerous. Some materials may be fragile and need extra care in handling and storing. Other materials may be expensive and must be secured before and after installation. Some items may be very large or heavy, which may require special arrangement for storage and handling. The procurement department must take care of all of the requirements of such types of materials.

A clear distinction must be made between the procurement department and the human resources department with regard to hiring people. The latter is responsible for hiring staff employees, such as managers, engineers, administrators, and so forth.

## MANAGEMENT OF SUBMITTALS

A **submittal** is a sample, manufacturer's data, a shop drawing, or another item submitted to the owner or the design professional by the contractor for approval or other action, usually a contractual requirement. Submittals are an important part of the schedule. In many cases, placement of a posttensioned cable, reinforcement, structural steel detail, or framing cannot proceed until the shop drawing is approved. In the case of samples, such as types and colors of carpet or paint, the procedure includes the submittal of the samples and the owner's selection or acceptance of one or more of them.

In the case of shop drawings, the cycle consists of four steps:

1. Preparation of the shop drawings by the subcontractor or supplier.
2. Submittal of the drawings to the contractor, who then forwards them to the architect or engineer, or the party responsible for reviewing them.
3. Review of the drawings by the appropriate party (architect or engineer). Typically, the drawings are accepted as is, rejected, or accepted with changes. If they are rejected, the subcontractor or supplier must redo them and then resubmit them.
4. After approval, fabrication of the work by the subcontractor or supplier.

The formal chain of command should be specified in the contract. It usually restricts correspondence between parties who have a contractual agreement. For example,

Structural steel fabricator
↓
Structural steel subcontractor
↓
General contractor
↓
Architect
↓
Structural engineer

The direction of these arrows is reversed when the drawings are sent back after the review has occurred. This chain may be shortened, in order to speed up the process, by sending the drawings from the fabricator or subcontractor directly to the structural engineer. Such an arrangement requires the approval of the main contracting parties. Most likely, it also requires copying all other involved, in both directions. Electronic correspondence helps expedite this process.

The submittal procedure in the contract must be precise in terms of time limits. Ambiguous expressions such as "the owner will review submittals within a reasonable period of time so as not to delay work progress" and "as soon as possible" must be avoided. Document/contract management software tracks shop drawings and other submittals and documents. They show the party that is holding the process (ball in court) and sends alerts before any deadlines.

Another important point, from a scheduling point of view, is the possibility of rejection.[18] If the shop drawing cycle is on a critical or a near-critical path, the contractor must be careful when handling the submittals. The contractor should try to determine the results of the review as soon as possible in order to plan for the next step. Allowing a contingency time in the schedule for the possibility of rejection is a good idea.

## THE MASTER SCHEDULE AND SUBSCHEDULES

In a typical construction project, many parties are involved: the general contractor, the owner, the architect or engineer (which could be several entities), subcontractors,

[18] If the objections of the reviewer are minor, the actions maybe "Accepted as noted, " which indicates a need for corrections and/or changes in the submittals but allows the work to continue while corrections and changes are being made.

government agencies, vendors, and so forth. There are two approaches to scheduling in this situation:

1. *Build a master schedule that includes several subschedules*: Each subschedule represents the activities belonging to one party involved in the project. The external relationships will show only in the master schedule. In this approach, when scheduling (performing the CPM calculations for) a subschedule, the scheduler must be sure to consider the external relationships because the software may ignore them. For instance, consider the three activities shown in Figure 10.4. Assume the relationship between activity GC230 and activity SDF1270 is external. If you schedule the SDF schedule alone, you may get early dates for activity SDF1270 as (35, 40) instead of (51, 56).

This solution was ideal under the old Primavera P3, where the user could not open more than one project at a time but could open one master schedule with several subschedules under it. In the enterprise version of Oracle Primavera P6, the user can open as many projects as he or she wants, simultaneously. The user in P6 also can link activities in different projects with the option to consider or ignore external relationships when scheduling. The user in P6 can also take advantage of the EBS (enterprise breakdown structure) by placing the subschedules at one level below the master schedule.

2. *Include all activities in one schedule and assign a responsibility code for each contracting party*: The scheduler can later apply a filter to show activities belonging to only one party. In this way, the "external relationships" are always there, even if they are not shown.

It is important to include external relationships for proper project management. For example, an owner's furnished kitchen equipment for a commercial project may have to be delivered after the structure has been erected and after mechanical and electrical rough-ins are completed, but before doors and windows are installed and before

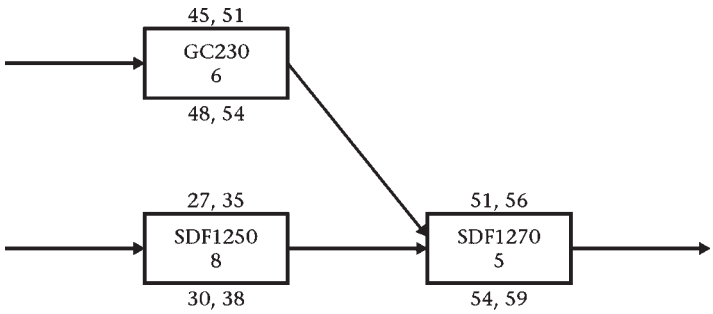



**Figure 10.4 Subnet of a master schedule with two activities belonging to one subschedule and one activity belonging to a different subschedule**

mechanical and electrical finishing are completed. Such operations involve coordination among several entities.

In many situations, the master schedule is not the creation of one party (the general contractor or the project management consultant, PMC). Contracting parties, such as subcontractors, create their own schedules (using the same or compatible software) and submit them to the general contractor (or PMC). The general contractor (or PMC) then assembles these subschedules, along with his or her schedule, in one master schedule, using one of the two approaches just mentioned.

## MULTIPROJECT MANAGEMENT

In large corporations or government agencies, tens or hundreds of projects may have to be managed simultaneously. Typically, there are two levels of project management:

1. *Management at the individual project level (micromanagement)*: The PM should be managing or monitoring all activities and all project details. The project is the focus of the PM. Depending on the size and complexity of the project, the management team can be composed of one part-time person or several people.

   For such a PM, the basic unit of control is the activity, with related information, such as duration, logic (predecessors, successors, lags), constraints, calendar, resources, budget, cost, notes, and so forth. The information may be rolled over to a WBS (work breakdown structure) level or other codes within the project (e.g. floor, area, phase, segment, mile marker). The highest level of roll-up is the project itself, in which only one unit shows, with the total duration, total budget, and so forth.

   In some owner's organizations, such as governmental agencies (counties, municipalities, etc.) and developers, every project has two managers: the owner's PM and the contractor's PM. The owner's PM monitors the project and makes sure that the contractor is performing according to the terms of the contract. He or she also authorizes payments to the contractor. The contractor's PM is the "real" construction manager. He or she is responsible for the day-to-day construction operations for the project. It is also possible, and likely, that a PMC is involved who represents the owner. In this case, the PM will be micromanaging the project, representing the owner's interest.
2. *Management at the corporate or enterprise level (macromanagement)*: The corporate manager will look at all projects, with each project represented as one basic integral unit (usually represented by a single bar in a bar chart). The corporate manager (possibly a program or portfolio manager) may not get involved in the details of individual projects (although he or she usually can, and will do so in certain cases). The basic unit in this case is the project. Projects can be grouped by organizational breakdown structure, such as department, section, program, and so forth.

Oracle Primavera P6, for example, is a product designed for the "enterprise," with a multiproject management capability.[19] It offers three breakdown structures:

a. The *EBS (enterprise breakdown structure)* is a breakdown for the corporation (enterprise). Typically, this structure includes the departments in the organization. Each department can be broken down further into sections and so on, where projects reside.
b. The *OBS (organizational breakdown structure)* is a breakdown of the functional responsibilities. Typically, you tie the EBS to the OBS to define people, along with their departments (who does what).
c. The *WBS (work breakdown structure)* is a typical project breakdown structure (PBS). Unlike the EBS and the OBS, the WBS is at the project level, and it can differ from one project to another.

## TIME CONTINGENCY AND MANAGEMENT OPTIONS

When a scheduler or a PM creates a schedule, he or she must include a time contingency that represents the expected nonworkdays. This time contingency includes two types of nonworkdays:

1. *Known dates, such as holidays and planned shutdown days*: The scheduler must enter these days in the calendar of the computer program. The computer program will not allow any work on an activity on such days (provided the activity uses that calendar).
2. *Unknown dates*: The scheduler should typically expect some occurrences that will prevent work from taking place, such as severe weather conditions or accidents. For example, for a 1-year project, the scheduler might allocate 18 nonworkdays. This 18-day *schedule contingency* can be considered total float for the entire project, in addition to the calculated total float. It can be handled in one of the following two ways, or a combination of both can be used:

   a. *Allow the crews to control this float*: In this case, the durations of all activities are stretched by a percentage that extends the entire schedule by 18 days. This is not a recommended option, because human nature makes the workers stretch work to fill the given time span. As an alternative, the PM may assign these 18 days to certain activities according to his or her discretion.
   b. *Give management control of these days and allow them to "be spent" as needed*: Management must be careful not to use such time contingency days to

[19] As mentioned in chapter 7, Microsoft has developed solutions, such as Microsoft Enterprise Project Management (EPM) Solution for project and portfolio management.

compensate for poor performance or low productivity. The challenge in this approach is how to implement such days in the baseline schedule. There are two ways to do so:

i. *Distribute these days evenly along the duration of the schedule*: In this case, the scheduling program treats these days the same as holidays and scheduled nonworkdays. This approach may cause some problems in tracking the project if a certain day is shown on the schedule as a nonworkday when, in fact, it is not. The advantage of this method is that the schedule is most realistic in the occurrence distribution of nonworkdays, although the specific date may be incorrect. As a remedy, the scheduler can adjust dates for nonworkdays during the update.

ii. *Put all 18 days at the end of the project*: This method makes the actual schedule look worse than it is. As the project progresses, nonworkdays occur but they are not reflected in the schedule, so the schedule looks like it is behind schedule until the end. At this point, the 18 contingency days start, and the negative float (up to 18 days) disappears.

One approach used in some organizations, particularly municipal governments, is to have two different completion dates:

1. *An internal completion date*: This is the date when the project manager is responsible to management for completing the project.
2. *An external completion date*: This is the date when management is responsible to the client (owner/board of commissioners or trustees) for completing the project.

   The first date is, obviously, the earlier one. The difference between the two dates is "management float" or "time contingency." Management uses that as a bank and authorizes the PM to use days out of it only for a valid excuse. It is not a good idea for management to exaggerate this time contingency. One possible problem with such an exaggeration is in the timing of funding. This may be a particular problem for public agencies (municipalities and local governments). Budget departments may distribute the cost of the project over its fluffed duration; it then takes less time than officially reported. This early execution[20] of the project may mean an earlier request for money than anticipated (even though the total is unchanged) and the agency may have the money committed for the next, not the current, fiscal year.

Besides using the nonworkdays, the contractor may create *hidden float*. Hidden float can be created either by inflating the duration of an activity or by manipulating the logic. For example, assume that the durations and logic in Figure 10.5a are correct,

[20] Not really early but compared to the "fluffed" schedule.

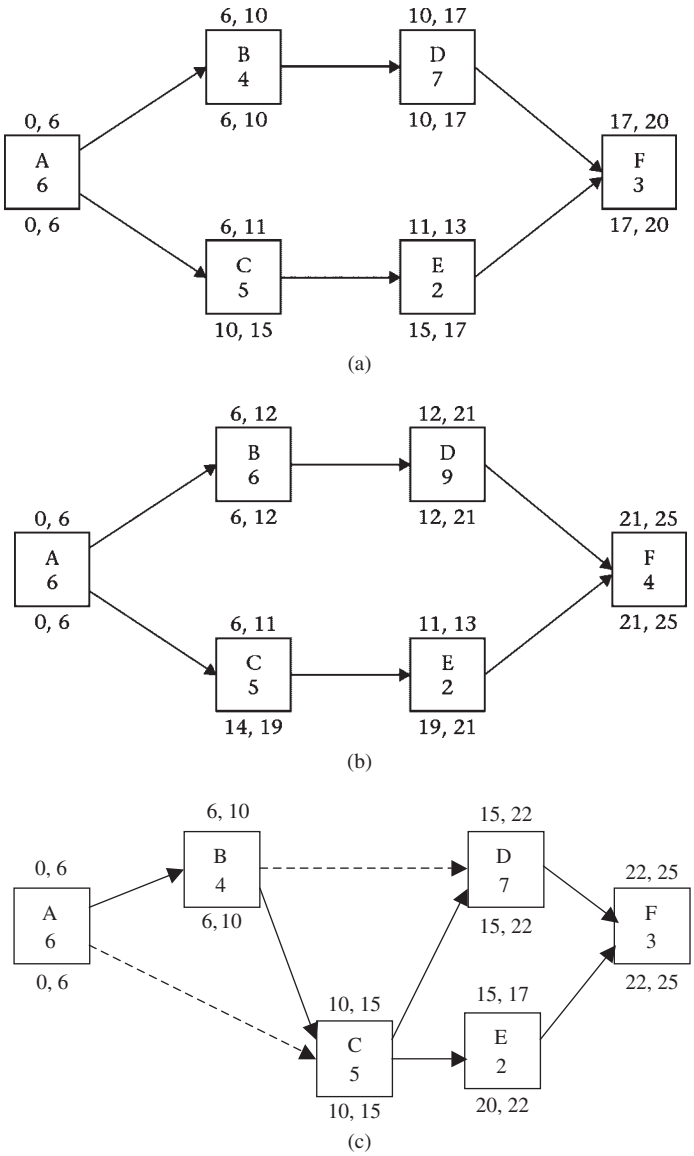



**Figure 10.5 (a) Real durations; (b) "fluffed" durations; (c) manipulated logic**

but the contractor wants to show that the project takes 25 days instead of 20. The contractor can "fluff" the durations, as shown in Figure 10.5b, or add an unnecessary link to extend the critical path and thus extend the duration of the project, as shown in Figure 10.5c.

The author strongly opposes the tactic used in Figure 10.5c. Phony logic should never be allowed in a schedule. Fluffing the duration is a controversial subject and also

is discouraged. The danger of using a fluffed duration in project control and performance measurement is that it may skew the performance observations and conclusions, and subsequently future estimates.

## CHAPTER 10 EXERCISES

1. Discuss three ways in which cost estimating and scheduling are interrelated.
2. Discuss the evolution of a cost estimate. How does this relate to the creation of the schedule?
3. What is an *estimate-generated schedule?* What precautions must the scheduler take before using such a schedule?
4. What is a *cost-loaded schedule?*
5. What are the two methods of loading cost into a schedule? Which method is more powerful? Why?
6. How does accounting relate to scheduling? Discuss briefly.
7. How do change orders affect a schedule? What should the scheduler do for objective project control when changes occur?
8. What is the "total project management suite" computer program?
9. Define *procurement*. What are the main objectives of procurement?
10. How does procurement relate to scheduling?
11. Explain the cycle of submittal management.
12. What can the scheduler do to account for potential delays during the submittal cycle?
13. When you take on a large project made up of several smaller projects, how can you handle this situation in the schedule?
14. When using the "master project" and "subprojects" approach, what pitfalls may occur in the schedule? How should you deal with them?
15. In a highway project, both the contractor and the government schedulers must keep track of the schedule. However, their roles differ significantly. Explain.
16. The scheduler must include a time contingency in the schedule. How many ways can you implement such a contingency? What are the pros and cons of each method?
17. After you prepare a schedule for a shopping mall, the architect issues a design change in which an escalator is added inside one of the areas that will be occupied by a major store in the mall. The subcontractor in charge of the escalator submits her schedule, showing that the work can be completed in 6 weeks. First, mention the work packages that will be affected (e.g., concrete, electrical, etc.). Second, do you believe that the master schedule will affect the escalator schedule, the escalator schedule will affect the master schedule, or both? Explain the potential interdependencies between the escalator work and other subcontractors' work. Why do you believe that the escalator work will take more than 6 weeks?

Chapter **11**

# Other Scheduling Methods



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## INTRODUCTION

Although the critical path method (CPM) is the predominant method that is used for scheduling construction projects, other methods can be used for particular types of projects or in other industries. In this chapter, three of these methods are discussed. (*Note*: Some of the information discussed in this chapter requires a basic knowledge of statistics.)

## PROGRAM EVALUATION AND REVIEW TECHNIQUE (PERT)

### Definition

The **program evaluation and review technique (PERT)** is an event-oriented network analysis technique that is used to estimate a project's duration when individual activity duration estimates are highly uncertain. PERT applies the CPM to a weighted-average duration estimate. PERT is considered a probabilistic, or stochastic, method.

### Background

In the 1950s, the U.S. Navy had a budget overrun and a schedule delay of as much as 50% in the Polaris missile system project. The main problem was the lack of any relevant historical data. The project team—the U.S. Navy (the owner), Lockheed Aircraft Corporation (the prime contractor), and Booz Allen Hamilton (the management consultant team)—launched a joint research effort to develop a tool to assist in the planning of the Polaris project. The objective was to devise a method that would predict the completion date of a project with a certain likelihood using the theory of probability. In 1958, this tool was developed under the name *program evaluation and review technique* and later became known by its acronym, PERT.

The PERT system was adopted in its early days by the U.S. Department of Defense (DoD) under the name *program evaluation procedure (PEP)*. After that, PERT was modified several times and had different names: PERT I, PERT II, PERT III, PERT/TIME, and PERT/COST. In June 1962, the DoD and the National Aeronautics and Space Administration (NASA) adopted a uniform approach to planning and controlling procedures for major weapon systems (Popescu and Charoenngam, 1995).

### Concept of PERT

Like the regular (deterministic) CPM, PERT uses logic networks to calculate the completion date of a project or the date of any other event in a schedule. In PERT, a probability (likelihood) is associated with any event date. This probability depends on uncertainty in the durations of the activities that lead to the desired event (e.g., project completion). PERT realizes that actual durations vary from those assigned, so it attempts to compensate for this variation with a "time range" during which activity

durations may realistically occur. This topic is discussed in more detail after the details of PERT are covered.

### How PERT Works

PERT uses a probabilistic approach, which requires a duration frequency distribution for each activity. In most cases, such distributions are unknown or unavailable. Because of this, PERT requires the user to set three durations that constitute the practical range of the duration for each activity. For example, Assembling and Erecting the Falsework[1] for an Elevated Slab will most likely require 5 days. If all goes well, without interruption or snags, the duration may be cut to 4 days. However, in the realistic worst-case scenario, this activity may take 8 days. These three durations give a "distribution" for the activity, and we can produce the statistical mean and variance for the duration of the activity.

When we need to compute the probability that a certain event, such as Substantial Completion of a building, will occur by a certain date, we need to take into account all of the preceding events, starting at the beginning of the project and including the continuous chain of activities until Substantial Completion, going through all paths. Using the **central limit theorem**, PERT treats the means of the durations of these activities as a **normal distribution**, no matter what distributions these durations followed. PERT then uses simple statistics to calculate the mean and variance (or standard deviation) of the time required to complete the chain of events leading to Substantial Completion. It calculates the probability that Substantial Completion will occur by a particular date, or, conversely, it calculates the date that the Substantial Completion event will happen with a certain level of confidence (probability).

### PERT Calculations

As mentioned previously, the path (chain of activities or events) leading to the examined event (e.g., Substantial Completion) must be chosen. For each activity on that path, three durations must be estimated:

$T_o$: Optimistic duration
$T_m$: Most likely duration
$T_p$: Pessimistic duration

The preceding values are estimated by the scheduler or project manager, who uses his or her experience and good judgment to do so. The optimistic duration is the amount of time that the activity will take if everything goes smoothly and efficiently.

[1] Technically, falsework includes the concrete formwork, plus all supporting materials, such as shores, scaffolding, braces, jacks, and so forth. Formwork includes only the materials that are directly in contact with the newly placed concrete.

The pessimistic duration is the duration under the worst-case scenario. Both values must be within the realistic, although perhaps unlikely, realm of expectations.

The mean-weighted value for these three durations is called the **expected duration** ($T_e$). It is calculated as follows:

$$T_e = \frac{T_o + 4T_m + T_p}{6} \tag{11.1}$$

The weights assigned to these times (coefficients of $T_o$, $T_m$, and $T_p$) may be adjusted, but the denominator must equal the sum of all of the weights. The weights in equation 11.1 represent a population of durations made up of 16.7% (one-sixth) optimistic ($T_o$); 66.7% (four-sixths) most likely ($T_m$); and 16.7% (one-sixth) pessimistic ($T_p$).

Several symbols are used in other textbooks to represent the mean (arithmetic average), such as μ and $X$.

The standard deviation for the expected duration ($\sigma_e$) is

$$\sigma_e = \frac{T_p - T_o}{6} \tag{11.2}$$

and the variance ($V_e$) is

$$V_e = \sigma_e^2 \tag{11.3}$$

Now, add the expected duration for all activities on the studied path ($T_E$),

$$T_E = \sum_{i=1}^{n} (T_e)_i \tag{11.4}$$

The variance ($V_E$) and standard deviation ($\sigma_E$) *for the entire path* are calculated as

$$V_E = \sum_{i=1}^{n} (\sigma_e^2)_i \tag{11.5}$$

and

$$\sigma_E = \sqrt{V_E} \tag{11.6}$$

With the information just calculated for the examined path, we can calculate the probability that an event will occur on or by a certain date ($T_S$) by using the normal distribution formulas:

$$Z = \frac{T_S - T_E}{\sigma_E} \tag{11.7}$$

where $Z$ (called the **Z-function**) represents the number of standard deviations ($\sigma_E$) away from the mean ($T_E$).

Plugging the *Z* value just calculated into the *Z* table (Table 11.1), we can find the probability.

PERT can also predict the date by which a certain event will be completed with a certain level of confidence (i.e., probability). This date is calculated by using the set probability value (level of confidence) to find the corresponding *Z* value in the *Z* table.

**Table 11.1 Z Table: Cumulative Probability of the Standard Normal Distribution**

| Z | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| **0.0** | 0.5000 | 0.5040 | 0.5080 | 0.5120 | 0.5160 | 0.5199 | 0.5239 | 0.5279 | 0.5319 | 0.5359 |
| **0.1** | 0.5398 | 0.5438 | 0.5478 | 0.5517 | 0.5557 | 0.5596 | 0.5636 | 0.5675 | 0.5714 | 0.5753 |
| **0.2** | 0.5793 | 0.5832 | 0.5871 | 0.5910 | 0.5948 | 0.5987 | 0.6026 | 0.6064 | 0.6103 | 0.6141 |
| **0.3** | 0.6179 | 0.6217 | 0.6255 | 0.6293 | 0.6331 | 0.6368 | 0.6406 | 0.6443 | 0.6480 | 0.6517 |
| **0.4** | 0.6554 | 0.6591 | 0.6628 | 0.6664 | 0.6700 | 0.6736 | 0.6772 | 0.6808 | 0.6844 | 0.6879 |
| **0.5** | 0.6915 | 0.6950 | 0.6985 | 0.7019 | 0.7054 | 0.7088 | 0.7123 | 0.7157 | 0.7190 | 0.7224 |
| **0.6** | 0.7257 | 0.7291 | 0.7324 | 0.7357 | 0.7389 | 0.7422 | 0.7454 | 0.7486 | 0.7517 | 0.7549 |
| **0.7** | 0.7580 | 0.7611 | 0.7642 | 0.7673 | 0.7704 | 0.7734 | 0.7764 | 0.7794 | 0.7823 | 0.7852 |
| **0.8** | 0.7881 | 0.7910 | 0.7939 | 0.7967 | 0.7995 | 0.8023 | 0.8051 | 0.8078 | 0.8106 | 0.8133 |
| **0.9** | 0.8159 | 0.8186 | 0.8212 | 0.8238 | 0.8264 | 0.8289 | 0.8315 | 0.8340 | 0.8365 | 0.8389 |
| **1.0** | 0.8413 | 0.8438 | 0.8461 | 0.8485 | 0.8508 | 0.8531 | 0.8554 | 0.8577 | 0.8599 | 0.8621 |
| **1.1** | 0.8643 | 0.8665 | 0.8686 | 0.8708 | 0.8729 | 0.8749 | 0.8770 | 0.8790 | 0.8810 | 0.8830 |
| **1.2** | 0.8849 | 0.8869 | 0.8888 | 0.8907 | 0.8925 | 0.8944 | 0.8962 | 0.8980 | 0.8997 | 0.9015 |
| **1.3** | 0.9032 | 0.9049 | 0.9066 | 0.9082 | 0.9099 | 0.9115 | 0.9131 | 0.9147 | 0.9162 | 0.9177 |
| **1.4** | 0.9192 | 0.9207 | 0.9222 | 0.9236 | 0.9251 | 0.9265 | 0.9279 | 0.9292 | 0.9306 | 0.9319 |
| **1.5** | 0.9332 | 0.9345 | 0.9357 | 0.9370 | 0.9382 | 0.9394 | 0.9406 | 0.9418 | 0.9429 | 0.9441 |
| **1.6** | 0.9452 | 0.9463 | 0.9474 | 0.9484 | 0.9495 | 0.9505 | 0.9515 | 0.9525 | 0.9535 | 0.9545 |
| **1.7** | 0.9554 | 0.9564 | 0.9573 | 0.9582 | 0.9591 | 0.9599 | 0.9608 | 0.9616 | 0.9625 | 0.9633 |
| **1.8** | 0.9641 | 0.9649 | 0.9656 | 0.9664 | 0.9671 | 0.9678 | 0.9686 | 0.9693 | 0.9699 | 0.9706 |
| **1.9** | 0.9713 | 0.9719 | 0.9726 | 0.9732 | 0.9738 | 0.9744 | 0.9750 | 0.9756 | 0.9761 | 0.9767 |
| **2.0** | 0.9772 | 0.9778 | 0.9783 | 0.9788 | 0.9793 | 0.9798 | 0.9803 | 0.9808 | 0.9812 | 0.9817 |
| **2.1** | 0.9821 | 0.9826 | 0.9830 | 0.9834 | 0.9838 | 0.9842 | 0.9846 | 0.9850 | 0.9854 | 0.9857 |
| **2.2** | 0.9861 | 0.9864 | 0.9868 | 0.9871 | 0.9875 | 0.9878 | 0.9881 | 0.9884 | 0.9887 | 0.9890 |
| **2.3** | 0.9893 | 0.9896 | 0.9898 | 0.9901 | 0.9904 | 0.9906 | 0.9909 | 0.9911 | 0.9913 | 0.9916 |
| **2.4** | 0.9918 | 0.9920 | 0.9922 | 0.9925 | 0.9927 | 0.9929 | 0.9931 | 0.9932 | 0.9934 | 0.9936 |
| **2.5** | 0.9938 | 0.9940 | 0.9941 | 0.9943 | 0.9945 | 0.9946 | 0.9948 | 0.9949 | 0.9951 | 0.9952 |
| **2.6** | 0.9953 | 0.9955 | 0.9956 | 0.9957 | 0.9959 | 0.9960 | 0.9961 | 0.9962 | 0.9963 | 0.9964 |
| **2.7** | 0.9965 | 0.9966 | 0.9967 | 0.9968 | 0.9969 | 0.9970 | 0.9971 | 0.9972 | 0.9973 | 0.9974 |
| **2.8** | 0.9974 | 0.9975 | 0.9976 | 0.9977 | 0.9977 | 0.9978 | 0.9979 | 0.9979 | 0.9980 | 0.9981 |
| **2.9** | 0.9981 | 0.9982 | 0.9982 | 0.9983 | 0.9984 | 0.9984 | 0.9985 | 0.9985 | 0.9986 | 0.9986 |
| **3.0** | 0.9987 | 0.9987 | 0.9987 | 0.9988 | 0.9988 | 0.9989 | 0.9989 | 0.9989 | 0.9990 | 0.9990 |

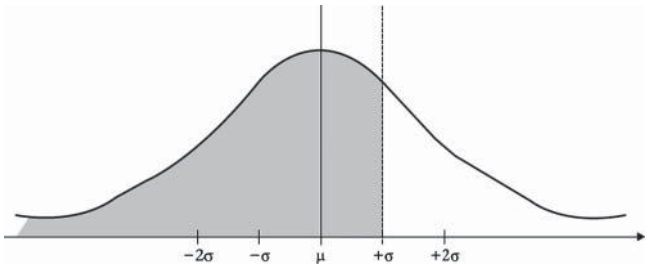



**Figure 11.1 Probability density function curve (shaded area indicates the probability that an event will occur by a certain date)**

Rewriting equation 11.7, we get

$$T_S = \sigma_E \cdot Z + T_E \tag{11.8}$$

These calculations are clarified further in the following examples.

### Graphic Explanation

The **probability density function (PDF)** of a normal distribution is represented by a bell-shaped curve. The area under the curve represents the **probability universe**, where all possibilities are covered, which is 1.00, or 100%. The probability that an event will occur by a certain date (i.e., on or before that date) is the area under the curve to left of that date. See Figure 11.1.

### Example 11.1

In a CPM network, the critical path includes five activities. Their durations are tabulated next.

| | Duration (Days) | | |
|---|---|---|---|
| Activity | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) |
| A | 2 | 4 | 7 |
| B | 5 | 8 | 14 |
| C | 4 | 6 | 8 |
| D | 2 | 2 | 2 |
| E | 7 | 10 | 21 |

Compute the following nine values:

1. The probability that the project will finish by the end of day 32
2. The probability that the project will finish by the end of day 34

3. The probability that the project will finish before day 30
4. The probability that the project will finish on day 32
5. The probability that the project will finish no later than day 35
6. The probability that the project will finish at least 2 days early
7. The probability that the project will finish at least 2 days late
8. The probability that the project will finish on day 32 ±1 day
9. The completion date with at least a 90% confidence level

**Solution**

Before computing any of the nine values, we need to calculate the expected duration ($T_E$) and the standard deviation ($\sigma_E$) of the path ABCDE. We start by performing the calculations for the individual activities. For every activity, we calculate the expected duration ($T_e$) and standard deviation ($\sigma_e$) by using equations 11.1 and 11.2. After this, we calculate the variance ($V_e$) by using equation 11.3. We tabulate the results as shown next.

| | Duration | | | | | |
|---|---|---|---|---|---|---|
| Activity | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) | Expected Duration (*Te*) | Standard Deviation ($\sigma_e$) | Variance $V_e = \sigma_e^2$ |
| A | 2 | 4 | 7 | 4.167 | 0.833 | 0.694 |
| B | 5 | 8 | 14 | 8.500 | 1.500 | 2.250 |
| C | 4 | 6 | 8 | 6.000 | 0.667 | 0.444 |
| D | 2 | 2 | 2 | 2.000 | 0 | 0 |
| E | 7 | 10 | 21 | 11.333 | 2.333 | 5.444 |
| | | | | *TE* = 32 | *VE* = 8.833 | |

The next step is to do the calculations for the entire path. We simply add the expected durations and variances, as explained in equations 11.4 and 11.5, to obtain $T_E$ and $V_E$.

Next, take the square root of $V_E$ (use equation 11.6) to find the standard deviation ($\sigma_E$) of the path:

$$T_E = 32 \text{ days}$$

$$V_E = 8.833 \text{ days}$$

and

$$\sigma_E = \sqrt{8.833} = 2.972 \text{ days}$$

Note that $\sigma_E \neq \sum_{i=1}^{n} (\sigma_E)_i$

1. *The probability that the project will finish by the end of day 32*. Using equation 11.7, we find that $Z = (32 - 32)/2.972 = 0$. From the $Z$ table (Table 11.1), we find that

$$\Pr(T_s \leq 32) = 0.5 = 50\%$$

See Figure 11.2.

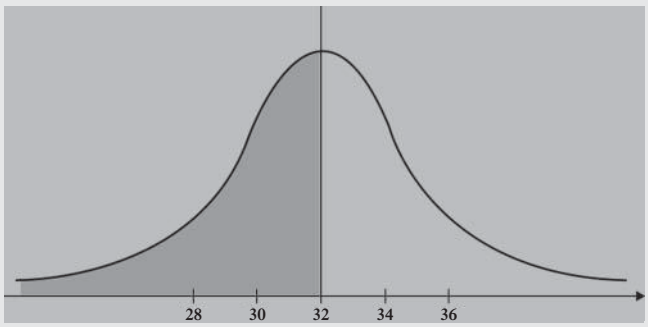



**Figure 11.2 Solution to example 11.1, part 1**

2. *The probability that the project will finish by the end of day 34*.

$$Z = (34 - 32)/2.972 = 0.67$$

From Table 11.1, we find that

$$\Pr(T_s \leq 34) = 0.749 = 74.9\%$$

See Figure 11.3.

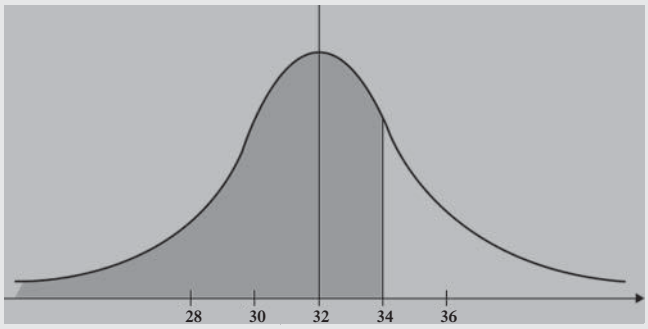



**Figure 11.3 Solution to example 11.1, part 2**

3. *The probability that the project will finish before day 30*. This probability is the same as the probability of finishing by the end of day 29.

$$Z = (29 - 32)/2.972 = -1.01$$

When $Z < 0$, take the probability that corresponds to the positive value of $Z$ and then subtract it from 1.0 (100%):

$$\Pr(T_s \leq 29) = 1 - 0.844 = 0.156 = 15.6\%$$

See Figure 11.4.

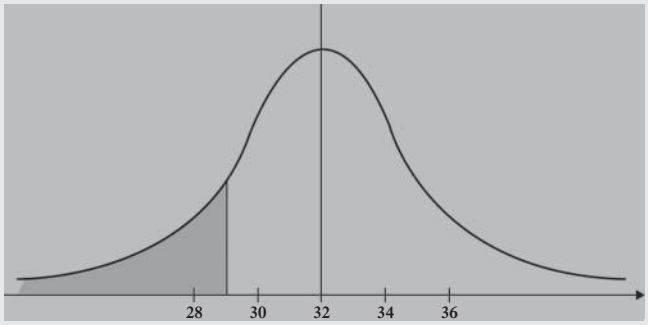



**Figure 11.4 Solution to example 11.1, part 3**

4. *The probability that the project will finish on day 32*.

$$\Pr(T_s = 32) = \Pr(T_s \leq 32) - \Pr(T_s \leq 31)$$

We already calculated $\Pr(T_s \leq 32) = 0.5 = 50\%$ (part 1). For $\Pr(T_s \leq 31)$,

$$Z = (31 - 32)/2.972 = -0.34$$

$$\Pr(T_s \leq 31) = 1 - 0.633 = 0.367 = 36.7\%$$

and

$$\Pr(T_s = 32) = \Pr(T_s \leq 32) - \Pr(T_s \leq 31) = 50\% - 36.7\% = 13.3\%$$

See Figure 11.5.

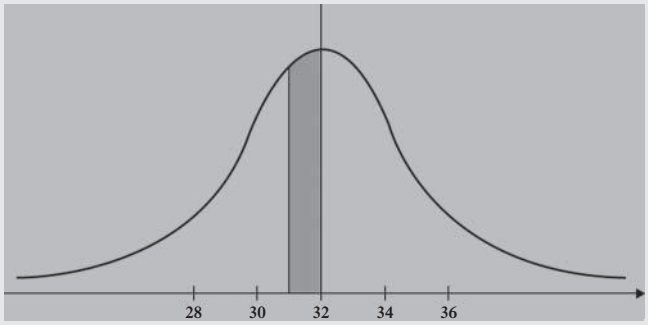



**Figure 11.5 Solution to example 11.1, part 4**

5. *The probability that the project will finish no later than day 35*. This probability is the same as the probability that the project will finish by the end of day 35:

$$Z = (35 - 32)/2.972 = 1.01$$

and

$$\Pr(T_s \leq 35) = 0.844 = 84.4\%$$

See Figure 11.6.

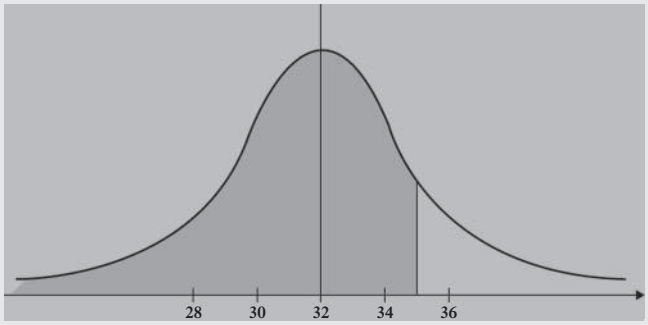



**Figure 11.6 Solution to example 11.1, part 5**

6. *The probability that the project will finish at least 2 days early*. This probability is the same as the probability that the project will finish on

day 30 or earlier, or the same as the probability that the project will finish by the end of day 30:

$$Z = (30 - 32)/2.972 = -0.67$$

and

$$\Pr(T_s \leq 30) = 1 - 0.749 = 0.251 = 25.1\%$$

See Figure 11.7.

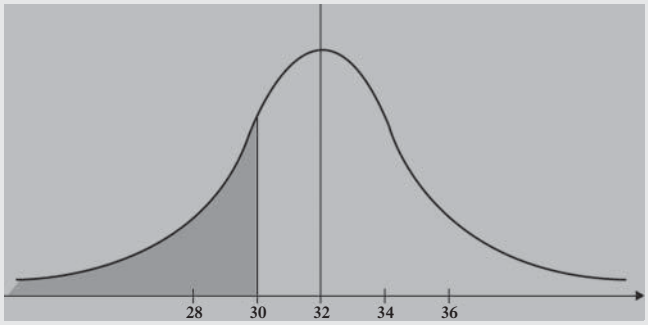



**Figure 11.7 Solution to example 11.1, part 6**

7. *The probability that the project will finish at least 2 days late*. This probability is the same as the probability that the project will finish by day 34 or later, or the same as the probability that the project will finish after day 33:

$$\Pr(T_s > 33) = 1 - \Pr(T_s \leq 33)$$

For $\Pr(T_S \leq 33)$

$$Z = (33 - 32)/2.972 = 0.34$$

and

$$\Pr(T_s \leq 33) = 0.633 = 63.3\%$$

Thus,

$$\Pr(T_s > 33) = 1 - 0.633 = 0.367 = 36.7\%$$

See Figure 11.8.

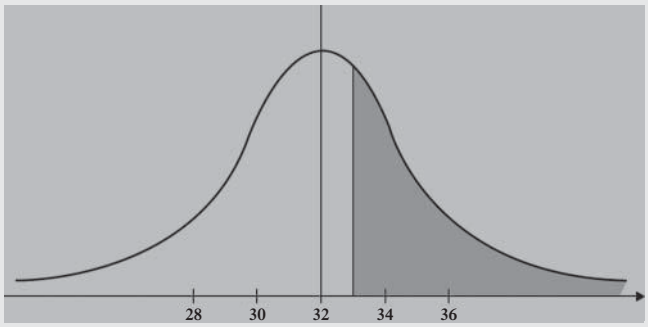



**Figure 11.8 Solution to example 11.1, part 7**

Note that if the instruction had said "the probability that the project will finish *more than* [rather than *at least*] 2 days late, "it would have meant $\Pr(T_S > 34)$.

8. *The probability that the project will finish on day 32 ±1 day*. This means that the project will finish on day 31, 32, or 33.

$$\Pr(T_s = 31,\ 32,\ 33) = \Pr(30 < T_s \leq 33) - \Pr(T_s \geq 33)\,\Pr(T_s \leq 30)$$

and

$$\Pr(T_s = 31,\ 32,\ 33) = 0.633 - 0.251 = 0.382 = 38.2\%$$

See Figure 11.9.

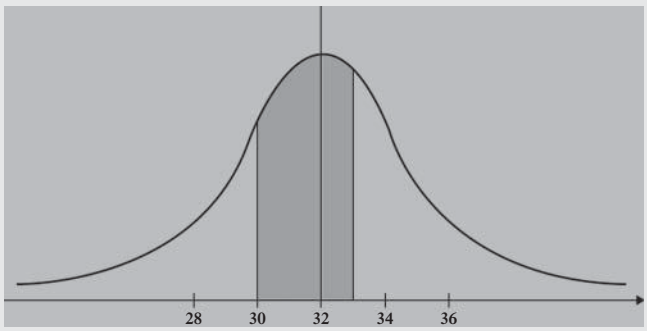



**Figure 11.9 Solution to example 11.1, part 8**

9. *The completion date with at least a 90% confidence level*. Go to Table 11.1 and pick a probability value close to (but not less than) 0.9. Read the corresponding $Z$ value. You should read 1.28. Apply equation 11.8:

$$T_S = \sigma_E * Z + T_E = 2.972 * 1.28 + 32 = 35.8 \approx 36 \text{ days}$$

### Difference between "Most Likely" and "Expected" Durations

From a linguistic viewpoint, the terms *most likely* and *expected* may be thought of as similar. However, statistically they are different. The "most likely" duration is simply the duration that we believe has more likelihood of happening than any other duration. In our case, it is a user-defined amount; that is, we provide it along with other durations (optimistic and pessimistic) in the equation so that we can calculate the expected duration and the standard deviation. It does not represent the arithmetic mean or the median.

The "expected duration" is the amount of time that we expect the project or path duration to take, considering the different durations (optimistic and pessimistic), their values, and their weights. It is a computed amount. For example, consider a case in which 6, 8, and 10 are the optimistic, most likely, and pessimistic durations, respectively. The expected duration will be equal to 8. In this case, it is equal to the most likely duration because the optimistic and pessimistic durations "deviate" by the same amount from the most likely duration (6 to 8 and 10 to 8). Now, suppose that the pessimistic duration is 13 days, whereas the optimistic and most likely durations are still the same. The expected duration is calculated as 8.5 days by using equation 11.1. The expected duration value has increased as a result of the increase in the skewness of the pessimistic duration. Even though the probability of the occurrence of the pessimistic duration (or the weight) is still the same in both examples (one-sixth), the consequences have worsened in the second case.

### Is the Longest Path Still the Most Critical?

A typical network project has tens or hundreds (perhaps even thousands) of paths. Typically, we define the critical path as the longest path from the start until the end of the network (see the full definition of *critical path* in Chapter 4). In addition to the duration, another factor must be considered in the criticality of the path in PERT. This factor is the "uncertainty" of the duration of the path, measured by the standard deviation. Let us look at example 11.2 for an illustration.

### Example 11.2

Draw the network for the following project.

| Activity | IPA | Duration (Days) | | |
|---|---|---|---|---|
| | | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) |
| A | – | 4 | 5 | 6 |
| B | A | 10 | 12 | 14 |
| C | A | 7 | 9 | 16 |
| D | B | 14 | 17 | 22 |
| E | B, C | 10 | 15 | 30 |
| F | C | 4 | 7 | 13 |
| G | D | 12 | 20 | 40 |
| H | D, E | 10 | 12 | 15 |
| I | F, H | 8 | 9 | 10 |

Compare the three paths: ABDHI, ABDG, and ABEHI. Calculate the expected duration and standard deviation for each path. Considering all three paths, what is the duration of the project with at least a 95% confidence?

### Solution

With regular CPM calculations (using most likely durations), the critical path is ABDHI with 55 days, followed by paths ABDG and ABEHI at 54 and 53 days, respectively (Figure 11.10). Now, let's do PERT calculations.

| Activity | Duration | | | Expected Duration (*Te*) | Standard Deviation ($\sigma_e$) | Variance ($V_e = \sigma_e^2$) |
|---|---|---|---|---|---|---|
| | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) | | | |
| A | 4 | 5 | 6 | 5.00 | 0.33 | 0.11 |
| B | 10 | 12 | 14 | 12.00 | 0.67 | 0.44 |
| C | 13 | 9 | 16 | 9.83 | 1.50 | 2.25 |
| D | 20 | 17 | 22 | 17.33 | 1.33 | 1.78 |
| E | 10 | 15 | 30 | 16.67 | 3.33 | 11.11 |
| F | 4 | 7 | 13 | 7.50 | 1.50 | 2.25 |
| G | 12 | 20 | 40 | 22.00 | 4.67 | 21.78 |
| H | 10 | 12 | 15 | 12.17 | 0.83 | 0.69 |
| I | 8 | 9 | 10 | 9.00 | 0.33 | 0.11 |

With regard to path ABDHI,

$$T_E = 5.00 + 12.00 + 17.33 + 12.17 + 9.00 = 55.50 \text{ days}$$

$$V_E = 0.11 + 0.44 + 1.78 + 0.69 + 0.11 = 3.14$$

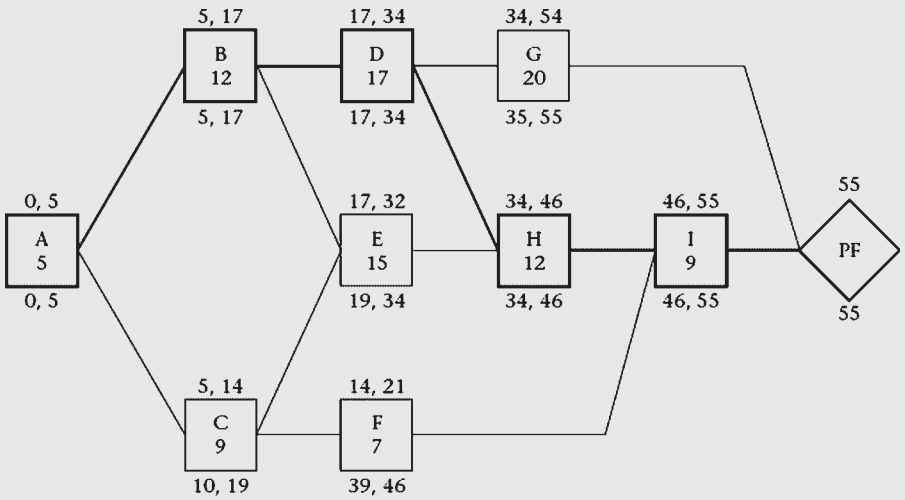



**Figure 11.10 CPM network solution to example 11.2**

and

$$\sigma_E = \sqrt{3.14} = 1.77 \text{ days}$$

To find the duration with a minimum level of confidence of 95%, find the $Z$ values associated with the probability of 0.95. From the table, this $Z$ value is 1.645 and

$$T_S = \sigma_E Z + T_E = 1.771.645 + 55.50 = 58.41 \text{ days}$$

Applying the same calculations to path ABDG, we find

$$T_E = 5.00 + 12.00 + 17.33 + 22.00 = 56.33 \text{ days}$$

$$V_E = 0.11 + 0.44 + 1.78 + 21.78 = 24.11$$

$$\sigma_E = \sqrt{24.11} = 4.91 \text{ days}$$

and

$$T_S = \sigma_E Z + T_E = 4.911.645 + 56.33 = 64.41 \text{ days}$$

Applying the same calculations again to path ABEHI, we find

$$T_E = 5.00 + 12.00 + 16.67 + 12.27 + 9.00 = 54.83 \text{ days}$$

$$V_E = 0.11 + 0.44 + 11.11 + 0.69 + 0.11 = 12.47$$

$$\sigma_E = \sqrt{12.47} = 3.53 \text{ days}$$

and

$$T_S = \sigma_E Z + T_E = 3.531.645 + 54.83 = 60.64 \text{ days}$$

Let us discuss the results: when we look at the most likely durations (as single-value, or deterministic, durations), path ABDHI is the longest, at 55 days. When we look at the expected durations, path ABDG is the longest, at 56.33 (say, 57) days. When we consider the standard deviation and the 95% required confidence level, the same path, ABDG, is longest (by a larger margin), at 64.41 (say, 65) days. Note also that in this case, path ABEHI is second in importance (at 60.64 days), after path ABDG and before path ABDHI. In other words, the path considered longest by the deterministic CPM calculations was superseded by two other paths that were considered by means of PERT to be more critical.

*Note*: The preceding calculations were done using an Excel spreadsheet. The answers were rounded for simplicity.

Example 11.2 illustrates the importance of considering near-critical paths, especially those with high uncertainty (a large standard deviation). Simulations may be used to determine which path is the most critical.

### Using PERT to Calculate the Date of an Event with a Certain Level of Confidence

The main focus in PERT is the event, not the activity.[2] You can use the same probabilistic approach with any event (e.g., delivery of a custom item, the building is watertight, substantial completion). In this case, you consider the path from the start of the project (or data date, if project has already started) until, and including, the event under consideration.

#### Example 11.3

Calculate the date of completion of activity F in example 11.2 with 95% confidence.

#### Solution

From the calculation table in example 11.2, we take the path ACF.

[2] The terms *event* and *activity* were introduced in Chapter 3. An activity has a start date, a duration, and a finish date. An event has just one date (start or finish) with no duration. An event can be the start or finish of an activity.

| Activity | Duration | | | Expected Duration (*Te*) | Standard Deviation ($\sigma_e$) | Variance ($V_e = \sigma_e^2$) |
|---|---|---|---|---|---|---|
| | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) | | | |
| A | 4 | 5 | 6 | 5.00 | 0.33 | 0.11 |
| C | 13 | 9 | 16 | 9.83 | 1.50 | 2.25 |
| F | 4 | 7 | 13 | 7.50 | 1.50 | 2.25 |
| | | | *TE* = 22.33 | | | *VE* = 4.61 |

($V_e = \sigma_e^2$) The $Z$ value associated with a probability of 95% is 1.645, and

$$T_S = \sigma_E \cdot Z + T_E = 2.15 \cdot 1.645 + 22.33 = 25.87 \approx 26 \text{ days}$$

*Note*: The preceding calculations were done using an Excel spreadsheet. The answers were rounded for simplicity.

### Determining the Probability of a Certain Project Finish Date (Multiple Paths Considered)

In statistics and probability, the probability that two *independent* events will happen simultaneously is equal to the product of the two probabilities:

$$\Pr(A \cap B) = \Pr(A) \cdot \Pr(B) \tag{11.9}$$

Equation 11.9 holds true only if events A and B are independent. If they are dependent, the probability that both events will happen at the same time will depend on the correlation between the two events and cannot be defined in one simple equation. For example, in the network of Figure 11.10, paths BDG and CFI may be, but not necessarily, independent. We cannot be sure until we know everything about them. Even though they are not linked by a logical relationship, they could be dependent, for example, if activities on both paths are performed by the same crew or use materials that will be delivered in the same shipment.

Theoretically, if we need to calculate the probability that the project in Figure 11.10 will finish by a certain date, we need to consider all paths. In our small example, we have five paths: ABDG, ABEHI, ABDHI, ACEHI, and ACFI. Since they all share at least one activity, A, they have dependencies. Calculating the probability that the project will finish by a certain date requires not only complicated calculations but also correlation factors between activities that may be difficult to obtain or estimate. In real-life projects, we may have tens, hundreds, or even thousands of paths in a CPM network. For practical reasons, we focus on one path at a time, as we did in the last example.

### PERT and the Construction Industry

Even though PERT can be a good tool for predicting event dates, it is rarely, if ever, used in the construction industry. There are four reasons for this:

1. The main area of effective application for PERT is experimental projects or those with a great deal of uncertainty with regard to durations. In construction projects, even if the project design is new, the basic elements of the construction operations are usually well known. Project managers usually feel comfortable with the estimated durations they provide. A good project manager's estimates may be slightly over or under for the duration of individual activities, but the overall duration of the project should be fairly accurate.
2. As shown previously, PERT focuses on a single path. The scheduler must study different paths and analyze them for the highest uncertainty (least likelihood) of meeting a specific finish date. This process may be complicated and time-consuming.
3. Project managers may have a problem providing three durations (optimistic, most probable, and pessimistic) for each activity. During a discussion with the author, one project manager sarcastically said, "We can barely come up with one duration per activity, and you want me to provide you with *three* durations?"
4. Many project managers adopt the practice of adjusting and correcting the durations (and possibly the logic) while updating the schedule. Even though we are required to do such adjusting and correcting while updating, this practice must not be an excuse for poorly prepared schedules. The project manager should always remember that the project schedule could be a legally binding document, as part of the contract. In such a case, it may be used in court later to prove or disprove a delay claim.

### PERT and Computer Project-Scheduling Software[3]

Several computer software programs perform **Monte Carlo simulations**, generating random numbers that follow the distribution of individual activities (optimistic, most likely, and pessimistic, along with their weights). The program generates results for each run. It is typical to do 100 runs or more. The more runs you do, the more confidence you will have in the results. Some products run Monte Carlo simulations in a "generic" environment. Crystal Ball (Decisioneering, Inc., Denver, Colorado) performs risk analysis by using Monte Carlo simulations in MS Excel. Other products

[3] There is more discussion on PERT (three-point estimate) and its applications in risk management in Chapter 14.

tie in with specific scheduling software. For example, Oracle's Primavera Risk Analysis[4] runs risk analysis by integrating with Primavera scheduling products. You can assign an uncertainty to activity durations, costs, and resources, and then determine the probability of completing the project on time and within budget. Risk+ (ProjectGear, Inc., Tacoma, Washington) and @Risk (Palisade Corp., Newfield, New York) are compatible with MS Project for calculating risk and probabilities based on PERT calculations. Regardless of the product you use, you must ensure that it integrates with the scheduling program you are using.

Some software companies call precedence network diagrams *PERT*. In most cases, the displayed diagram is nothing but a precedence network applying the deterministic CPM calculations. Because of this, many people in the construction industry have begun to use the term *PERT* simply, and erroneously, to indicate a CPM logic diagram, as compared with a bar chart. The author has even observed this error in terminology in some owners' specifications, calling for "PERT reports" to be submitted. The author strongly recommends refraining from this use of the term *PERT*.

## GRAPHICAL EVALUATION AND REVIEW TECHNIQUE (GERT)

The **graphical evaluation and review technique (GERT)** is a network analysis technique that allows for conditional and probabilistic treatment of logical relationships (i.e., some activities may not be performed) (Project Management Institute, 2000). GERT is similar to PERT but considers both deterministic and probabilistic branching. It incorporates both in the network analysis. GERT allows additional branching features that are not provided by CPM or PERT.

In deterministic branching, as shown in Figure 11.11a, we consider all activities leaving the node. In other words, activities A, B, and C in Figure 11.11a will all take place. In probabilistic branching, as shown in Figure 11.11b, we consider one branch at any given time. For example, in Figure 11.11b, we consider either A or B. However, the sum of the probabilities for each branch leaving a probabilistic branching must equal 100% (Fair, 1994).

Furthermore, GERT allows looping, something both CPM and PERT do not allow. For example, Figure 11.12 shows three possible outcomes following activity A: activity B (with 30% probability), activity C (with 50% probability), *or* activity D (repeat of activity A, with 20% probability). We can think of activity A as Shop Drawing Submittal, activity B as Accepted As Is, activity C as Accepted with Changes, and activity D as Rejected—Resubmit.

[4] Originally called Pertmaster Professional Risk, created by Pertmaster Ltd., London, United Kingdom, and then acquired by Primavera Systems, Inc., and renamed Primavera Pertmaster. With the recent acquisition of Primavera by Oracle, Primavera Pertmaster was again renamed Oracle Risk Analysis.

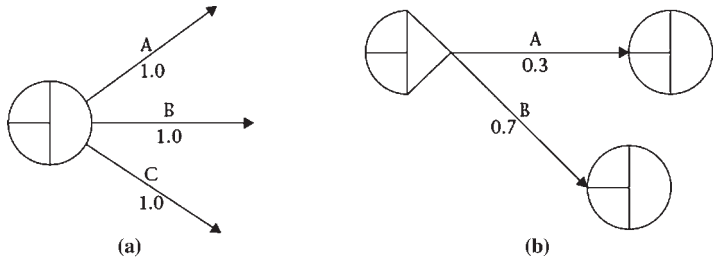



**Figure 11.11 (a) Deterministic and (b) probabilistic branching**

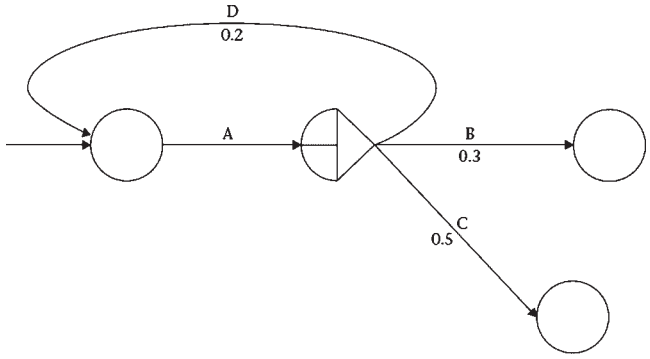



**Figure 11.12 Three possible outcomes following activity A**

GERT has not gained popularity in the construction industry. In fact, it has not gained any interest beyond stimulating some academic research[5].

## LINEAR SCHEDULING METHOD (LSM)[6]

Construction projects differ in their type, size, and nature. Scheduling methods also differ in their efficacy, depending on the type of project they are serving. Bar charts are generally good for small, simple projects.[7] CPM networks are used for medium-size

[5] Scheduling of Industrialized Construction Project using Graphical Evaluation and Review Technique (GERT), by Tanmay Ramani and Ramesh Kannan. Proceedings of Second International Conference on Advances in Industrial Engineering Applications(ICAIEA2014), Anna University, January 6-8, 2014.

[6] There are very similar, almost identical, methods to LSM, such as line of balance (LOB) method and vertical production method (VPM). Also, LSM method is known in some parts of Europe as time couplings method (TCM).

[7] Practically speaking, bar (Gantt) charts are obsolete as a scheduling method. However, they are alive and popular as a reporting method for projects that are scheduled using CPM networks and calculations. In this case, bar charts are effectively used in large projects, focusing on a small group of activities or presenting the schedule in the form of summary activities. Refer to the discussion in Chapters 2, 3, and 9.

to large projects that consist of large numbers of small activities. Some construction projects consist of a few activities (usually with large quantities) that must be done in the same order or sequence, such as heavy construction projects (e.g., roads, earthwork, or utility piping). Let us consider a project to lay down 5,000 linear feet (LF) of an underground utility pipe. The basic activities are Excavation, Prepare Subbase, Lay Pipe, Backfill, and Compact. If we are to use CPM networks for this project, we can take one of the following two approaches:

1. Create a project with only five large activities. Connect these activities with start-to-start (with lags) and finish-to-finish relationships.
2. Divide each major activity into a number of subactivities (e.g., 50 subactivities), in which each represents a distance of 100 LF, and connect them with finish-to-start relationships with no lags.

#### Steps Required to Build a Schedule by Using the LSM

Three simple steps (similar to the first three steps in the CPM, discussed in Chapter 4) are necessary to build a schedule by using the LSM.

1. Determine the work activities. As mentioned previously, we expect only a few activities in LSM schedules.
2. Estimate activity production rates. Such an estimation is similar to determining durations. We still estimate durations, but we are more concerned with production rates.
3. Develop an activity sequence, similar to determining logical relationships. All relationships are start to start (with lags) with finish to finish (with lags too).

Before applying the LSM, we must make sure it is the most appropriate method.

#### How the LSM Works

In the LSM, since the *x*-axis represents time and the *y*-axis represents distance, the slope represents the "speed," or rate, of production (Figure 11.13). When we have two or more activities, the production rate will differ from one to another. The horizontal distance between two lines represents the float of the earlier activity. In the LSM, we call it the *time buffer*. The vertical distance represents the distance separating the two operations. We call it the *distance buffer*. See Figure 11.14.

Lines are not allowed to intersect, because an intersection literally means that the successor has gotten ahead of the predecessor, which is impossible (see Figure 11.15).

Keep in mind that the "Location" label on the Y-axis works mostly with horizontal construction projects, such as highways, utilities, and so forth. This label can be changed to "Work Quantity" or another physical measure criterion for other types of projects.

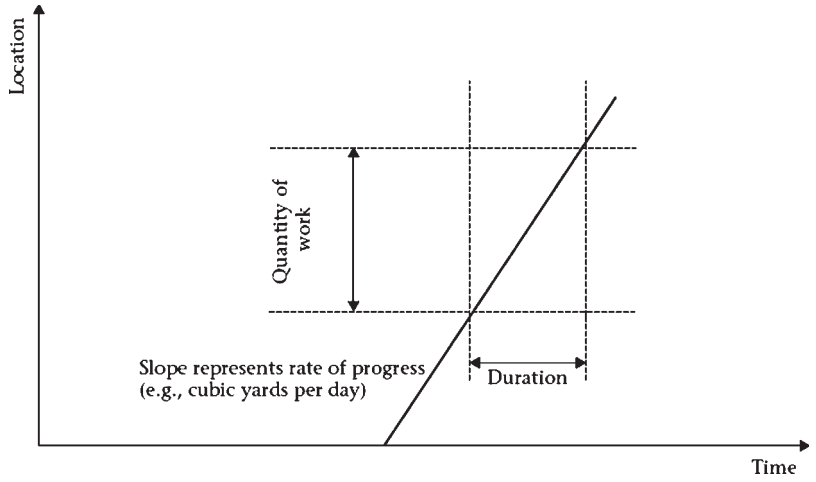



**Figure 11.13 The linear scheduling method (LSM)**

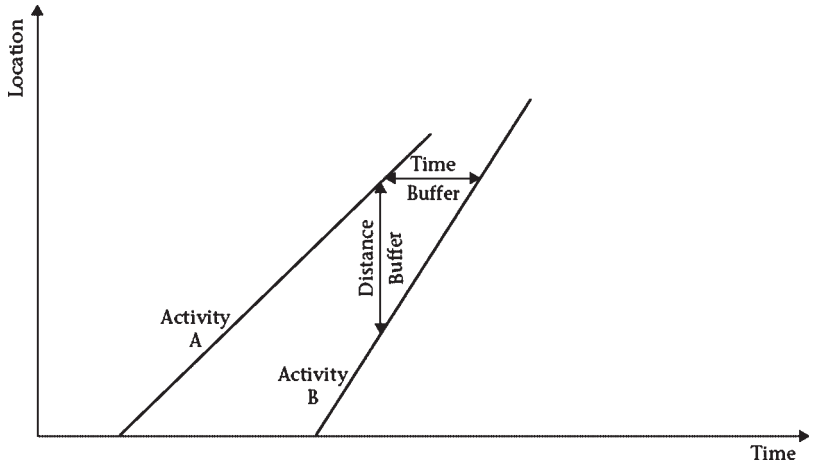



**Figure 11.14 Time and distance buffers in the LSM**

Consider, for example, a carpentry crew that is installing and taping drywall for a total of 10,000 square feet (SF). The production rate for the crew is 500 SF per day for installation and taping. The painting crew is directly behind, at a production rate of 800 SF per day. Assume that the painting crew starts on day 2 (1 day after the carpentry crew started); then, at the end of day 3, the carpentry crew would have finished $500 \cdot 3 = 1{,}500$ SF, but the painting crew would have finished $800 \cdot 2 = 1{,}600$ SF, which is impossible. There are four solutions for this problem.

1. Speed up the rate of the carpentry crew.
2. Slow the rate of the painting crew.

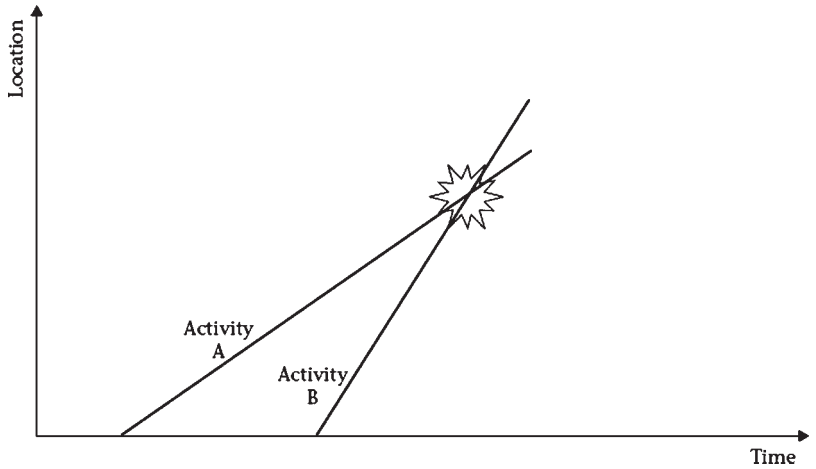



**Figure 11.15 A successor's getting ahead of its predecessor: an illegal relationship**

3. Make the painting crew start later (calculate the time buffer).
4. Make the painting crew work in intervals: once they catch up with the carpentry team, they can stop for a period, resume, and so on.

Solution 1 would increase the slope of activity A. Solution 2 would decrease the slope of activity B. Solution 3 would increase the time buffer. All three solutions aim at preventing the intersection of the two lines. Solution 4 would be represented in an LSM diagram, as shown in Figure 11.16. The horizontal lines (slope = 0) represent an interruption or stoppage time (no production). If the productivity of the crew changes, the slope changes, too. Therefore, alternatively, instead of completely halting

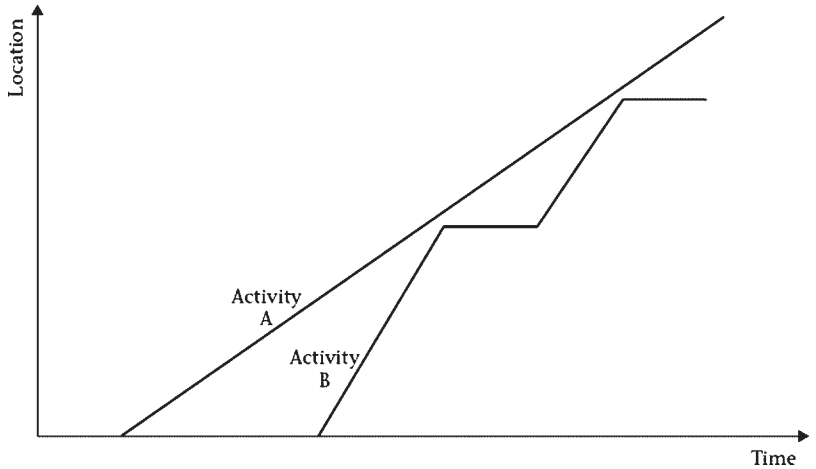



**Figure 11.16 Solution 4 for avoiding an intersection in the LSM**

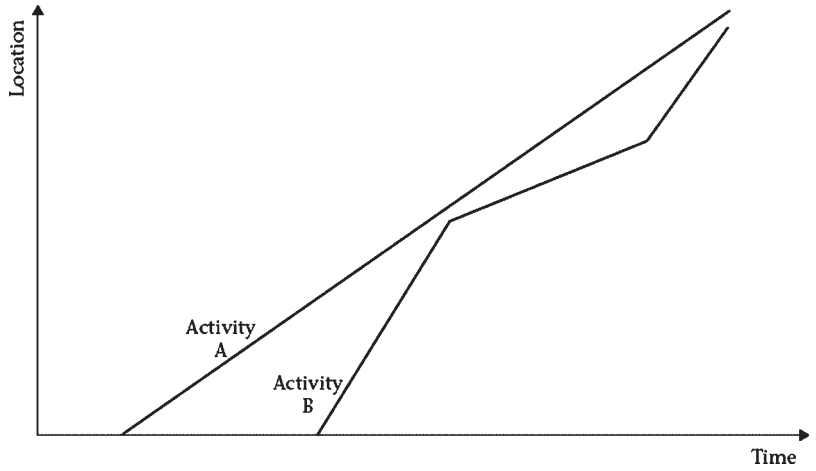



**Figure 11.17 Combination of solutions 2 and 4 for avoiding an intersection in the LSM**

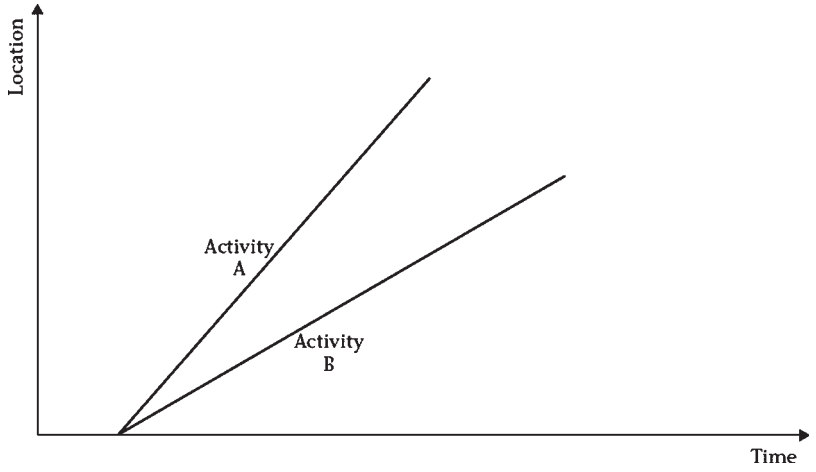



**Figure 11.18 Rate of successor slower than rate of predecessor in the LSM**

activity B during intervals, we can reduce the crew size to slow the rate until there is a safe time buffer (a combination of solutions 2 and 4; see Figure 11.17).

The time buffer is necessary only if the rate of the successor is faster than the rate of the predecessor. If the rate of the successor is slower than the rate of the predecessor, the time buffer can start at zero. Naturally, the successor (activity B) will finish after the predecessor (activity A). See Figure 11.18.

To calculate the time buffer (Figure 11.19), we start from the end: allow activities A and B to finish simultaneously. Then,

$$\text{Duration A} = \text{Duration B} + \text{Time buffer}$$

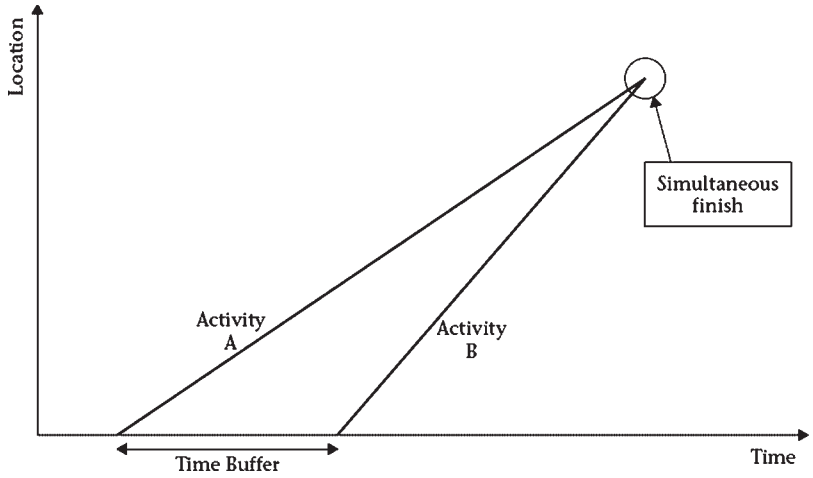



**Figure 11.19 Time buffer calculation in the LSM**

or

$$\text{Time buffer} = \text{Duartion A} - \text{Duration B} \tag{11.10}$$

With multiple activities, you must consider two activities at a time. Starting from the beginning, do the following:

1. Compare the durations of activities 1 and 2. If activity 2 has a shorter duration, determine the time buffer from equation 11.10. If activity 2 has a longer duration, there is no need for a time buffer (practically speaking, we need a minimum buffer because a predecessor and a successor cannot start at exactly the same time).
2. Repeat step 1 for activities 2 and 3, and so on.

**Example 11.4**

A project consists of five activities:

A. Excavating a trench
B. Laying a subbase of gravel
C. Laying a concrete pipe
D. Backfilling
E. Compacting

Assume that the length of the pipe is 1,000 LF and that the productivity rates for the five activities are 100, 125, 75, 200, and 150 LF per day,

respectively. Draw the project diagram, using the LSM. Leave a *minimum* 1-day time buffer.

**Solution**

First, determine the durations by dividing the total quantity, 1,000 LF, by the production rate for each activity. The following durations result: 10, 8, 14, 5, and 7 days for activities A through E, respectively.

If we start activity A on (end of) day 0, it will finish on day 10. Activity B lasts only 8 days, and we must leave at least a 1-day time buffer so that we can finish this activity on day 11. Subtracting its duration of 8 days, we find the starting point: day 3. Activity C lasts 14 days, so we lag it by 1 day and start it on day 4. It will finish on day 18. Activity D can finish no earlier than day 19. It will start on day 14. Finally, activity E can start on day 15 and finish on day 22. See Figure 11.20.

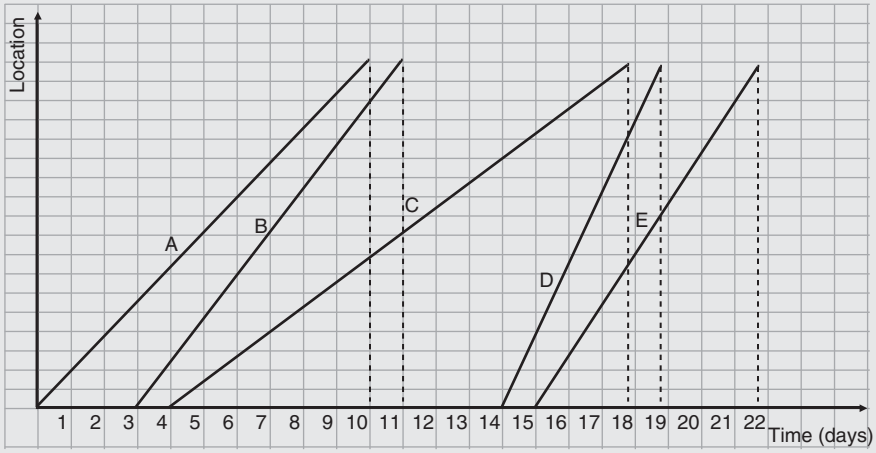



**Figure 11.20 Solution to example 11.4**

## LSM AND PROJECT SCHEDULE ACCELERATION

The nature of the LSM lends itself to project acceleration because activities overlap while activities are mostly sequential in critical path networks. Accelerating projects using LSM works by shifting activities until they overlap as much as possible, making the schedule more compact. First, choose the minimum yet appropriate buffers among activities. Second, modify productivities of certain activities by modifying the crews, if possible. This will help to eliminate work stoppages when a successor's production

is faster than the predecessor's and will make activities as parallel as possible. This may not be always possible or may be possible within limitations due to standard equipment production. Physical space also has to be observed in order to create a safe and effective work environment.

A new method of calculating linear schedules, called the productivity scheduling method has recently been developed (Lucko 2008). It employs singularity functions, which have the feature that they can be turned on when they are needed. The productivity of activities is translated into the slope of their respective functions, which are then added sequentially to the linear schedule, separated by buffers, in an algorithm that guarantees the minimum total project duration.

### LSM Computer Software Programs

The LSM method has not found a wide acceptance in the construction industry despite its analytical advantages. One drawback appears to be the lack of major software packages offering LSM capabilities. However, the method is believed to be making a comeback as a growing number of programs are becoming available, commercially as well as academically, that employ this versatile method. Examples include:

- Vico Control™ (formerly Graphisoft® Control/DYNAProject™ at Helsinki University of Technology) by Vico Software in Finland
- TILOS by Asta Development in Germany
- Spider Project PM System by Spider Management Technologies in Russia
- PlaNet by Artemis International Solutions in Finland
- LinearPlus Time Chainage Charts by PCF that is part of QEI Exec Project Management Software and was developed for the Channel Tunnel
- Earlier programs, including Q. Scheduling by Misronet Construction Information Services, TimeChg 2000 by Peter Clarke, and TransCon Xposition by TransCon Consulting in Richmond, Virginia, now Milestone Consultants

Researchers at several universities have created prototype software, including UNaLSS (University of Naples Linear Scheduling Software) in 2005 in Italy, PULSS (Purdue University Linear Scheduling Software) in 2001, FLSP (Florida Linear Scheduling Program) in 1999 at the University of Florida, and LCPM (Linear Construction Project Manager) in 1998 at Texas A&M University (Dell'Acqua et al., 2005), as well as PSM (Productivity Scheduling Method) in 2008 at Catholic University of America, LBMS (Location-Based Management System) in 2006 at Swinburne University of Technology in Australia, POLO (Planning & Optimization for Linear Operations) in 1995 at Purdue University, and various other older computer implementations.

LSM has been used in the form of diagrams that were drawn in computer-aided design (CAD) software, for example, for a pipeline project. Finally, any spreadsheet software, for example, Microsoft Excel as well as scientific computing environments,

for example, MATLAB®, can be set up manually to perform calculations and draw linear schedule diagrams that can be updated during the project's execution.

### Graphical Path Method (GPM)[8]

The graphical path method (GPM) was developed by Dr. Gui Ponce de Leon as an alternative to database-driven CPM models. Rooted in robust mathematics, GPM algorithms enable graphical, synchronous, and interactive tools that facilitate hands-on, real-time scheduling. A GPM application lets users plan and schedule simultaneously, allowing them to carry out resource leveling, schedule optimization, and time/cost trade-offs as the network is built and the schedule is generated. The goal of GPM is to transform conventional planning and scheduling into an engaging, planning-dominated experience for project stakeholders. This method posits a number of new concepts: *planned dates, float, drift, gap, buffer, proportional link offsets*, and *forensic total float*. They are briefly introduced in this summary.

In GPM, planning proceeds by drawing a graph of logically related, dated objects (*activities*, *milestones*, and *benchmarks*) into a time-scaled project network model. At the core of this model is LDM (logic diagramming method), a blend of both PDM (precedence diagramming method) and ADM (arrow diagramming method). In a way, LDM resembles a time-scaled version of ADM that allows for PDM overlapping logic. Start-to-start (SS), finish-to-finish (FF), and start-to-finish (SF) logic is accepted through *embedded nodes*, placed in between or directly on an activity's start or finish nodes. Figure 11.21 shows an LDM schedule for a sample project.

From links and object dates, GPM continually calculates *gaps* for all links and *float attributes* for dated objects. GPM allows activities to be placed on any date between their early and late dates, and this date is referred to as a *planned date*. Gaps are then calculated from the dates of the two connected activities, and floats, drifts, and total floats are algorithmically calculated from gaps. An activity that slips and/or extends to later dates without causing an overrun of project completion (or deadline) has float. An activity that backslides and/or extends to early dates without causing an earlier project start (or interim release date) has preceding float, or *drift*. An activity that has neither float nor drift is *critical*. For every object, float plus drift is a constant equal to CPM total float. In other words:

- Float measures the extent that a positive-drift activity may be delayed beyond planned dates while not extending the project completion date or an interim required completion date, and is equal to (Late finish date – Planned finish date).
- Drift measures the extent that an activity may gain schedule while not forcing an earlier project start or interim release date, and is equal to (Planned start date – Early start date).

[8] This section was mainly written by the method developer, Dr. Gui Ponce de Leon.

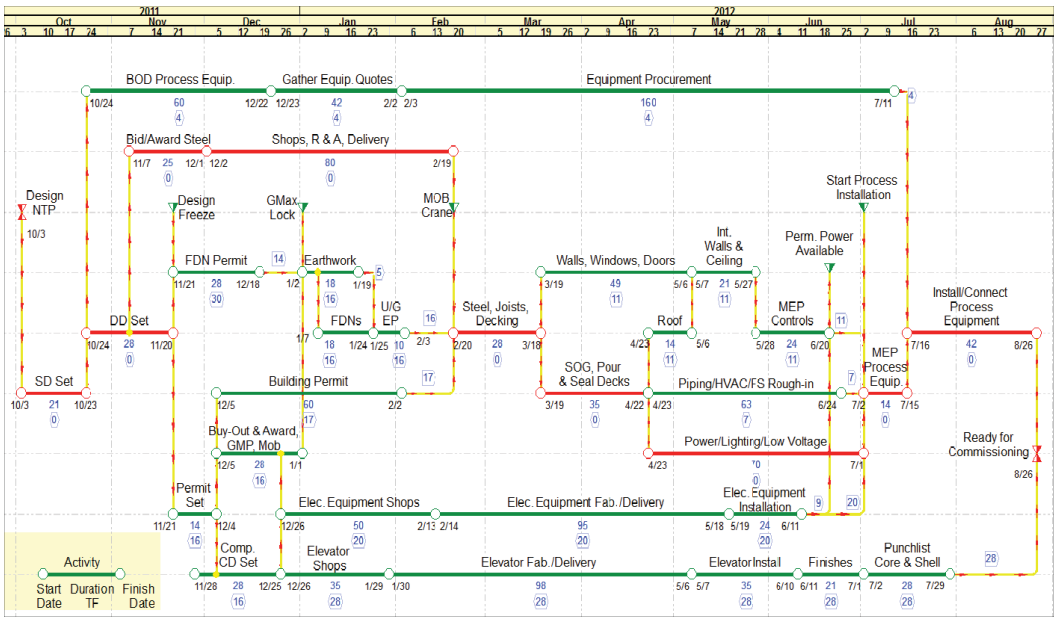



**Figure 11.21 Logic diagramming method (LDM notation)**

- For two linked objects, gap measures the extent to which the predecessor may be delayed and not impact the successor; gap (in this case, drift-gap) also measures the extent to which the successor may gain schedule and not impact the predecessor.
- Buffer (equivalent of CPM free float) measures the minimum of the gaps on logic ties to the activity's successors. It is a GPM-perfected free float concept, since it homogenizes all relationship types to a single formula.

Unique to GPM is that it continuously updates durations, dates, floats, resource profiles, and all schedule data on a real-time basis; thus, it eliminates the black-box mystery behind many CPM applications. This embodies a paradigm shift from CPM by providing synchronous feedback and an interactive interface that is suited for collaborative planning and scheduling. Additionally, GPM is not "early date biased," as it allows activities with total float to be scheduled anywhere within the total float range, focusing on planned dates instead of early dates.

GPM introduces the concepts of *proportional link offsets* and *forensic total float*. Proportional link offsets allow the amount of overlap in a SS, FF, or SF relationship to be contingent on the duration of the host activity. In many situations, this better reflects the reality in the field than a more traditional, constant overlap does. In addition, GPM has the ability to calculate drifts, floats, and therefore total floats *left of the data date*, that is, for completed activities. Forensic total floats can be crucial for accurately identifying as-built critical paths, and their calculation facilitates retrospective delay analysis.

Currently, the only GPM software application available is NetPoint®. NetPoint is mathematically based and intuitive to learn and use, making it ideal for scheduling practitioners and nonscheduling-trained stakeholders alike. This tool allows project managers, superintendents, subcontractors, and other stakeholders to collaboratively, in one session, build a schedule by graphically positioning activities on a planning surface and using a variety of simple and intuitive logic ties to convey relationships. Development of NetPoint started in 2004 and was commercially released in the fall of 2009. An example of a simple NetPoint schedule is shown in the Figure 11.22. The histogram at the bottom represents resource profiles in color-coded bars, both in daily and cumulative formats.

As a collaboration tool, the NetPoint application provides planning, scheduling, resource management, and other project control capabilities that are similar to what Primavera Project Management and Microsoft Project offer; however, looking within the software architecture, there exist major differences and enhancements that underscore how GPM provides a planning-centric, real-time/synchronous, collaborative, and intuitive planning environment. Unlike CPM applications anchored in database-driven scheduling engines that are controlled by a keyboard and mouse, NetPoint, as an interactive and object-based system, allows hand-directed planning and scheduling using touch or a stylus.

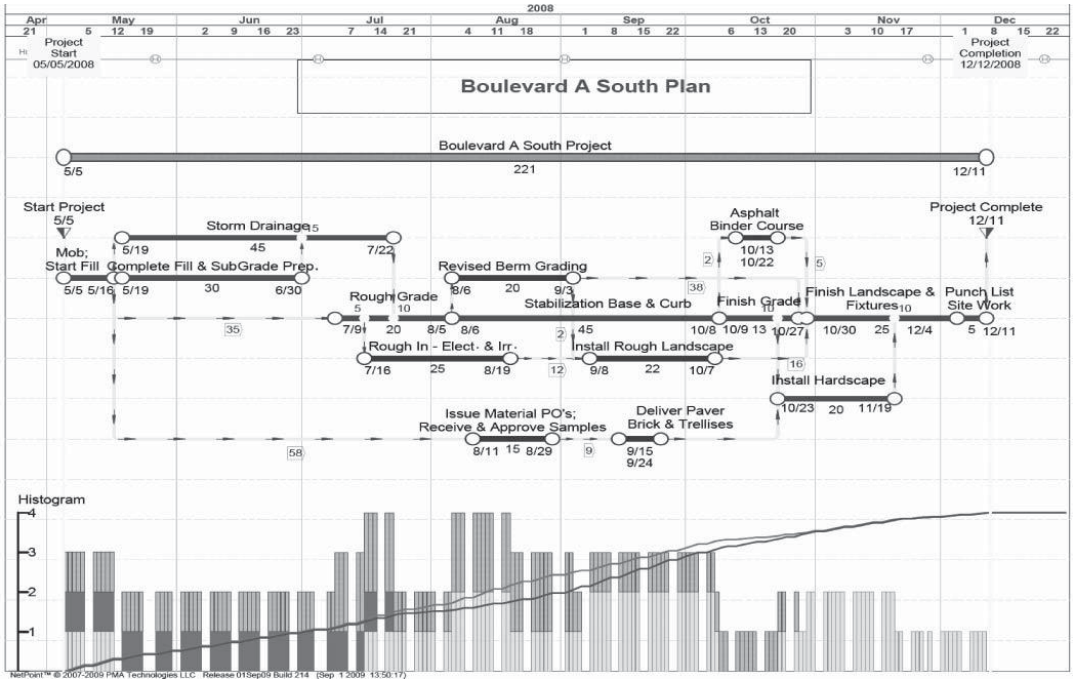



**Figure 11.22 NetPoint schedule with resources**

The following additional definitions may be useful in understanding GPM.

- Benchmark: *reference* network object denoting a fixed start or completion event (occurs in an instant) that has zero total float and that is used to model an overarching milestone or contractual deadline
- Embedded node: event intermediate of, or right on, the start or finish node of an activity, for which the activity is connected to a predecessor or from a successor activity, milestone, or benchmark
- Link or logic tie: network object drawn as a directed edge connecting the two activities, and activity and an event (milestone or benchmark), or two events
- Logic diagramming method (LDM): timed-scaled network notation that uses bars from start-to-finish nodes to represent activities and that links activities through their start or finish nodes or through embedded nodes. LDM networks model the four types of PDM logic commonly allowed in CPM networks when using precedence diagraming method notation
- Network: flow graph of the schedule comprising rule encoded, algorithmic activities, embedded nodes, milestones, and benchmarks, which are linked by designated predecessor-successor links
- Planned dates: physically manipulated dates, between early and late dates, that do not replace early dates and generate drift, thereby preserving total float
- Synchronous: interface that in real time, in response to, and during manipulation by the user of network objects along the timeline, recalculates and refreshes the display of the schedule in its instant state.

### Relationship Diagramming Method (RDM)[9]

In 2004, the relationship diagramming method (RDM) was introduced by Dr. Fredric Plotnick to address issues resulting from ambiguities of logic in software implementations of the precedence diagramming method (PDM). *Engineering News-Record (ENR)* magazine highlighted a number of these issues in a 2003 cover story that cited Dr. Plotnick, a scheduling and legal expert.

RDM started from a premise that ADM (arrow diagramming method) and PDM improved upon the Gantt chart by recording (and use for further calculation) some of the data that the project manager and team considered in preparation of a plan and schedule. However, the quantity of data that could be stored in early computers was limited, and, thus, many assumptions relating to the logic were not recorded. The general solution to the problem was therefore to obtain, record, and then use information relating to these assumptions.

The RDM format begins by allowing the recording of this additional information and then augments the calculations and resultant data output. While the primary

[9] This section was mainly written by the idea's developer, Dr. Fredric Plotnick.

focus of additional recorded data relates to the restraints between activities, including noting the reason why such are provided in both a code format and a freeform description, there are five areas of additional information that may be recorded and used for further calculation in the full implementation of RDM. These five classes of information include:

1. *Events*: RDM restores the concept of a discrete event at the start and finish of an activity, similar to that of the original ADM format, but it adds the concept of events *within* an activity whenever the logic restraint between activities relates to the completion of some portion of one activity before the start of another activity, or the completion of one activity before the start of the final portion of another activity. Events may also be freestanding from an activity as true milestones and as such do not have a "start" date and a "finish" date but, rather, an "occur" date. A freeform description or "title" may be assigned to an activity, as may be event codes that are analogous to activity codes supported by many software products.
2. *Duration*: RDM records and utilizes several of the assumptions relating to activity durations. These include the calendar and several other assumptions that are either recorded for all durations via a system setting in some software implementations or are ignored by others that provide only one option. While, in most cases, this data will not affect the calculated output for an initial CPM, they may impact the calculated output for an update, especially if the progress of the past period is not as initially planned. The first consideration is to recognize that durations between activities (known as *lag* in the PDM format) are just as important as the durations of activities and that the duration calendar and other duration codes may be recorded for each such duration. Duration codes include the following:

    a. *P/C/K (Progressed/Clocked/ClockCheck):* Durations may indicate work to be performed, which must then be monitored during the course of subsequent updates, or may merely represent a period of time that will continue without further monitoring once work commenced. Curing of concrete is one such example. While actual labor may be required (such as to provide periodic spraying with water), the completion of the activity may be calculated without further monitoring of its progress. The ClockCheck option is designed for a special situation in which monitoring of the progress is not required (or, in many cases, not possible) but completion may and should be noted before the scheduling of successor activities occurs. Approval of a shop drawing is an example; once the drawing is submitted, the software will automatically count down the duration of the approval period but will stop at one day for manual verification that the approval has been sent by the engineer to the contractor.
    b. *C/I/S (Continuous/Interruptible/Stretched):* Where an activity is subject to a restraint to its start and also to its finish (such as by separate SS and FF

restraints), the early finish may be later than the early start plus duration. Many software products assume that a project manager will not deploy resources until they may be used continuously and without interruption and, therefore, that the software will recalculate the early start as being equal to the early finish minus the stipulated duration. When this is done, and is not understood by the user of the software, issues will occur when such an activity is connected to yet another by a SS (start-to-start) restraint, which will be based upon the new, delayed early start. While this mode of calculation may be shut off by a system setting in some software, the choice really should be on an activity-by-activity basis. A third option is to recalculate the duration as being EF − ES and adjusting resource usage by $DUR_{old}/DUR_{new}$.

c. *M/R/P (Modified/Retained/ProgressOverride Logic):* Where an activity has been performed out of sequence, there have (in some software products) been two options for how to calculate the schedule of started-but-not-finished and subsequent activities. The first option is named *retained logic*. Here, the original logic is used to schedule the remaining work on the started activity. Therefore, continued work on the started activity may not occur until after all predecessors of this activity have been completed. The second, named *progress override*, is to assume that if an activity has started out of sequence, it will most likely continue through the completion and that subsequent activities may also then continue without regard to the uncompleted predecessors of the out-of-sequence activity. Current software offerings either lock into one of these two calculation models or provide a system option for all activities. RDM provides the choice of option for each activity and also provides a third option (which is the default setting). This third option is called *modified logic*, which schedules the continuation of the started-but-not-finished activity on the data date but creates a FF (finish-to-finish) restraint on the finish of the activity from the finish of all predecessors to that activity (similarly to the retained logic option).

d. *Calendar—Shift/Hourly—RDM* recognizes that a shift is a discrete time unit and not merely (any) 8 hours. An activity of original duration of 10 days reported 35% complete will calculate a remaining duration of 7 days and not 6-1/2 days. Similarly, an activity with 5 days duration but on a two-shifts-per-day calendar, will then push a successor activity on a one-shift-per-day calendar to start at the beginning of the third day.

3. *Restraint types*: RDM recognizes several additional restraint types to the standard PDM choices of FS, SS, FF, and SF (finish-to-start, start-to-start, finish-to-finish, and start-to-finish, respectively). These include a PS (progressed-to-start) and FR (finish-to-remainder) restraint, as well as several other specialty restraints beyond the discussion of RDM in this text. RDM recognizes a distinction between a restraint measuring time elapsed from the calculated or reported start of an activity to the start of another

and a restraint from a point (event) within an activity representing some portion completed to the start of another. The first is the traditional SS restraint, but the latter is a new PS restraint. Similarly, RDM recognizes a distinction between a restraint from the finish of one activity to the finish of another, possibly with a specified period of delay, and a restraint from the finish of one activity to permitting the continuation and completion of effort on another. The first is the traditional FF, and the latter is the new FR, or finish-to-remainder restraint.

4. *Restraint reason/Why*: RDM records (or, in some instances, calculates) the reason why a restraint has been placed between two activities. The primary reasons are either P (for physical) or R (for resource.) Since one of the attributes of a good CPM is that each activity (other than the first and last) must have both a physical predecessor to its start and a physical successor to its finish (to avoid issues such as when a crew shows up to erect a roof and the walls have not yet been erected), this information may be used to provide a better software diagnostic to assure adherence to this rule. The "why" of the code is typically "gravity" or "contract requirement" for physical restraints, and a listed resource or activity code (such as subcontractor) for the resource restraints. The codes may be augmented by a freeform description or title assigned *to the restraint*, similar to that provided to activities. A special form of the physical reason why is coded as J (for just-in-time) and is used in calculation of a second backward pass for determining the latest dates of predecessors to support the early start of the immediate successor to the J restraint. Other special forms are used in automated leveling routines and are beyond the scope of discussion of RDM in this text.
5. *Restraint relationship*: RDM calculates and records the various relationships between the two activities (or events) at the start and the finish of a restraint. This calculation may be performed on all activity (or event) codes (including resource codes) and registers when such a change. This, in turn, may be used to create custom reports to highlight when there is a handoff between crafts or subcontractors (calling for greater supervision by the project manager) or when a crew moves from one location to another (calling for a manual or automated check for a *lag* duration to account for moving of forms and equipment). Comparison of the two sets of activity codes may result in equal, not equal, greater than, lesser than, one (or both) code fields blank, or other noted relationships. (An increasing or decreasing crew size would be one example of differential comparison.)

   The implementation of RDM in commercial software is in its infancy. Primavera Pertmaster[10] is currently the only product that implements this concept. More information can be obtained at www.RDCPM.com.

[10] Primavera Pertmaster has been renamed Oracle as Risk Analysis in the recent acquisition to Primavera by Oracle.

## CHAPTER 11 EXERCISES

1. What do the acronyms PERT, GERT, and LSM stand for?
2. What is the main concept of PERT?
3. How does the PERT method work?
4. What are the main differences between CPM and PERT?
5. In a CPM network, the critical path has five activities. Their durations are tabulated next.

| | Duration (Days) | | |
|---|---|---|---|
| Activity | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) |
| A | 2 | 5 | 9 |
| B | 3 | 4 | 8 |
| C | 4 | 6 | 9 |
| D | 5 | 10 | 20 |
| E | 3 | 5 | 9 |

Compute the following:

a. The probability that the project will finish by the end of day 32
b. The probability that the project will finish by the end of day 34
c. The probability that the project will finish before day 30
d. The probability that the project will finish on day 32
e. The probability that the project will finish no later than day35
f. The probability that the project will finish at least 2 days early
g. The probability that the project will finish at least 2 days late
h. The probability that the project will finish on day 32 ±1 day
i. The completion date with at least a 90% confidence level

6. In a CPM network, the critical path has five activities. Their durations are tabulated next.

| | Duration (Days) | | |
|---|---|---|---|
| Activity | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) |
| A | 4 | 6 | 9 |
| D | 6 | 10 | 15 |
| G | 7 | 11 | 15 |
| H | 10 | 20 | 36 |
| M | 8 | 10 | 14 |
| O | 4 | 5 | 8 |

Compute the following:

a. The probability that the project will finish by the end of day 64
b. The probability that the project will finish by the end of day 65

c. The probability that the project will finish before day 60
d. The probability that the project will finish on day 62
e. The probability that the project will finish at least 6 days early
f. The probability that the project will finish no more than 4 days late
g. The completion date with at least a 95% confidence level

7. In a CPM network, the critical path has six activities. Their durations are tabulated next.

| | Duration (Days) | | |
|---|---|---|---|
| Activity | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) |
| B | 2 | 3 | 5 |
| D | 4 | 8 | 13 |
| F | 5 | 6 | 8 |
| K | 3 | 3 | 3 |
| N | 7 | 10 | 15 |
| S | 3 | 5 | 8 |

Compute the following:

a. The probability that the project will finish by the end of day 36
b. The probability that the project will finish by the end of day 39
c. The probability that the project will finish before day 38
d. The probability that the project will finish on day 35
e. The probability that the project will finish at least 3 days early
f. The probability that the project will finish more than 4 days late
g. The completion date with at least a 90% confidence level

8. Draw the network for the following project. Perform the CPM calculations on the basis of the most likely durations. Pick the longest three paths. Calculate the expected duration and the standard deviation for each path. Considering all three paths, what is the duration of the project with at least a 90% confidence level?

| | | Duration (Days) | | |
|---|---|---|---|---|
| Activity | IPA | Optimistic (*To*) | Most Likely (*Tm*) | Pessimistic (*Tp*) |
| A | — | 4 | 6 | 11 |
| B | — | 3 | 4 | 6 |
| C | — | 6 | 9 | 15 |
| D | A, B | 3 | 4 | 11 |
| E | B | 5 | 7 | 10 |
| F | D | 4 | 5 | 8 |
| G | D, E | 7 | 10 | 16 |
| H | C, F, G | 6 | 8 | 10 |
| I | C, G | 3 | 3 | 5 |
| J | H, I | 2 | 2 | 2 |

9. What is the risk of using PERT and focusing on the critical path only?
10. What types of projects are best for the PERT application?
11. Is PERT popular in the construction industry? Why?
12. What is the main difference between PERT and GERT?
13. What types of projects are best for the LSM application?
14. What are the steps for preparing an LSM schedule?
15. Define *time buffer* and *distance buffer*. Use words and graphs to explain your answer.
16. Draw an LSM schedule for a 5-mile stretch of a road project. Consider the following activities:

| Activity | Daily production (LF) |
|---|---|
| A. Excavation | 500 |
| B. Subbase | 300 |
| C. Base | 240 |
| D. Paving | 1,000 |
| E. Striping and Signage | 1,500 |

17. Draw an LSM schedule for a 2-mile road-resurfacing project. Consider the following activities:

| Activity | Daily production (LF) |
|---|---|
| A. Milling | 2,000 |
| B. Structural Course | 1,000 |
| C. Friction Course | 800 |
| D. Striping and Signage | 1,200 |

Chapter **12**

# Dynamic Minimum Lag Relationship[1]



Mirage JW Marriott Hotel, Cairo, Egypt

[1] This is a new concept in CPM scheduling, introduced by the author and presented in both the PMI College of Scheduling Fifth Annual Conference in Chicago, April 2008, and the PMI Global Congress in Colorado, October 2008.

## INTRODUCTION

When the critical path method (CPM) was introduced in the late 1950s as a tool for scheduling projects, activity on arrow (AOA) networks were used for depicting the logic and performing the calculations. There was only one type of logic relationship: finish-to-start (FS). Shortly later, activity on node (AON) networks were introduced but also with FS relationship only; however, they were capable of incorporating lags. In the early 1960s, Stanford Professor John Fondahl introduced precedence diagrams with four types of relationships: finish-to-start (FS), start-to-start (SS), finish-to-finish (FF), and start-to-finish (SF). Precedence diagrams revolutionized project scheduling because they accommodated overlapping activities for the first time in CPM networks without the need to split them.

**Dynamic minimum lag (DML)** is a new type of relationship in CPM networks. Unlike the traditional relationships, the DML relationship is dynamic, not stationary at the start or finish points of the predecessor or successor activities. It moves along the work progress in the successor activity parallel to the work progress, not allowing the successor to get ahead of (or undesirably close to) the predecessor (see Figure 12.1). It maintains a minimum lag between the successor and the predecessor during the entire course of work progress.

### Why DML?

Traditionally in precedence networks, overlapping activities are connected with an SS, an FF, or—in most cases—a combination SS + FF relationship. If productivity is assumed to be linear in both the predecessor and the successor, and if actual work progress conforms to the estimated productivities and durations, then the DML relationship will act the same as the SS and/or FF relationship.

However, we all know that things rarely, if ever, go as planned. There are many situations in which the successor can theoretically get ahead of the predecessor or be within less than the specified lag:

> **Definition:** The dynamic minimum lag (DML) is a new type of logic relationship in critical path method (CPM) scheduling. The DML relationship is dynamic, moving along with the predecessor and successor activities in parallel with work progress, to ensure that the minimum lag is maintained at all times, not just at the start or finish of the predecessor or successor activity.
>
> **Assumption:** The DML assumes that the predecessor activity can take any type of linear or nonlinear distribution. The successor activity, however, is assumed to be linear.




**Figure 12.1 The dynamic minimum lag (DML) relationship**

## SIMILARITY BETWEEN THE DML CONCEPT AND THE LINEAR SCHEDULING METHOD (LSM)

The DML relationship is similar to the LSM method[2] in maintaining a distance or time buffer (see Figure 12.2a), but they are not the same. There are two main differences:

1. LSM is a different scheduling method from CPM and cannot be implemented in network scheduling or use CPM calculations. DML is just a logic relationship that is fully compatible with CPM calculations and network scheduling.

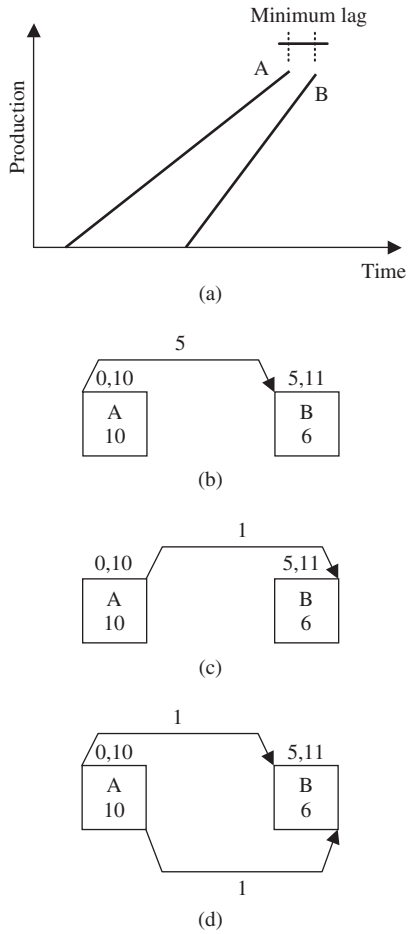



**Figure 12.2 Two overlapping activities represented in LSM graph and three different PDM networks (SS, FF, and SS + FF), all leading to the same dates. Activities are assumed to be contiguous.**

[2] Refer to the linear scheduling method (LSM) discussed in Chapter 11.

2. DML works with linear and nonlinear productivities for the predecessor (the successor is assumed linear), while the LSM (as the name implies) works strictly with linear activities.

## HOW DOES DML WORK?

We start with the percent complete (PC) of both the predecessor and successor activities:

$$PC_A > PC_B$$

The successor is still assumed to be linear, while the predecessor can follow any productivity distribution (the example in Figures 12.3b and 12.3c can be implemented by a DML relationship, but the example in Figure 12.3a cannot). If we assign a minimum lag, $L$, then:

$$PC_A \geq PC_B + L(\text{days}) \tag{12.1}$$

However, equation above is not homogeneous; percent complete is unitless, whereas the lag has a time unit (day). In order to correct the equation, we need to analyze the percent complete to its basic components:

$$PC = \frac{AD}{ACD} = \frac{AD}{(AD + RD)} \tag{12.2}$$

where:

$AD$ = Actual duration
$ACD$ = At completion duration
$RD$ = Remaining duration

Substituting equation 12.2 for Activity B in equation 12.1, we get

$$PC_A \geq \frac{AD_B + L}{AD_B + RD_B} \tag{12.3}$$

All of the four variables in equation 12.3 are usually assigned by the user; however, the lag ($L$) is set when the schedule is being created. The predecessor's percent complete, $PC_A$, is assumed to be given (reported/estimated by the field team). This leaves us with the successor's durations, $AD_B$ and $RD_B$: if one is given by the user (known), the other one is calculated by the equation:

$$PC_A \cdot (AD_B + RD_B) \geq AD_B + L$$

$$RD_B \geq \frac{AD_B(1 - PC_A) + L}{PC_A} \tag{12.4}$$

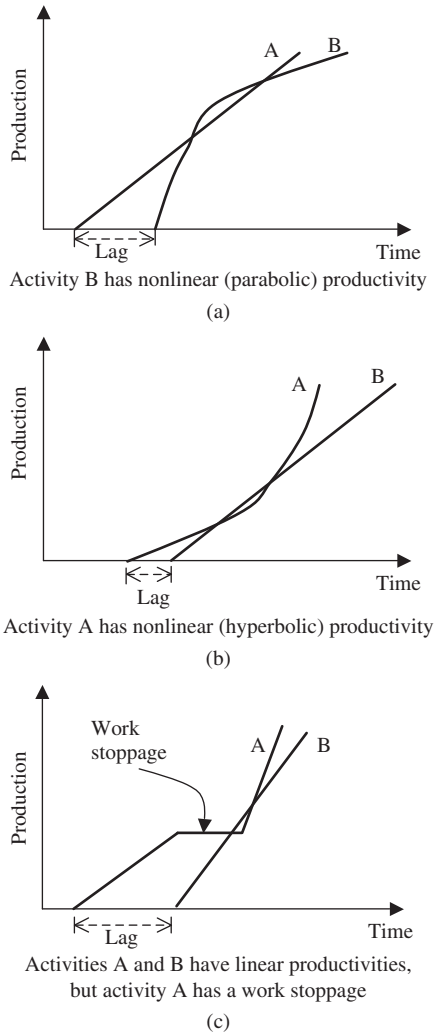



**Figure 12.3 Examples in which the successor (activity B) has gotten ahead of the predecessor (activity A) at some point, although there was no violation of the traditional SS and FF relationships**

Since this is an "inequality," $RD_B$ has to be equal to or greater than the right-hand side. So, in a software program situation, the program calculates the minimum value for $RD_B$ but the user can override it with a larger, not a smaller, number.

It is also possible—although not recommended—to allow the user to give the $RD_B$. In this case, equation 12.3 will solve for $AD_B$, that is, will limit its value:

$$AD_B \leq \frac{PC_A \cdot RDB - L}{1 - PC_A} \tag{12.5}$$

Similarly, the software program calculates the maximum value for $RD_B$, but the user can override it with a smaller number.

When using the DML relationship, the software program should use equation 12.4 as the default; that is, $AD_B$ is given and $RD_B$ is calculated. The software program may give the user the option to reverse the rule.

## DML RELATIONSHIP IN CPM CALCULATIONS

When you are creating a schedule for a project, obviously all activities are 0% complete before the start of the project. The DML equation 12.4 cannot be applied, since it will involve division by zero. For this reason, the calculations (manually or by the software program) will implicitly include both SS and FF relationships. The SS relationship applies until the predecessor starts, so the denominator in equation 12.4 becomes greater than zero and the DML relationship is now active. Practically speaking, the DML equation does not differentiate itself from the SS relationship until the successor starts. The FF relationship may be needed only to compare results with $RD_B$, calculated by the DML equation, where the greater value governs, as will be demonstrated in examples 12.1 and 12.2.

However, when the user assigns a DML relationship, there should be no need to add SS and FF relationships, as these two relationships should be automatically built into the DML relationship, that is, in the mathematical background. More clearly: the difference between the DML relationship and the current SS + FF combination relationship is that the latter guards against the successor activity violating the lag with the predecessor activity when it starts and when it ends. The DML relationship does that but, in addition, guards against the violation of the lag during the entire duration of the successor activity.

A DML relationship also works (with the same equations above) with interruptible (noncontiguous) activities. However, the user has to be careful in **defining actual duration (AD)** and **at completion duration (ACD)**, so they will not include unproductive time (see note 4 of "Dicussion on example 12.1").

**Rounding Numbers**: Since most schedulers use the "day" as the unit of time, software programs need to round up $RD_B$ to the nearest larger day (or unit of time) in equation 12.4 and truncate $AD_B$ to the nearest smaller day (or unit of time) in equation 12.5.

**Note of Caution**: Percent complete may be interpreted differently by different people in different situations.[3] Software programs have numerous types of activity percent complete. For DML calculations, percent complete is strictly defined in equation 12.2.

[3] Review the discussion on percent complete in Chapter 7.

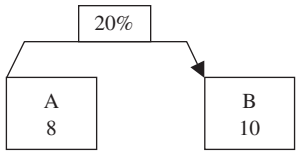



**Figure 12.4 SS Relationship with a percent lag**

### Can the Lag in the DML Relationship Be a Percentage?

The answer to this question depends on how we define *percentage*: If the SS + 20% relationship shown in Figure 12.4 means a constant lag of 20% of the original duration of activity A, that is, $20\% * 8 \approx 2$ days, then it becomes just like a fixed time duration (unless the original duration of activity A changes during updates, to be replaced by the at- completion duration). In this case, the implementation in the DML relationship is possible using the same methodology and equations explained earlier.

However, if the lag in Figure 12.4 means 20% of the remaining duration of activity A, then this lag gets smaller and smaller as the work progresses until it becomes zero toward the end, that is, simultaneous finish. This understanding of the percent-lag negates the premise of DML (of maintaining a minimum lag) and is not compatible with the DML equations.

### Example 12.1

Assume the following two activities:

| Activity Title | Original Duration (days) |
|---|---|
| Roof Sheathing | 20 |
| Install Shingles | 16 |

We need to maintain at least a 1-day lag between the two activities at all times, as shown in Figure 12.5. Activities are contiguous. Assume activity B (Install Shingles) to be linear.

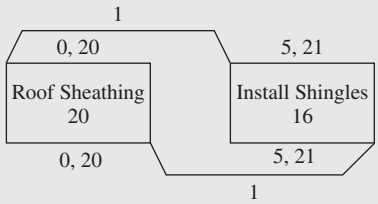



**Figure 12.5 Activity A (Roof Sheathing) as the predecessor an activity B (Install Shingles) as the successor**

**Project Update and Solution**

1. Using traditional CPM relationships, we calculate the regular early and late dates for both activities at day 0, that is, before any work occurs.
2. By day 10 (end of day 10), assume only 40% of activity A (Roof Sheathing) is completed.

   *Activity A*: Started on time: end of day 0, that is, beginning of day 1

   Actual duration = 10 days

   Remaining duration = 10 days (productivity will pick up in the last 10 days)

   At completion duration = 20 days

   *Activity B*: Started end of day 3, that is, 2 days earlier than scheduled

   Actual duration = 7 days

   Remaining duration = 11 days(assuming the end of activity A + 1 day)

   Using the DML equation:

$$RD_B \geq \frac{AD_B(1 - PC_A) + L}{PC_A}$$

$$RD_B \geq [7(1 - 0.40) + 1]/0.40 = 13 \text{ days}$$

   Finish date for Activity B ≥ day 23, *not* day 21 as calculated by the FF relationship.
3. Day 15: Assume only 70% of activity A (Roof Sheathing) is completed:

   Activity A:

   Actual duration = 15 days

   Remaining duration = 5 days

   At completion duration = 20 days

   Activity B:

   Actual duration = 12 days

   Remaining duration = 6 days (Assuming the end of activity A + 1 day)

Using the DML equation:

$$RD_B \geq \frac{AD_B(1 - PC_A) + L}{PC_A}$$

$$RD_B \geq [12(1 - 0.70) + 1]/0.70 = 6.6, \text{ say 7 days}$$

Finish date for Activity B = day 22, not day 21 as calculated by the FF relationship.

4. Assume there was work stoppage between day 10 and day 15: activity A is still 40% complete:

   Activity A:

   Actual duration = 15 days( including stoppage)

   Remaining duration = 12 days (estimated)

   At completion duration = 27 days

   Activity B:

   Actual duration = 12 days

   Remaining duration = 13 days(Assuming the end of activity A + 1 day)

   Using the DML equation:

$$RD_B \geq \frac{AD_B(1 - PC_A) + L}{PC_A}$$

$$RD_B = [12(1 - 0.40) + 1]/0.40 = 20.5, \text{ say 21 days}$$

   Finish date for Activity B = day 36.

**Discussion on Example 12.1**

1. The DML equation is independent of the estimate of activity A's remaining duration. Rather, it is dependent on its percent complete. For example, in part 4 above, the scheduler may not have updated the remaining duration of activity A, so it shows only 5 days. The DML equation still gives the same answer for $RD_B$, that is, 21 days. This is particularly important when production in an activity differs from reality and the scheduler fails to adjust/update the remaining duration.
2. The DML equation is dependent, however, on the actual duration of activity B. For example, if activity B in the previous example had started

at end of day 5, not day 3, its remaining duration, according to the DML equation, would be different:

In part 2, after 10 days:

$$RD_B \geq [5(1 - 0.40) + 1]/0.40 = 10 \text{ (versus 13 days)}$$

In part 3, after 15 days:

$$RD_B \geq [10(1 - 0.70) + 1]/0.70 = 5.7 \text{ (versus 6.6 days)}$$

The explanation for this observation is in the assumption of linearity of activity B: if it took a number of days to reach the current situation (AD), it will take a proportional number of days to complete the activity (RD). With a smaller AD and constant percent complete, we are assuming a higher productivity. Thus, the remaining duration will be less.

3. Remember the assumption of linearity for the successor. If, however, this assumption does not hold, as in the case where the production rate is known to increase later, the scheduler may not use the DML relationship. Figure 12.6 shows two cases of nonlinearity of the successor, where the DML relationship does not work.

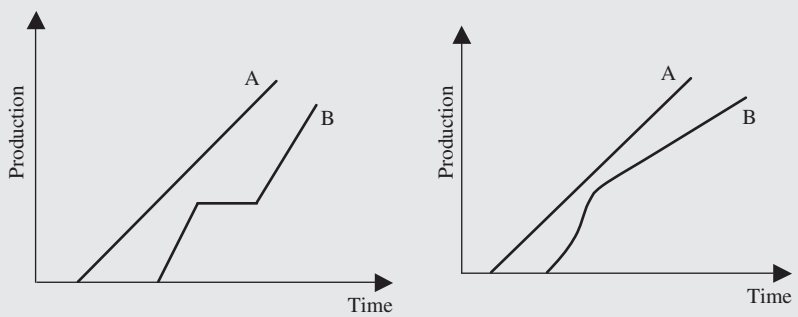



**Figure 12.6 Situations in which the DML relationship does not work because the successor's production is nonlinear or linear with changing production rates**

4. he result of part 4 in Example 12.1 seems too high. It is, because the value used for $AD_B$ includes unproductive time (days 11 through day 15). This is generally a problem that software programs need to address in calculating production rates (quantity/duration) and true

percent complete. For example, the production rate for activity A until the end of day 15 should be:

Performed work(Quantity)/Productive duration (i.e., 10 not 15 days)

Another point to be taken into consideration: did the work stop on activity B during all or part of the stoppage of activity A? If yes, then what is the true actual duration for activity B? If we assume that activity B stopped when activity A did, then

$AD_B$ = 7 days and $RD_B$ is calculated the same as in part 2 earlier,

that is, 13 days.

This is an important point, in general, for calculating actual duration, *AD*, and at-completion duration, *ACD*. These two variables are part of the calculation of production rates and percent complete, two very important parameters in project management, not only in scheduling but also for estimating and finance.

**Example 12.2**

In the previous example, let's take a different and opposite case: the production in the predecessor activity (Roof Sheathing) was faster than estimated.

**Project Update and Solution**

Using traditional CPM relationships:

1. Day 10 (end of day 10): Assume 70% of activity A (Roof Sheathing) is completed:

   Activity A: Started on time: end of day 0, that is, beginning of day 1

   Actual duration = 10 days

   Remaining duration = 10 days (no update was done)

   At completion duration = 20 days

   Activity B (Install Shingles): Started end of day 3, that is, 2 days earlier than scheduled.

Actual duration = 7 days

Remaining duration = 11 days(assuming the end of activity A + 1 day)

Using the DML equation:

$$RD_B \geq \frac{AD_B(1 - PC_A) + L}{PC_A}$$

$$RD_B = [7(1 - 0.70)+]/0.70 = 4.43, \text{ say 5 days}$$

This result sounds like a violation of the FF relationship with activity A, which puts the remaining duration of activity B at 11 days. In reality, the remaining duration of activity A will be, most likely, a lot less than 10 days. Assuming linear production: If activity A reached 70% completion in 10 days, it could reach 100% in $10 * (100\%/70\%) = 14.29$ days, that is, the remaining duration = 4.29 days, which is slightly less than the 4.43 days calculated by the DML equation as the minimum for $RD_B$. Practically speaking, $RD_A$ and $RD_B$ can be 4 and 5 or 5 and 6 days, respectively.

2. Repeat step 1, assuming that activity B started as scheduled, that is, at the end of day 5.

Activity B (Shingles):

Actual duration = 5 days

Remaining duration = 11 days(Assuming the end of activity A + 1 day)

Using the DML equation:

$$RD_B \geq [5(1 - 0.70) + 1]/0.70 = 3.6, \text{ say 4 days}$$

The same argument as previously given applies: $RD_A$ and $RD_B$ will most likely be 4 and 5 days, respectively.

## CONCLUSION

The DML relationship is a new and potentially useful concept in project scheduling. It should be used mainly for a situation involving overlapping activities when the predecessor has to stay ahead of the successor by a certain margin from start to finish.

For example, in building construction, this relationship can be used for the series of four activities: framing, drywall, pasting and taping, and wall painting. In infrastructure construction, it can be used for trench excavating, subbase, laying pipe, backfilling, and compaction operations. The DML relationship can have numerous applications in all types of projects.

The DML relationship eliminates the need for the SS + FF combination relationship and most of the situations in which a single SS or FF relationship is used.[4] However, there will be a few situations in which a single SS or FF relationship can still be used (e.g., in the case of a developer who is planning to build an apartment complex on a large piece of land). In this case, the developer needs to "Clear and Grub" a certain portion of the land where the building will be erected. There is no connection between the finish "Clear and Grub" and "Excavate," as shown in Figure 12.7. The scheduler, in this case, has to make sure that the minimum required percentage of "Clear and Grub" is completed before the excavation can start. A safer way to depict that logic is demonstrated in Figure 12.8.

An example of FF relationship dependency that does not require a DML relationship is the situation in Figure 12.9. The Landscape activity's start is independent of the Parking Lot activity, but you need to finish the Parking Lot activity before you can finish the Landscape activity.

The DML relationship is a new concept. It may, and most likely will, need more research and fine-tuning before it is applied commercially.

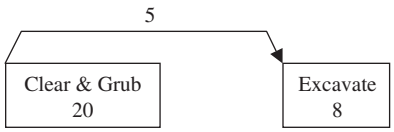



**Figure 12.7 A situation in which the DML relationship cannot be used in lieu of the SS relationship**

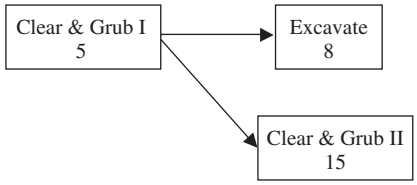



**Figure 12.8 A better alternative to depict the logic of the network in Figure 12.7**

[4] As explained earlier, the SS and FF relationships' calculations will be included with the DML calculations but will not appear to the user because they will be in the background. In other words, the user will only assign a DML relationship, not a combination relationship.

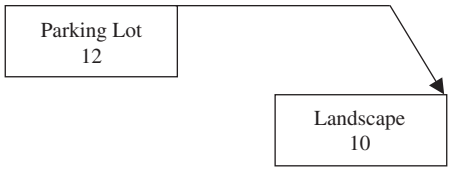



**Figure 12.9 A situation in which the DML relationship cannot be used in lieu of the FF relationship**

## CHAPTER 12 EXERCISES

1. What is the main idea of DML? What makes it different from the logic relationships of the precedence diagramming method (PDM)?
2. Give two examples of construction work (combination of 2 to 4 activities, each) for which DML would be suitable.
3. What are the limitations of DML?
4. For the following two activities:

| Activity Title | Original Duration (days) |
|---|---|
| A. Trench Excavation | 18 |
| B. Laying Pipe | 13 |

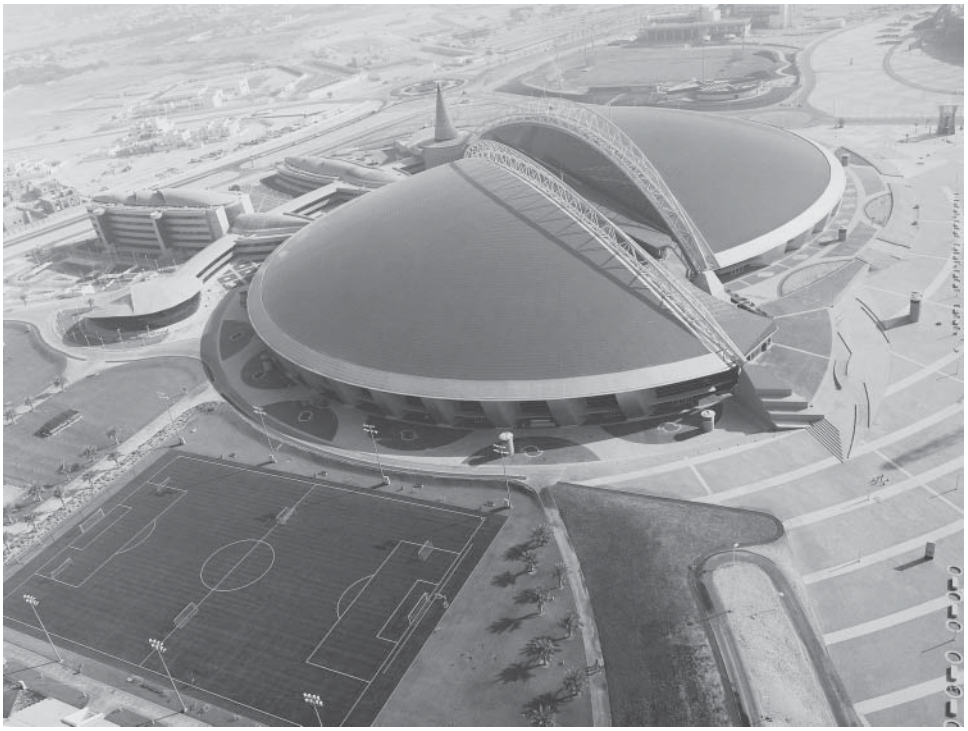
   we need to maintain at least a 1-day lag between the two activities at all times. The activities are contiguous. Assume activity B (Laying Pipe) to be linear. What is the minimum $RD_B$ according to the DML equation in these stages? What is the $RD_B$ that you should consider, taking into consideration both the DML and the FF relationships?

   a. After 5 days, activity A is 25% complete. Activity B started two days early, that is, $AD_B = 1$ day
   b. After 8 days, activity A is only 30% complete. Activity B's $AD_B = 4$ days. Assume that activity A will finish on time.
   c. After 10 days, activity A is still 40% complete. Activity B's $AD_B = 6$ days. Assume that activity A will finish on time.
   d. After 13 days, activity A is 70% complete. Activity B's $AD_B = 9$ days. Assume that activity A will finish on time.

5. What is the challenge in taking the lag in the DML relationship as a percentage of the predecessor's duration?
6. Give an example of an SS relationship that should not be replaced by a DML relationship.
7. Give an example of an FF relationship that should not be replaced by a DML relationship.

Chapter **13**

# Construction Delays and Other Claims[1]



Khalifa Sports Hall, Qatar

[1] This chapter was written with contributions from Attorney Barry B. Bramble, who can be contacted at barrybramble@comcast.net.

## PREFACE

Construction delays and their resolution is a complicated subject. Many attorneys retain consulting enginers, schedulers, and other experts to assist them in understanding the technical issues that arise in construction-related cases as well as to provide expert witness testimony. Some attorneys go back to school to obtain college degrees in engineering and construction in order to acquire technical knowledge in addition to their legal knowledge.[2] Many books, seminars, and organizations have been dedicated to this subject. This chapter merely touches on the subject and provides some "common-sense" concepts and general outlines. This author strongly commends that readers refer to books and specialized sources for a more in-depth study.

## INTRODUCTION

In its simplest definition,[3] a **delay** is the action or condition that results in finishing a project later than stipulated in the contract. A delay can also pertain to starting or finishing a specific activity later than planned. On the other hand, a **claim** is a request from one contract party (usually the contractor) to another party for additional compensation, an extension of time, or both. If we put the two terms together, a *delay claim* simply means a claim related to a delay.

As is well known, construction projects involve many risks because things rarely, if ever, go as planned. As a result, claims have become almost inevitable in construction projects.

Claims can be initiated by any project participant against any other project participant. An architect may initiate a claim against an owner or vice versa. A supplier may initiate a claim against the contractor or the owner, and so on. Since the contractor is the party that is usually responsible for performing the physical work on the project and since the contractor does not traditionally have a contractual relationship with the designer (A/E), most claims are initiated by the contractor against the owner.

It is important, though, to note that a claim is not necessarily a negative thing; nor does it automatically indicate a confrontation. Many claims are legitimate and are routinely resolved to the satisfaction of both parties.

## DELAY CLAIMS

A delay claim can be for an extension of time in the contract, monetary compensation, or both. Delays are also classified into excusable, compensable, and nonexcusable (explained later).

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[2] Conversely, some engineers and architects go back to school to obtain a degree in law and utilize their technical background.

[3] In the construction management context.

A claim for only monetary compensation often forms the basis for a change order (CO). A change order may be initiated upon the request of the owner, contractor, subcontractor, and so on. For example, an owner may wish to change the color of the brick, the type of floor tile, or the light fixtures. Such a change order may be initiated by the owner submitting a change order request for a work directive. This could be an owner's decision or a "what-if" inquiry. In the latter case, the owner sends a request for a change order price or quotation,[4] along with relevant architectural/engineering details (drawings/specifications), if necessary, to the contractor. The contractor evaluates the new changes, including their impact on the work plan, and issues a quote to the owner. The contractor's change order proposal or quote typically includes a cost estimate but also may include any impact on the schedule. In response, the owner accepts, rejects, or negotiates the quotation with the contractor. Once the owner and contractor agree on the terms of change, the owner issues a change order. The change order signals the owner's acceptance of the cost and other terms already agreed upon with the contractor, and authorizes the contractor to execute the work. A change order can be for an addition, deletion, or substitution items in the original contract. An example of a deletion change order is an owner deleting a swimming pool from the contract to build a house. In such cases, the contractor is obligated to issue a credit to the owner. This credit can be, and usually is, less than the amount originally estimated in the contract for that item.

For this reason and in order to minimize the number of change orders, it is strongly recommended that owners do a thorough job of defining the scope of the project and selecting a competent designer or architect/engineer (A/E). Many projects suffer from the "cost-creep" syndrome[5] when change orders keep adding to the project budget and put it at a level that is far beyond what the owner originally planned. From the contractor's perspective, change orders may be a source of headache, but they can be a source of extra income as well. Many experts contend that if all change orders were taken into consideration prior to designing the project, the total cost to the owner would be a lot less. Some owners, when they are not sure about certain major items, bid projects with alternates. For our example, the base bid can be the house without a swimming pool with an alternate to add a pool. In this case, the bidder must provide a base bid price and an additional amount for the pool in case the owner decides to add it. If the owner is leaning more toward including the pool, the owner may include the pool in the base bid with an alternate to omit it.

Timing of the changes makes a big difference, too. The later the change is made, the more expensive (and perhaps more time-consuming) it gets. Let us take a simple example. An owner decides to change a few doors from 2 feet 8 inches wide to 3 feet

[4] Some contractors called this a "request for price"; however, it should not be abbreviated as RFP, which is an industry acronym for "request for proposal."

[5] Directly related to "scope creep."

0 inches wide. Let us consider the following five different scenarios, along with the cost associated with each:

*Scenario 1*: The owner makes the change before the design is completed. The cost is minimal (the difference in the door prices).

*Scenario 2*: The owner makes the change after the design is completed but before the bidding begins. There may be a minor additional cost associated with the architect redoing some of the drawings and specifications.

*Scenario 3*: The owner makes the change after signing the construction contract but before the doors are delivered and the work on that portion has started. The cost may still be minimal, but this has become a change order. The contractor may try to make some "extra profit."

*Scenario 4*: The owner makes the change after the door openings have been framed (in masonry walls) but before the walls are finished. The change includes the cost of widening the door openings, that is, demolition of part of the masonry walls, and installing new door frames. If the doors have been delivered, there is an extra charge for delivery and restocking.

*Scenario 5*: The owner makes the change after everything has been finished. This is a more significant change order that includes widening the door openings, that is, demolition of part of the masonry walls that are covered by drywall and painted, and installing new door frames. There will also be a cost to redo the masonry walls, drywall, paint, and for cleanup. The doors—after painting—may not be returnable to the vendor, so their cost will be a waste, which needs to be added to the total loss.

Scenarios 4 and 5 have the potential to impact the project schedule.

In certain cases, the change order process may be shortened if there exists a certain level of trust between the owner and the contractor, when the owner is constrained due to lack of time or when the change order has a minimal economic impact. In such cases, the owner may issue a "directive" to the contractor before authorizing the cost. The contractor performs the work and then charges the owner later.

## REASONS FOR CLAIMS

Claims usually occur because of "unexpected" events or developments, regardless of who is at fault. Unlike other industries, no two construction projects are the same. Even when two projects have the same design and are performed by the same company, they may differ in site conditions, climate, regulations, subcontractors, market conditions, and team members. Consequently, it is difficult to anticipate every event that will impact a construction project, even when the projects are substantially similar.

There are several reasons a claim may arise on any construction project. Among the reasons are the following:

1. *Differing site conditions*: A contractor may initiate a claim in the event that the actual site conditions differ from those mentioned in the contract documents. A contractor may encounter underground water that wasn't mentioned in the contract documents. Types of soil may also be found to be different from what was mentioned in the geological (soil) report. The contractor may encounter soil contamination or unexploded bombs that wasn't known or mentioned in the contract. One of the possible reasons for differing site conditions is that the architect/engineer may use old site plans that may not reflect recent activities. The contractor may find a temporary structure that needs to be demolished or a utility pole that needs to be relocated, and it may not have been shown in the design drawings. It is always a good idea for the owner to provide accurate information about the site and for the contractor to visit the site before mobilization and even before bidding.

   The risks of dealing with unknown site conditions are usually addressed in the contract documents in provisions known as the "site inspection" and "differing site conditions" clauses. These clauses typically impose upon the contractor the duty of site investigation and the assumption of responsibility for bearing the cost of conditions that a bidder who is performing a reasonable prebid investigation may encounter. However, the differing site conditions clause allows the contractor to recover the cost for unknown site conditions that differ from the contract documents or are unusual. The owner often bears the cost of dealing with matters that fall within the terms of the differing site conditions clause.
2. *Design errors or omissions*: Errors or omissions in design may, and usually do, require the contractor to perform additional work than originally contemplated. Not all design errors or omissions form the basis of a compensable claim. Courts have rejected some contractor claims when an error or an omission is patently obvious and a contractor could have discovered it during the bidding or negotiation phase. For example, if the floor joist spacing is shown as 16' rather than 16''[6] on center, it should be obvious that it is a typographical error. Also, if the structural drawings do not show any reinforcement on a concrete column or beam section, the contractor should know that such a member has to have reinforcement. The contractor, in general, must inquire about obvious design errors prior to submitting the bid. Failing to do so means the contractor must proceed at his or her own risk.[7]

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[6] In Imperial units, the ' symbol represents feet and the '' symbol represents inches.

[7] *Blinderman Construction Co. v. United States,* 17 Cl. Ct. 860 (1989).

3. *Changes in the owner's requirements*: This may constitute a change to the contract and a need for a change order. As discussed earlier, owners are always encouraged to specify exactly what they want within the limit of their budget.[8]
4. *Unusually adverse weather conditions*: Most contracts allow for certain expected weather delays without allowing time extensions for them in the contract.[9] A contractor who is rained out for 5 or 6 days during the month of July in Tampa, Florida, probably will not get a break from the owner because such a delay is not unexpected or unusual. A weather condition that is not usual for that geographic area during that time of year may provide grounds for the contractor to make a time extension claim. A hurricane or a tornado may be regarded as *force majeure*[10] and provide grounds for a time extension even if that area is known to have hurricanes or tornados.
5. *Other factors*: There may be other factors that may not be the claimant's fault, such as the owner's failure to provide a project site, late notice to proceed (NTP), labor strikes,[11] delay in delivery of owner's furnished equipment, or events that can be classified as *force majeure*, or problems deemed to be the responsibility of the owner.

   Note that the preceding factors may entitle the contractor to monetary compensation, a time extension, both, or neither.

## FORCE MAJEURE

The term ***force majeure*** (also written as *force majure*) came into use around 1883 and comes from the French term meaning "superior force." In the context of construction projects, this term generally combines three important elements:

1. Superior, overwhelming, or overpowering, that is, cannot be prevented

[8] On a project in which the author was involved, a city municipality asked an architect if it would be possible to design a parking garage in a certain location with a capacity for 280 cars within a budget of $2.5 million. The architect confirmed the cost based on a "plain" design with a simple finish and no fancy options. The contractor's estimate for that design was indeed just below the $2.5 million mark. During the detailed design phase, the city started adding options, such as a sprinkler system, a security system, retail space, planters, pavers, trees and some landscaping, an extra half-floor that would increase the capacity to about 325 cars, and so on. These additions increased the cost until it topped $4.2 million. The city liked the design but was shocked to see the contractor's price tag. It asked the architect, "We thought we were getting the parking garage for about $2.5 million?" The architect replied, "You can't get a Cadillac for the price of a Chevy!" The city had to go back and remove many of the added options but insisted on keeping some of them. The project was eventually constructed for slightly over the original budget.

[9] See the American Institute of Architects, document A201–1997, paragraph 4.3.7.2.

[10] This term is discussed later in detail.

[11] In some cases when the contractor signs the construction contract at a time when a labor strike is looming, the courts have ruled that the strike is not grounds for granting a time extension.

2. Unexpected or cannot reasonably anticipated or controlled, and
3. Has a destructive or disruptive effect on the construction process.

The term *force majeure* is usually used for events that satisfy the criteria just noted in order to excuse the contractor from certain contractual requirements, such as earthquakes, hurricanes, tornados, wars, labor strikes, and acts of sabotage or terrorism.

Other contractual terms with similar meaning include *vis major*, which has a Latin origin and means "superior force" and in legal usage is refers to an "act of God." In this author's opinion, it is more appropriate to use the term *force majeure* rather than "act of God" in this context, because it indicates an event that could not have been prevented with a reasonable effort. Even though the term "act of God" has been construed to mean the same thing as *force majeure*, it might be interpreted differently according to individuals' religious beliefs or philosophy. In some extreme cases, one may argue that every action happens in this world is an "act of God," whether or not we have control over it or responsibility for it.

## TYPES OF DELAYS

With regard to construction schedules, delay events are classified into the following three types (Bramble and Callahan, 2014, §1.01 [A], [B], and [D]):

1. *Excusable delay*: An excusable delay entitles the contractor to additional time for completing the contract work. Excusable delays usually stem from reasons beyond the contractor's control. These delays are further classified into:
   a. Delays that are beyond the control of, and are not the fault of, the owner, such as those caused by unusual weather conditions, natural disasters (earthquakes, floods, hurricanes, etc.), wars or national crises, or labor strikes. These types of delays most likely entitle the contractor to a time extension but not to monetary compensation (noncompensable delay).[12]
   b. Delays caused by the owner or the designer (architect/engineer). These types of delays typically allow the contractor to recover the costs and time associated with the delays and are known as "compensable delays."
2. *Nonexcusable delay*: By definition, a nonexcusable delay does not entitle the contractor to either a time extension or monetary compensation. Typically, a nonexcusable delay is any delay that is either caused by the contractor or not caused by the contractor but should have been anticipated by the contractor under normal conditions. Examples of the first type include slow mobilization, poor workmanship, labor strikes due to unfair labor practices, or accidents on the project site caused by the contractor's negligence or lack of preparation. Other examples include late delivery of the contractor's furnished materials and

[12] In most cases, the contractor's builder's risk insurance covers such losses.

equipment, the contractor's cash-flow problems, adverse weather conditions that are expected for that location during that time of the year, or a lack of skilled labor.

3. *Concurrent delay*: A combination of two or more independent causes of delay during the same general time period may be considered to be concurrent delays. Often the concurrent delays are excusable and nonexcusable delays. For example, the author was involved in a case in which the contractor was performing at a slow rate and falling behind schedule because the contractor didn't have an adequate workforce on the site. During the middle of the project, the owner issued a major change order. The contractor requested 120 days of time extension due to this change order. In order to prove his point, the contractor presented two schedules: an original (baseline) schedule and an "impact schedule." After an analysis, this author found that the change order justified only 56 days of delay. The rest, that is, 64 days, were a nonexcusable delay. The contractor was trying to hide this nonexcusable delay behind the owner's change order.

It is important to note that just because the additional work may require time to perform, the contractor is not automatically entitled to an extension of time. The contractor may have to demonstrate that the additional work impacts the critical path of the project. The use of CPM schedules and scheduling experts are often necessary to prove or disprove such a claim.

Conversely, the contractor—in a case of a change order—may be entitled to extra monetary compensation in lieu of a time extension even if the contractor finished by the original finish deadline. Typically, this extra payment covers the contractor's effort—above and beyond the original work plan—for accelerating the schedule. Such effort may include overtime payments and/or extra labor and equipment. In such cases, when an owner issues a schedule-impacting change order or causes a delay, the contractor may negotiate with the owner for finishing on time in exchange for extra payment.

## SCHEDULING MISTAKES RELATED TO DELAY CLAIMS

Construction projects take months or years to finish, with many people and events involved. In many cases, people are replaced in the middle of the project for a myriad of reasons. Participants in the project may forget details of what occurred in the project. The importance of diligently maintaining daily reports, journals, and the like cannot be overemphasized. Many a case or claim has been won or lost on the quality of the record keeping performed on a construction project.

One of the most important documents in delay claims is the as-planned baseline schedule.[13] It represents the manner (timing, sequence, and possible resources) in

[13] Defined and discussed in Chapter 6.

which the contractor plans to perform the work and the owner's acceptance of that plan. The 2007 version of the AIA A201 General Conditions document requires the contractor to submit a schedule that complies with the contract completion date. Most contract forms used by public and private owners today also require a schedule prepared by the contractor and accepted or approved by the owner. Such schedule, once adopted as the baseline schedule in the contract, becomes a very important document because it constitutes the yardstick for measuring any variation if it is properly updated and maintained. Because of a lack of knowledge or experience, negligence, or other reasons, many contractors commit errors or submit faulty schedules. Following is a list of some of the frequent scheduling mistakes that some contractors commit.

1. *Baseline schedules that don't show logic*: Some contractors use spreadsheets or simple bar charts as schedules. Spreadsheets are not scheduling programs, and they are used merely like color ribbons to indicate when the contractor intends to start and finish each activity without showing interdependencies. When an activity is delayed or shifted, there is no mechanism to reflect the impact of this delay or shifting on other activities.
2. *Baseline schedule with dates rather than logic*: Some schedules, even if they are built using scheduling programs, use "events" rather than "activities." For example, instead of showing "Excavation" as a 20-day activity, the schedule shows two milestones (events): "Start Excavation" and "Finish Excavation." There are several problems with this approach. Some contractors use constraints to "fix" the date of an event. This negates the introduction of logic in the schedule. This approach also deprives the control manager (on both the contractor's and the owner's side) from evaluating the percent complete of that activity.
3. *Overuse of constraints*: Instead of logic ties, the contractor "schedules" activities by assigning start and finish dates to them, usually by the use of "Constraints." Similar to the previous example, activities "get nailed" with such constraints and cannot react to logic and other changes. Often in construction, activities get delayed, omitted, or adjusted, or they finish early. Such changes can have an impact on succeeding activities but won't show if activities are constrained.[14]
4. "*Erasing footprints*": A contractor may build or update the schedule as the project progresses without keeping a copy of the original or previous updates. This schedule will be an "as-built" schedule. It shows how the project was actually built, not how the contractor intended to build it. This conduct leaves no footprints to track and no baseline to compare the progress to.
5. *Unrealistic baseline schedules*: Some contractors don't realize that a baseline schedule that is approved by the owner may be a legal and binding document.

[14] Some computer programs introduce different types of constraints: some are subject to logic, and some override logic.

Contractors cannot get relief by complaining of unrealistic duration or logic in the schedule later during construction, unless a change in work circumstances warrants such relief.

6. *Schedules with logic errors*: Errors may render a schedule useless and cause it to be thrown out by the court in the case of a dispute.[15] A schedule must be prepared by a construction professional. Contractors who don't have scheduling capability usually hire CPM consultants. It is important to note that the reliability and correctness of the schedule may have nothing to do with the contractor's field practice. The contractor may deviate from the schedule or planned sequence (network logic), but the schedule is still evaluated based on its own merit.

   Another problem can arise with creating many hubs[16] in a schedule. A hub has a greater likelihood of causing a delay than other normal activities.

7. *Skipping periodic updates*: A contractor may be tempted not to update the schedule on a regular basis because "things are going just fine." In many cases, we find only a baseline schedule and an updated schedule that reflect work progress 6 months after the start of construction. This leaves a large gap in between the two schedules and makes it difficult to trace back events during that period of time. Courts may not accept schedules to prove delays unless they are regularly updated.[17]

8. *Lack of proper documentation*: This can have serious repercussions. When updating a schedule, the scheduler should record any unusual events. For example, an excavation activity finished 1 week after its scheduled finish date. The scheduler should record the reason for this delay. Most scheduling programs provide "notes" or "log" functions at both the activity and the project levels.

9. *Lack of reasonable time contingency*: Contractors must have a reasonable amount of time contingency built into the schedule for delays such as expected weather conditions. One of the commonly overlooked scenarios is the possibility of rejection of submittals. A contractor may allocate 10 days for the review and approval of shop drawings on a tight schedule. If the drawings are rejected, the drawings have to be corrected and resubmitted for approval. This will likely cause the process to take more than 10 days and may cause a delay in the schedule. In most cases like this, the contractor has to absorb this delay with no relief from the owner.

10. *No allocation of the "pacing" or limited resources*: There has never been a project that has had unlimited resources. Hence, a schedule based on CPM's

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[15] *Fortec Constructors v. United States,* 8 Cl. Ct. 490 (1985).

[16] A hub is an activity or milestone that is a successor and/or predecessor to many activities. The concept of hubs was discussed in Chapter 4.

[17] *Wilner v. United States*, 26 Cl. Ct. 260 (1992).

early dates that assumes unlimited resources is not a realistic or rational schedule. Resource "loading" is only estimating the resource requirements, not scheduling them to smooth the demand in accordance with availability.

## PROJECT DOCUMENTATION

Characteristics for good communication were discussed in Chapter 9. This includes both oral and written communication. Written communication includes both text and graphic reports. The importance of good communication cannot be overemphasized. Most construction companies list "good communication skills" as one of their top criteria for hiring any project management personnel. Communication generally means conveying information from one party to another party within the same organization or across different organizations. Documentation, on the other hand, generally means saving the information in an organized manner for possible retrieval in the future. What should be in common between communication and documentation is the need for information to be clear, providing the right amount of details, and efficiently stored so that it can be easily retrieved.

Project documentation includes both home office and field office documentation. Since many types of information may be documented in the home office or on-site, we will list all the information to be documented wherever its location. With the advancement of communication technology, the home office and field office information are more and more integrated to make one comprehensive project database. There are several software packages that construction companies use for this purpose.[18] They are getting better, more powerful, and more capable of integrating with other systems, such as drafting, scheduling, estimating, accounting, Web publishing, and e-mail communications.

For the purpose of prevention and resolution of delay claims, the following information should be documented:

1. The project baseline schedule that was approved by the owner. Both an electronic copy and a printed report (bar chart, predecessors/successors table, etc.) should be kept both in the main office and the field office.
2. Periodic updates for the schedule. The scheduler should name and store updated schedules in a clear and consistent fashion. It is also a good idea to keep copies of these updates in the main office. Updates should include both the printout (bar chart and/or other reports) as well as an electronic copy of the CPM schedule.
3. Change orders, including the administrative and technical correspondence.

[18] The author is familiar with Oracle Primavera Contract Management (formerly Expedition), Meridian's Construction Project Management (formerly ProLog Manager), and Sage 300 Construction and Real Estate (formerly Timberline's Project Management).

4. The project manager's daily log. Even though the trend is to use electronic logbooks, many project managers still do it the old-fashioned way and use a traditional daily logbook. There are many logbooks that are commercially available (Prentice Hall, 2000). Also many companies print their own official logbooks. A typical logbook should include—on a daily basis—information such as:
   a. Weather conditions, such as temperature, humidity, precipitation, wind, lightening, etc.
   b. Work performed during that day. Record any disruption in the work, such as accidents or unforeseen conditions.
   c. Number of workers on-site and the entities (i.e., subcontractors) by whom they are employed. Record the number of work hours, especially overtime hours.
   d. Equipment on-site, along with the condition of the equipment (e.g., whether it is working or not).
   e. Any material delivered to the site, along with an inspection record.
   f. Materials used and materials stored on-site.
   g. Any telephone calls made by the project manager or other field personnel that are relevant to the project.
   h. Any visitors to the site; what time they arrived and what organization they represented.
   i. Any accidents that happened on-site.
   j. Any other events that may be related to the project, especially problems that caused delays.

   Nonworkdays (including weekends) should be marked as "no work" in the book. Every page must contain the project's name and date at the top of the page and must be signed by the project manager. Typically, logbook pages are numbered consecutively. In this way, if a page is ripped from the book, it should be easy to recognize that a page is missing.
5. A job diary book, which is an informal daily logbook. It may contain the accounts of the project manager or superintendent without following a certain format. It may also contain personal observations, suggestions, and opinions. Because of their informality and subjectivity, such diaries may not be accepted as direct evidence in the court of law but may be used to refresh someone's memory about a certain event.
6. Submittals such as shop drawings and material samples. In addition to shop drawings and material samples, the record must contain a log showing the dates and actions (accepted, rejected, etc.) taken for any submittal.
7. A record of any transmittals, such as requests for information (RFI), requests for clarification test lab results, warranties, and certificates.

8. Correspondence with the owner, architect/engineer, subcontractors, vendors and suppliers, or other contracting parties. The record must include the topic of the communication, the person with whom the project manager (or the project manager's staff) communicated, and the date of the communication.
9. Correspondence with the home office.
10. Meeting minutes, including the typical information recorded in any meeting's minutes (subject, date, location of meeting, names of people attending and absent people, etc.).
11. Procurement records, including materials and equipment orders and delivery tickets, equipment maintenance records, any quotations for materials; labor; or other receipts for any purchases or payments, and any other record that deals with acquisition of labor, materials, or equipment.
12. Government records, such as permits, code nonconformance reports, and forms/citations from the Occupational Safety and Health Administration (OSHA).
13. A record of payments (owner to general contractor and general contractor to subcontractors and vendors), along with the total amount billed, the total amount paid, retainage, and other financial details. The general contractor must also keep lien releases signed by subcontractors (the owner would keep lien releases signed by the general contractor).
14. It is a good idea for the resident project manager to keep a camera on hand to take photos for important events. Any picture must have the date printed on its back or front. Digital cameras are very effective because the picture can be downloaded to a computer and then attached to a document or to the project management software. Some Web sites have security cameras and recordings that are kept by the security company or IT department for a limited period of time, since it is impractical to store thousands of hours of recordings. The project manager should permanently store any video clips showing important events that may support a case in court later on.
15. E-mails, electronic schedules, electronic submittals, project databases, and similar electronic data in its native format.

The cost estimate may belong to a different department, but the scheduler and the scheduling department must have a copy of the baseline cost estimate as well as all cost estimate updates.

With a good documentation system, the project management team can store the information in a well-organized fashion so that it is efficient and easy to retrieve. One major challenge to anyone asserting a delay claim is to retrieve all of the information in an accurate manner and then re-create past events in their correct sequence. Keeping good records helps refresh the memory of any party involved, which not only will help in case of a dispute but also will help prevent such a dispute from emerging. A work

breakdown structure (WBS) is a convenient format for storing all documentation, as it unifies all of the pertinent data for each constructible feature.

## DELAY CLAIMS RESOLUTION

Most contracts contain clauses for the resolution of claim disputes. The process usually starts with the simplest and quickest procedure and then goes into the next level, and so on. Since the court system is time-consuming, costly, and complicated, other alternative dispute resolution methods have been used. The following are the methods that are usually used in resolving disputed claims:

1. *Negotiation*: This is the most direct method for resolving any type of construction claim. In many cases, the "truth" may not be entirely known or acknowledged, and "fairness" is seen differently by the different disputing parties. Negotiation requires certain skills that tend to reduce the gap between the negotiating parties. Although negotiation occurs basically between the disputing parties, independent experts or consultants may be asked to give opinions on certain issues. Negotiation starts with the parties at the project management level, but higher-level officers may get involved if the lower-level team fails to reach an agreement. While complete satisfaction may never be reached, the objective of negotiation is to reach a solution that is acceptable to both parties.
2. *Mediation*: When negotiation does not work, either because of lack of trust or skills, an independent neutral or a mediator may get involved to bring the disputing parties together. The mediator can be an individual or a team. The mediator usually starts by explaining the role of a neutral in bringing the parties to an agreement. The mediator must demonstrate neutrality and patience, and must collect all of the facts before making any recommendation. Typically, the mediator spends time with each party individually but—if the atmosphere is encouraging—may bring the parties to a meeting. The mediator, like the negotiator, must be skilled in narrowing the gap between the disputing parties and focusing on the positive side of any proposed solution. For example, although the dispute may be on financial issues between a general contractor and subcontractor, the mediator may sense that the subcontractor is concerned about security and future work. The mediator may then convince the subcontractor to accept a lesser financial settlement in exchange for an extended relationship with the general contractor.
3. *Dispute review board*: Rather than waiting until the end of a project to settle claims, a dispute review board (DRB) may be used to resolve disputes as they arise on a construction project. An independent neutral panel with construction experience is selected by the owner and contractor when the contract is signed, and the parties agree to call upon the neutral to assist them in resolving any disputes that may arise during construction. Since some cases involve

large, complicated, and lengthy projects, it may be very difficult for the parties to collect all of the information. The DRB technique was created to help this process by involving the neutral at the very early stages of the project. DRB members often visit the construction site periodically to become familiar with the progress of the work and to provide assistance in the early stages of disputes (Gould and Joyce, 2003).

Negotiation, mediation, and DRBs[19] are nonbinding. This means that the solution changes its shape—like a piece of dough—during the process until it reaches a form that is acceptable to both parties. No party is under any obligation until the party accepts the proposed solution.

4. *Arbitration*: Arbitration is usually a formal process that is performed by an independent professional arbitrator. It is defined by the American Arbitration Association as a "referral of a dispute to one or more impartial persons for final and binding determination. Private and confidential, it is designed for quick, practical, and economical settlements" (Peña-Mora, Sosa, and McCone, 2003). Arbitration in the construction industry is usually performed by experts in the industry, such as architects, engineers, or construction management professionals. Some jurisdictions grant the design professionals quasi-judicial immunity when they are acting as judge. Although arbitration is usually binding for both parties, arbitrators do not have the enforcement power that judges have. An arbitration award in a binding arbitration can be reduced to an enforceable judgment by a court of law, if necessary.

   It should be noted that in many contracts, arbitration is specified as a binding process if negotiation and mediation fail. As mentioned earlier, unlike judges, arbitrators cannot enforce their judgment on the parties involved. If a party refuses to comply with the arbitrator's judgment, it may be necessary for the other party to seek a court's intervention. Most state arbitration statutes specify grounds for reviewing an arbitrator's award, such as a proof of corruption or fraud, evidence of the arbitrator's partiality, or that the arbitrator exceeded his or her powers (Sweet and Schneier, 2008).

   Unlike litigation, arbitration is voluntary, at least until the parties accept it in the contract or after the dispute arises. Arbitration does not require the employing of lawyers, although it is not unusual for parties arbitrating important matters to employ lawyers. Not being subject to the complicated procedures and restrictions of the court system gives the arbitrator more freedom and makes the arbitration process proceed faster. The powers given to an arbitrator differ from one state to another. For example, in many states, arbitration does not allow for an effective method of discovery, the process by which attorneys in litigation can obtain evidence from the other party to prepare for the hearing (Sweet and Schneier, 2008).

   Mediation and arbitration can be combined into a two-stage process: The disputing parties select a mediator and agree that the mediator will become

[19] Unless stipulated in the contract.

the arbitrator if the parties fail to reach a mediated settlement within a specific time frame (Sweet and Schneier, 2008).

5. *Litigation*: When none of the previous processes works and the parties cannot reach a settlement, the complaining party may sue the other party in a court of the law. The legal process is complex and often involves pretrial discovery procedures, such as interrogatories (written questions to the other party), requests for the production of documents, and pretrial testimony in depositions. When the matter goes to trial, the facts may be decided by a jury or a judge who may be overwhelmed by the technical details involved in a construction delay claim. Construction litigation is usually complicated, time-consuming, and expensive. Many plaintiffs spend more money on attorney's fees than they later recover by the court's judgment.
6. *Adjudication:* For construction claims in the United Kingdom, there is an alternative dispute resolution method known as *adjudication*. The goal of adjudication is to provide a speedy and cost-effective method of resolving disputes on an "interim basis," allowing the decision to be "enforced pending final determination."[20] The procedure can be invoked during the course of construction to address payment disputes, performance problems, time extensions, delays, change order valuations, and other claims related to the construction contract. An adjudicator is appointed within 7 days of the notice of the dispute, and the adjudicator generally must decide a dispute in less than 42 days from the time the matter has been referred, although this can be extended by 14 days. Typically, the adjudicator may request documents and written statements, meet and question the parties and their representatives, make site visits, perform tests and examinations, and appoint experts. The adjudicator must ascertain the facts and the law relating to the dispute. In most cases, the adjudicator's decision is final and binding and may be implemented immediately. A party that is dissatisfied with the adjudicator's decision may have it reviewed by a court, but such proceedings may not be started before the contract's completion or termination (Bingham, 2003). In the majority of cases dealing with the challenges to enforcement, the courts have upheld the adjudicators' decisions (Knowles, 2002).[4] Thus, courts have helped to make adjudication a viable means of resolving disputes (Bramble and Callahan, 2014, §14.09).[5]

## THE IMPORTANCE OF CPM SCHEDULES IN DELAY CLAIMS

Resolving a delay claim may be a complicated and challenging task. There might be several concurrent factors that are impacting the schedule. A concurrent delay means that more than one delay has contributed to the project's delay; however, it does not necessarily mean that the delays occurred at the same time. A concurrent delay may

[20] *Macob Civil Eng'g Ltd. v. Morrison Constr. Ltd.,* BLR 156 (1999).

occur during the same period as another delay, but a concurrent delay may also include any delay that could have contributed to the overall project's delay, whether or not the delay overlaps with another (Callahan, Quackenbush, and Rowings, 1992). For example, the owner may have caused a 1-month delay, but the contractor may claim that the delay pushed the start of the schedule to the rainy season, which caused an additional delay. A delay of only 1 day by the A/E in reviewing and approving the shop drawing may cause the cancellation of the placement of concrete to a suspended slab. The contractor may not be able to reschedule the concrete delivery for another week or so. Concurrent delay may also involve two or more factors that happen at the same time, and it may be very difficult for the investigator to isolate the impact of each one. This is particularly important when one of the factors is the fault of the contractor and the other is not (e.g., if the materials delivery was delayed because of the contractor's negligence and severe weather happened concurrently). A contractor may be late due to his or her own fault, but when a change order comes from the owner, the contractor tries to hide its delay in the change order time-extension claim. The investigator must try to verify the effect of one factor at a time. This works theoretically by isolating other factors, which may be very difficult, if not impossible. This is why CPM schedules are so important. The claimant usually provides at least two CPM schedules: one without the impact of the change and one with the impact, in a bid to prove that the alleged change caused the claimed delay. The investigator, on the other hand, may develop several CPM schedules, each representing one factor isolated from other factors in order to show how much exactly of the alleged delay, if any, can be attributed to causes the contractor is claiming.

## METHODS OF SCHEDULE ANALYSIS

There are many methods that have been employed to demonstrate the impact of delays upon a project. Most involve sophisticated evaluation of schedules (Bramble and Callahan, 2014, chapter 11).[21]

### As-built schedule

As the name implies, the as-built schedule should reflect what actually happened in the field. Activities are plotted by their real start and real finish dates, disregarding any logic (as-built schedules may not have logic ties). It may also contain a real budget and actual resources numbers. Investigators usually develop the as-built schedule from project records, such as daily logs, diaries, project correspondence, and the like. It may require a considerable effort to develop the as-built schedule, and there may be some gaps left in the progress information to be filled in with the help of the project manager's recollection and the investigator's judgment. Again, documentation is very valuable in retrieving information that helps develop the case for proving or disproving a delay claim.

[21] See AACE International Recommended Practice No. 29R-03, Forensic Schedule Analysis (June 25, 2007).

### Updated Impact Schedule

The U.S. Army Corps of Engineers modified this method by creating an as-built schedule or updated schedule from the start of the project only to the point just before the delay occurred. The "original" or baseline schedule was updated with progress information and then compared to the impacted completion date on another schedule on which a delay was included (Callahan, Quackenbush, and Rowings, 1992).

### As-Planned Schedule

The as-planned schedule describes the manner in which the contractor intended to build the project. It is usually the same schedule that is submitted by the contractor to the owner and then later becomes the baseline schedule (Popescu and Charoenngam, 1995). However, in some cases the originally submitted schedule may contain some errors and need to be corrected (O'Brien and Plotnick, 2009, p. 480). When no CPM schedule is required, or when it is required but not submitted, or when it is submitted but not formally approved, it may be necessary to develop a revised or prototype schedule using the best and most credible information available to reflect the original plan and intentions (Wickwire, Driscoll, and Hurlbut, 2002, p. 377).

### Comparison Schedule

The original schedule (usually, the as-planned schedule) is revised to incorporate any claimed delays. Typically, for a delay claim, the contractor submits two schedules: one without the causative factors (factors allegedly causing the schedule delays) and one with the causative factors (called the "impacted" schedule). By comparing the two schedules, the contractor hopes to prove that the delay was caused by the alleged factors. The contractor may lump more than one factor in the delay claim. The investigator may then build an impacted schedule for each factor.

### Accelerated Schedule

An accelerated schedule is a schedule submitted usually by the contractor, who implements some adjustment to the project baseline schedule in order to complete the project by the contract finish date. By doing this, the contractor attempts to collect the cost associated with the acceleration of the project.[22] The owner tries to make sure that the contractor utilized all available float before any crashing takes place.

Recovery schedules (as discussed in Chapter 8) are similar to accelerated schedules in the sense that both schedules make adjustments to compress the schedule (or the remainder of it) to ensure the completion of the project by the contract finish date. However, the main difference is in the reason for the delay that triggered the compression. Recovery schedules are mainly used when the contractor causes the delay and the owner has become concerned and suspicious about the contractor's completion of the

[22] Review the discussion about the cost of schedule compression in Chapter 8.

project by the contract finish date. The owner may then demand that the contractor make adjustments and submit a recovery schedule that demonstrates a timely completion. Accelerated schedules are usually prepared by the contractor in case of a delay that the contractor alleges is caused by the owner, *force majeure*, or a third party.

### Who Owns the Float

Float may be defined technically as the maximum amount of time that an activity can be delayed from its early start date without delaying the entire project.[23] From a practical point of view, float is regarded as the time contingency associated with a path or a chain of activities (Wickwire, Driscoll, and Hurlbut, 1991). Some contracts give the owner the right to use the float in case of a delay. In this case, the contractor may not be entitled to a time extension or compensation until and unless the float is entirely exhausted. The contractor, on the other hand, has a range of time for each noncritical activity between its early and late dates. The contractor may choose specific dates within this range for efficient resource allocation or for other reasons.

#### *Conclusion on Delay and Float*

The subject of float is complicated and cannot be covered in this simple discussion. It was mentioned earlier, in Chapters 4 and 5, that there are several types of float, not just total and free float. Types of float such as interfering and independent float[24] may not mean anything to field personnel or even to a project manager. But these terms could be used in a case of dispute to illustrate dependency and distribution of float. Total float as defined earlier is more like a path-shared float, whereby if an activity at the beginning of the path uses that float, the rest of the activities on that path will be impacted. A very simple example is the network in Figure 13.1. If activity C uses its 5 days of float, activity E becomes critical and activity F's total float shrinks from 8 to 3 days. Free float represents the portion of total float that would not impact the succeeding activities. But free float is still subject to impact from preceding activities. For example, activity E has FF = TF = 3 days, but this float will disappear if activity C uses its float. The difference between total float and free float is interfering float (Int. F.), which is the part of the total float that will impact the succeeding activities. Independent float (Ind. F.) is the portion of free float that cannot be impacted by preceding activities and cannot impact succeeding activities. In other words, it is the only float that truly belongs to that activity. These are definitions that we don't usually deal with on a daily basis in the construction industry, but experts may have to understand and deal with them in some delay claim cases.

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[23] This is the definition of total float. See the definitions in Chapter 4.

[24] Additional compensation and/or time extension may be involved, because even with 3 days' time extension, the contractor still needs to hire the crew for 3 extra days (days 8 through 25 instead of days 8 through 22), unless the crew can do other work during the delay time (i.e., days 14, 15, and 16). The alternative is to hire a second crew and do E and F concurrently (finish them both by the end of day 22).

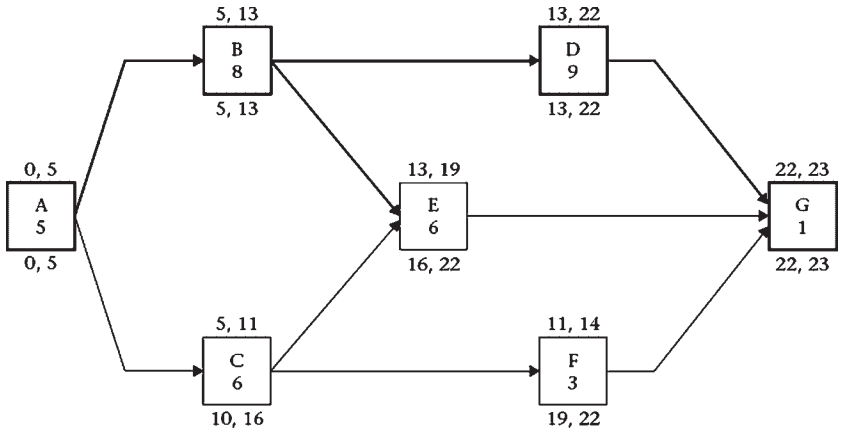



**Figure 13.1 CPM network for example 12.1**

### Example 13.1

In the construction project represented by the logic network shown in Figure 13.1 (a), the owner issued a work order to the contractor that would delay the start of activity E until day 16 (i.e., its late start date). Would the contractor be entitled to a time extension, compensation, both, or neither?

### Solution

As we see in Figure 13.1, activities C, E, and F have total float equals to 5, 3, and 8 days, respectively. Let's redraw the schedule as a bar chart, showing the amount of float—if any—that each activity has. See Figure 13.2.

The contractor may choose not to start noncritical activities on their early dates. Assume that these three activities require the same crew. For the most efficient use of the crew, the contractor chooses the plan shown in Figure 13.3. According to this plan, all activities are "critical," some by logic constraints and others by resource constraints. If we start activity C 1 or 2 days earlier than shown in Figure 13.3, we then have to hire the crew for an extra day or two (since activity E cannot be started earlier).

Now assume that the owner caused a delay of 3 days at the start of activity E (so it starts on its original late date). The owner can use the argument that activity E had 3 days of total float; thus, the contractor does not qualify for a time extension or compensation (see Figure 13.4).

The contractor argues that this delay will force it either to hire a second crew on days 20, 21, and 22 or finish the project 3 days late. For this reason, the contractor requests additional compensation and/or a time extension for

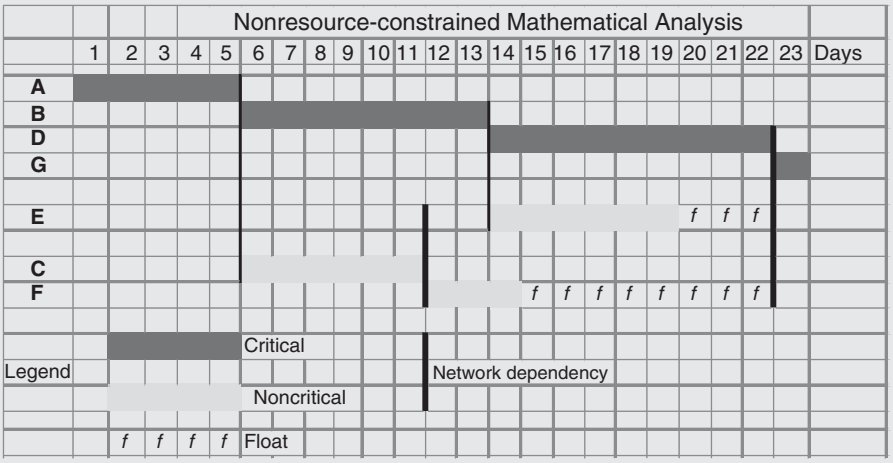



**Figure 13.2 Bar chart with sequence dependencies**

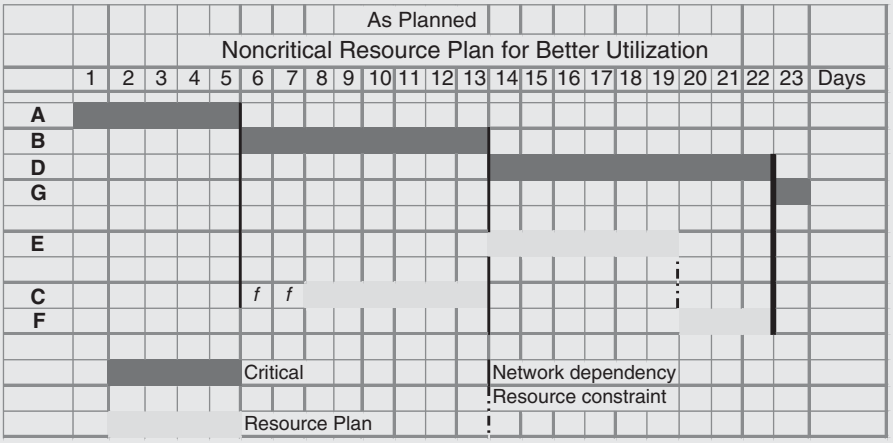



**Figure 13.3 Bar chart with resource constraints**

3 days.[24] The answer to this argument generally lies in the contract agreement. If the contractor granted the owner ownership of the float, the owner can use the float to absorb any delay. If the contractor has ownership of float, he may be entitled to a time extension or compensation if he or she can prove

[24] Additional compensation and/or a time extension may be involved, because even with 3 days' time extension, the contractor still needs to hire the crew for an extra 3 days (days 8 through 25 instead of 8 through 22), unless the crew can do other work during the delay time (i.e., during days 14, 15, 1nd 16). The alternative is to hire a second crew and do E and F concurrently (finish them both by the end of day 22).

that the delay disrupted the resource allocation plan, even though it affected a noncritical activity and did not delay the entire project (see Figures 13.5 to 13.7).

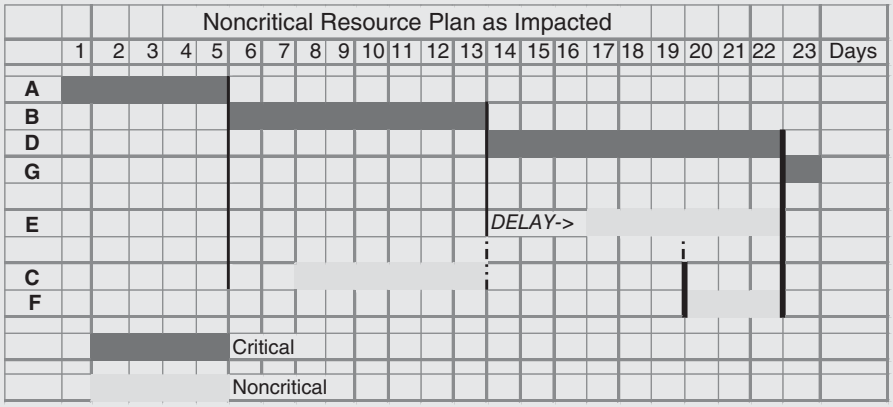



**Figure 13.4 Bar chart with impact of owner's delay to activity E. The owner's delay has disrupted the planned use of the noncritical resources. While the contractor would claim 3 days (14–16) of idle time plus 3 days (20–22) of extra crew time, a resequencing of the noncritical resource, if possible, would mitigate the owner's delay.**

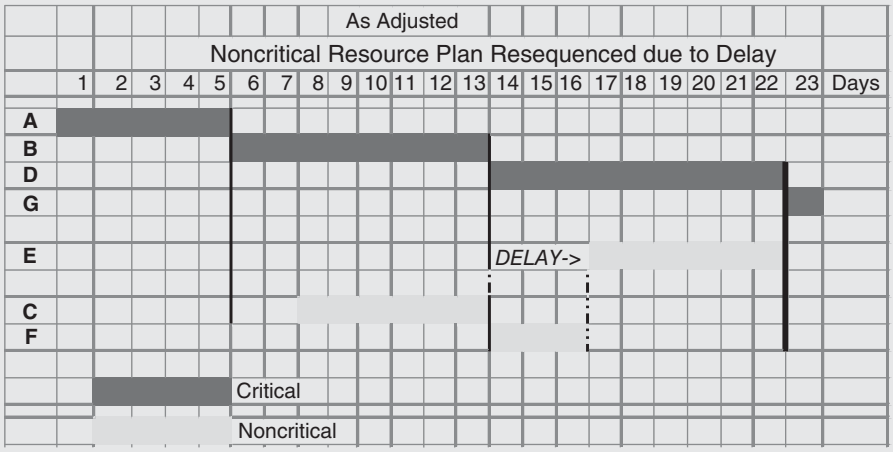



**Figure 13.5 With the impact of owner's delay to activity E but mitigated by resequencing activities E and F**

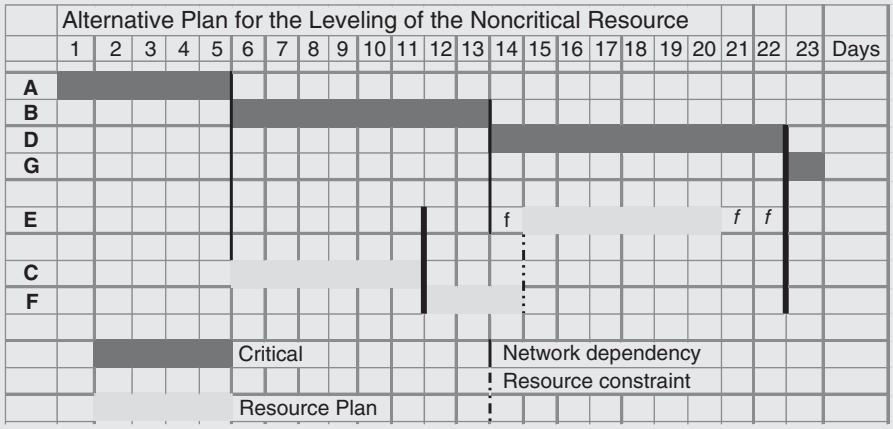



**Figure 13.6 Alternate version of Figure 13.3, redrawn with activities C, F, and E resource-constrained**

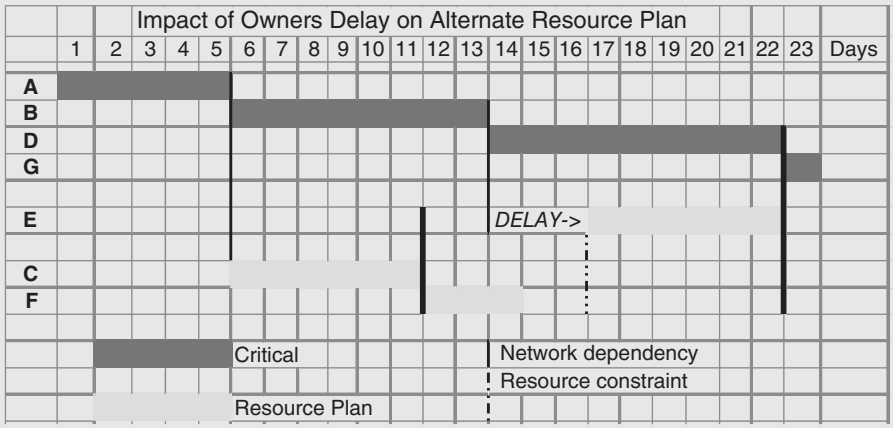



**Figure 13.7 The timing of the delay notification becomes important in permitting mitigation options. If the delay is known early enough, the start of activities C and F can be delayed without an early notification and the contractor can claim 2 days of an idle resource.**

Since we defined both *total float* and *free float* as characteristics that may be shared among activities, and since many activities in construction projects are performed by different companies, the big question is: "Who owns the float?" We mentioned earlier that the owner and the general contractor may agree on this point in the contract. But the issue is still far from over. There may still be disputes between the general contractor and a subcontractor, between two subcontractors, or between a vendor

and the general contractor or subcontractor. Generally, if there is a language in the contract that specifies obligations from the general contractor toward the owner, it usually becomes applicable to any subcontractor. Thus, if the general contractor grants ownership of the float to the owner, the owner then owns the float for all activities, whether they are performed by the general contractor or any subcontractor. The case may not be so simple if the general contractor owns the float. The general contractor may reach an agreement with the subcontractor for the distribution of the float. Some jurisdictions have determined the distribution of the float through case law, legislation, or contracts, but others have not. Researchers have studied this topic extensively and have come up with many suggestions and algorithms to distribute the float. There is still no "industry standard" for this issue, and contracting parties must make sure this issue is discussed and agreed on before signing the contract.

## CHAPTER 13 EXERCISES

1. Define a construction claim delay.
2. Who can initiate a construction claim delay?
3. How can owners minimize the number of change orders?
4. The earlier the owner decides on a change, the less extra cost and trouble will occur. Elaborate on this statement and provide a practical example.
5. What are the major reasons for change orders?
6. Define *force majeure*. Why is it preferred over the term "act of God"?
7. What are the types of delay claims?
8. If the owner adds additional items of work to the project, does this action automatically entitle the contractor to a time extension? Explain.
9. What can the scheduler—as part of the project management team—do to prevent delay claims and/or help resolve them? List the items that you must document.
10. List the methods usually used in resolving claims. Briefly explain each one. Classify them into binding and nonbinding methods.
11. Why is CPM important in proving or disproving construction delay claims?
12. Define:
    a. As-built schedule
    b. As-planned schedule
    c. Comparison schedule
    d. Accelerated schedule
13. If a subcontractor's activity has 5 days of total float, does the subcontractor have the authority to use that float however he or she likes? Explain your answer.
14. Can the owner require ownership of the float in the contract? If yes, can the owner add a 3-day work item to a path that has 5 days of total float without giving the contractor any time extension? (*Hint*: the answer is not a simple yes or no.)

Chapter **14**

# Schedule Risk Management[1]



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[1] This chapter was written with contributions from Chris Carson, FAACE, DRMP, PSP, CEP, CCM, PMP, Director of Program Controls, ARCADIS U.S., Inc., Virginia Beach, Virginia.

## INTRODUCTION

Schedule risks are both threats to and opportunities for the success of a project. Threats tend to reduce the success of meeting the project goals, and opportunities tend to increase the success of meeting the project goals. Risk management is the process of identifying, analyzing, qualifying, and quantifying the risks, and developing a plan to deal with them. This is routinely done during baseline schedule development as well as during schedule updates.

Implementation of risk management starts with early planning in both budgetary cost estimating and preliminary master scheduling in order to determine budgets and schedules with a comfortable level of confidence in the completion date and final cost.

While there are entire volumes addressing risk in construction projects, it is important to note that the issue of time-related risk has not been universally incorporated into planning. Assessing cost risk is more intuitive and very often is done through the use of heuristics, so it has become more of a standard in the industry than time-related risk management. Although some projects include extensive cost-risk management, many estimators simply add a percentage contingency to a cost estimate to cover the risk of performance based on the type of project and circumstances pertaining to the undertaking of the project. Estimators estimate this contingency using their own rules of thumb that they have developed over years of estimating as well as estimating manuals such as RSMeans' *Cost Data*[2]. However, when it comes to developing the critical path method (CPM) schedules, risk management is often overlooked, underestimated, or handled with intuitive approaches.

The purpose of this chapter is to provide an overview of risk management and the assessment process, as well as best practices for incorporation of risk management into CPM schedule development and maintenance. For more detailed information about schedule risk, the reader should refer to risk management books, particularly those that focus on project management. One of the best resources available is David Hulett's book, *Practical Schedule Risk Analysis* (2009).

Any risk management program starts with a good and accurate CPM schedule, created with the use of best practices and checked for quality, reasonableness, and appropriateness of the network model. Without a well-designed and developed CPM baseline schedule, a risk management process will not be effective. The risk analysis depends upon accurate and consistent calculations of the network logic, the appropriateness of the sequencing and phasing, and a reasonable approach to estimating activity durations.

Most CPM schedules are not adjusted for risk but, rather, are developed as if there were one right answer for the schedule's numerical data. Generally, activity durations are established by calculating the quantity of work represented by an activity, divided by the production rate, or by a sheer "gut feeling" of the project manager or crew leader. This production rate is normally established by the contractor's historical records or an estimating system, such as Means', which provides an accurate database

[2] The Gordian Group.

of average production rates. Once the durations are calculated, they are often used as deterministic values, assuming the durations are accurate and unlikely to change. This assumption ignores the fact that the schedule is attempting to predict how long it will take to complete an activity at some unknown time in the future, using an unknown crew composition, with variable experience, and working in unknown conditions. Risk management recognizes the uncertainty in duration estimating and provides a system to brainstorm other risks that may occur during the project. Probability distributions are the best way to model planned activity durations, as noted by Hulett (2009): "The best way to understand the activity durations that are included in the schedule is as *probabilistic statements of possible durations* rather than a deterministic statement about how long the future activity will take."

## TYPES OF RISK IN CONSTRUCTION PROJECTS

Everything that has ever gone wrong on a construction project is a potential risk for the next project. Many project managers instinctively develop a "lessons-learned" list of historical risks and take steps to minimize their exposure to those risks in the future.

Risks vary by industry and even by construction project type, as well as by personnel involved with the project. A roadway or bridge project has a different group of risks than a facility or building, and the selected contractors may have different degrees of influence on the level of risks to performance.

In addition to things that may go wrong on the project, the way the contract is written, the type of project delivery method, the requirement for insurances, and many other contractual and legal decisions will result in increased or decreased risk. Of course, the general effort with contracts is to reduce risk or at least to remove it from the owner.

Risks may affect cost, time, quality, safety, the contract, or anything else, from the program level down to the project level. Each type of risk is treated differently and with different emphasis by the project management team.

## SCHEDULE RISK TYPES

Looking only at the risks associated with time, schedule risks are still extensive. Schedule risks particularly drive cost risks more often than the reverse.

The selection of the project team can impact positively or negatively on the probability of the project's successful completion. Design-bid-build projects that use procurement philosophies allowing all financially capable contractors to participate will likely experience a much higher level of risk to on-time performance than a procurement philosophy that requires qualification of proposed contractors to ensure that they have the appropriate experience and resources to construct the project. A single weak subcontractor on a project will increase the risk of performance and require more management than may be anticipated. If this is not considered, everyone will be surprised when that subcontractor fails and the subcontractor's work subsequently must be augmented or corrected. Problems related to the management and possible termination of a failing subcontractor usually have serious negative impacts on the project.

The reputation of the construction manager (CM), as well as the corporate culture, will affect project performance. If the CM defines success with minimum time extensions as the only benchmark, there will likely be more conflict and a greater need for dispute resolution efforts. In addition, the management abilities of the CM directly affect many project tasks, such as the review of shop drawings and responses to requests for information in order to resolve questions about the construction.

Work by outside or third parties can carry significant risks of influence on the project's success. For example, a light rail station to be built on top of a parking garage under construction by a different contractor will run an increased risk of completion on time. The project manageement team, has no control over—and little ability to influence—the completion of the parking garage, which quickly becomes vital to the completion of the light rail project.

If an owner attempts to save money in preconstruction services by limiting the extent of field investigation or the development of as-built data, there will be a higher risk of discovery of unknown problems. The experience and competence of the architects and engineers who are handling the design of the project, as well as their quality control during the development of the working drawings, directly affect the construction efforts and, consequently, the risk associated with the plans and specifications.

Even if the owner has been proactive during preconstruction investigations, there is always a risk of unforeseen conditions. This can be a function of the type of soils found, the local municipality, and its culture and history of keeping good records of obsolete utilities. If the city in which the project is to be built has a history of requiring contractors to remove all abandoned underground lines, there is a much lower risk of encountering problems underground.

Most projects are affected by local weather conditions, which, when adverse, can significantly impede the projects' progress. Most specifications require the contractor to take into account the normal local weather conditions during schedule planning, which includes normal adverse weather, but also allow for time extensions when unusually adverse weather occurs. Different parts of the country and the world have a wide variance in weather conditions, so planning or failure to plan for the risk of local weather can significantly affect a project's success.

Local political situations, especially in volatile political climates, may hamper all efforts to construct a project efficiently. Countries with unstable political or economic systems will have higher risks in successful project completion than those with more stable systems. Countries or regions subject to wars, terrorism, turmoil, or other types of violence also run greater risks to successful project completion than others. If the locality has a policy of requiring detailed investigation into environmental issues or stringent or complicated bureaucracy, projects built in that locality will run a higher risk of late permits and problems during construction.

Another potentially big risk on any project is the experience and reputation of the project team for safe construction practices. Safety violations and accidents can shut down a job completely. Even minor safety failures can distract the project team and impede their performance. If a contractor has a poor safety record, the risk of delays because of safety violations is increased and should be taken into account during the schedule's development.

A large volume of change orders on a project will affect employee morale; there is nothing worse than asking a craftsman to rip out recently installed high-quality woodwork because of a requested change. If the CM has a good change management process in place, the risks of negative pressures due to changes are lowered. Without a good change management process, the risks may be significant enough to derail the project's completion.

Most conversations about risk are related to negative risks that impair successful performance, but often there are opportunities that would be overlooked without good risk assessment. A renovation project that calls for a three-story masonry wall to be demolished to the foundation in order to install a beam-and-column system could be redesigned with a pin beam temporary support structure, allowing the upper two stories to remain in place, saving time and money, as well as removing some risk. The brainstorming about risks needs to include looking for opportunities that could positively impact the project's time for completion.

It seems obvious that failure to plan for many risks that often can affect project performance will render the planning less accurate. Without risk management, every item that might appear on a risk register (a checklist of potential risks) will be a surprise to the project team if it should happen, diverting attention and emphasis from the project management and consuming valuable resources. Most disputes arise from risks that likely were not considered at the inception of the project but that could have been eliminated or mitigated with good risk planning.

Once a company develops a regular risk management culture, the risk register generates many of the same risks on project after project. However, a company's risk register should not be a fixed template, used as is on all of its projects. The project team must update and customize the list for each project, and taking into consideration that project's own risks. If these lessons are learned and incorporated into the project schedule using a risk management program, they become invaluable in helping to minimize threats that carry negative impacts and in taking advantage of opportunities that can have positive impacts on the project's completion.

Schedule risks fall into several broad areas:

1. General duration uncertainty
2. Specific risk events
3. Network logic risks that exist or are increased as a result of activity relationships

Each of these types of risk is analyzed differently using different tools.

### General Duration Uncertainty

General duration uncertainty is the risk resulting from the following conditions:

- The deterministic durations estimated by the stakeholders are inaccurate or overly simplistic, or they are based on assumptions that are not necessarily correct or accurate.

- The critical path identified in the deterministic approach may not be the same as those in the probabilistic critical path when risks are incorporated into the schedule.
- The combination of durations, where pessimistic durations may stack along a path—because of logic relationships—will significantly extend the predicted completion date.

When discussing duration uncertainty, many project managers believe that their initial estimations of durations are accurate and that, if the risk discussion continues, their durations are the "most likely" durations. This seems logical, and so the necessary discussion about the difference between deterministic and probabilistic schedule development rarely happens. Since the durations are estimates of future events, there is no certainty that the estimates will be accurate. In addition, duration estimates are based on predicted crew production rates. Crew production rates are based on a number of variables, including the composition of the crew, the crew's level of knowledge about the specific activity, weather conditions, the availability and condition of the equipment, crowding of the workspace, and many others. All of these factors can affect the actual duration of the activity, making it unlikely that the original estimate can be achieved in some cases. An additional problem with using deterministic approaches with no risk analysis is that many assumptions are made during the early development of the schedule, but rarely, if ever, are they questioned or reviewed again during the project. The assumptions themselves can lead to higher risks if they prove to be false or inadequate.

So, a probabilistic approach takes the concept of estimating durations based on average production rates to the next level; with this approach, we look at the range of possible project durations based on a spread (called *distribution* in statistics) in the estimated activity durations, commonly called a *three-point estimate*. The term *three-point estimate* comes from its general definition, which includes three duration estimates: the pessimistic, the most likely, and the optimistic. This allows for a compiling of all general risks to the duration into a three-point estimate by providing a range of durations that can be used in the risk analysis. It also helps with accuracy when there is a higher level of unknowns about the project, as is often the case in the early stages of any project but especially of design-build projects, where the design is under development at the same time as the schedule.

There is also a risk of the stacking of inaccurate or changed durations along the same path, which would magnify the uncertainty of duration estimating. With the correct risk management approach, the uncertainty of activity durations is more likely to be taken into account in the schedule's predictions.

The use of the Monte Carlo simulations makes general duration uncertainties relatively easy to analyze, as well as risks from activity relationships and some specific event risks. Monte Carlo analysis runs a large number of iterations based on the spread of the duration estimates so that many combinations of durations are used. This probabilistic approach recognizes that the more appropriate way to model durations is through the use of statistics, by which if enough iterations are run, the results will generally fall

into one of the common probability distributions of activity duration. One of these probability distributions that is commonly seen and used is the *normal distribution*, which graphs into a bell-shaped curve, with the most likely duration occurring at the highest peak of the curve and the less likely probabilities occurring as the curve diminishes in both directions. An understanding of statistics is important in order to use Monte Carlo analysis for risk management, especially when choosing the probability distribution and knowing how to evaluate the three-point estimates for use in the analysis. There are several features in the Monte Carlo computer simulation that produce interesting and useful results with the analysis, such as the ability to provide global or filtered duration estimate spreads and the ability to adjust risk by activity code. The Monte Carlo analysis provides statistically significant "confidence levels" for the probabilistic prediction of completion dates and, since schedules deal with unknowns, allows the schedules to have higher probabilities of meeting the chosen completion date.

The Monte Carlo simulation analysis is available in numerous software packages, such as PertMaster (acquired by Primavera Systems, which was later acquired by Oracle and now is called Primavera Risk Management), which can be linked to the CPM software by the same entity. There are also spreadsheet versions of Monte Carlo techniques, such as @Risk, published by the Palisade Corporation. The use of three-point estimates for risk analysis of uncertainties in duration originated in the late 1950s during the U.S. navy's Polaris missile program. That program was called PERT (Program Evaluation and Review Technique).[3] PERT was developed independently of, and concurrently with, CPM methodology and used the three-point estimate system to provide a weighted average duration for use in network calculations.

One important point to recognize about duration uncertainties is that the risk from pessimistic durations' stacking and causing a delay during a project's execution is greatly reduced when there is a robust and highly technical project controls effort used on the project. When there is this technical controls effort, as soon as activities start to miss their durations, the analysis and reporting raises a red flag about the problems related to durations. With this strong reporting and identification of problems, the project management team is in a stronger position to mitigate the time overruns from missing durations before the time overruns stack up. So, the industry is moving away from the need to analyze uncertainties in original durations and toward the analysis of risk drivers, which are treated similarly to the specific event risks in the next section.

However, there are important and valuable results that come from a Monte Carlo simulation. These results provide insight into the project and how the activities will be performed in a variety of situations. The simulation can provide a list of activities that most likely will appear on any or all the calculated critical paths and will display the results in a prioritized list that often is called a *tornado chart*. Then the topmost likely to be critical activities can be monitored more carefully, recognizing that many

[3] Explained in detail in Chapter 11.

conditions can push them onto the critical path. This is highly useful and makes the Monte Carlo simulation a valuable, worthwhile tool.

### Specific Risk Events

Specific risk events are potential impacts on the schedule that may or may not occur, such as accidents and other events that are difficult to predict. Specific risk events include several types that are analyzed by several methods, but the initial step in predicting them is to hold a brainstorming session in which the project's team members identify as many potential risk events as possible and create a risk register or checklist of those events. The process of identifying potential risk events for a project is valuable, because it helps the project management team to start thinking about risk issues and to produce a more realistic schedule.

Another type of specific risk event includes determining the additional scope of work activities that may or may not happen, activities that are present in the schedule but may require unplanned multiple cycles to complete, or activities that have significant variability. It is important during brainstorming to review historical records and experiences in order to determine which of these types of risks may occur during the project that is under way. These risks probably are dependent on other factors, such as the personnel involved, the type of project, the time frame, and the budget.

There are several methods that can be used to analyze specific risk events. Modeling a specific risk by creating a string of activities to represent the scope of work due to the risk (called a "what-if scenario") is one good way to attempt to determine the potential ramifications of the realization of that risk. This is the same approach that would be taken during a project if a changed condition appeared to impact the schedule and the project management team needed to assess the potential ramifications of that change. In this situation, the contractor would prepare a prospective time impact analysis (TIA). A prospective TIA would be prepared by using the current updated schedule, inserting a linked group of activities that would model the changed condition, and recalculating the schedule to see if the finish date changed. This linked group of activities is called a *fragmentary network,* or *fragnet.* The degree of change to the finish date is an indication of the number of days that the changed condition would affect the critical path and delay the project. An excellent description of a prospective TIA is provided by the AACE International in their Recommended Practice No. 52R-06, "Time Impact Analysis—As Applied in Construction." Specific risks also can be incorporated into a Monte Carlo analysis to provide a probabilistic approach toward modeling the risks.

### Network Logic Risks

Network logic risks are those risks that generally occur as a result of project management decisions that are made about the logic and sequencing of activities, determined by the activity relationships. If a number of paths originate or terminate in one activity, there is a significantly increased risk of a delay to path activities, causing a delay

to the project. Network logic risks include any risks that predominately relate to the schedule network, such as activities that occur at a "hub" or convergence point. A single activity that controls multiple activities of subsequent work, such as environmental controls, dry-in, above-ceiling inspections, or temporary traffic relocation, will cause serious delays and disruption if that activity is not completed on time.

Activities that require the same resource and have tight sequencing predictions are at a much higher risk of failure if resources are not as available as the schedule predicted, and failure in one activity will likely be reflected in all other activities that require that same resource. These network logic risks are often discovered only through a technical analysis of the schedule's components. A good review of the schedule should identify these risks if the reviewer is knowledgeable and is provided direction in the risk management plan.

Once the types of risk are understood, a good risk management plan should be prepared, which should include a brainstorming meeting with the project's major stakeholders. A master risk register is an invaluable tool for facilitating the brainstorming session, which is often called a *risk workshop*. This register is a logical place to collect any lessons that have been learned on a corporate level resulting from many project experiences. With a good risk register, organized by industry and type of risk, the process of brainstorming moves more quickly and focuses on a more comprehensive list of risks.

Just as a schedule development session should be a dedicated meeting with the project management team, the risk workshop should be treated as a stand-alone process, requiring the participation of the project's major stakeholders.. At a minimum, the project management team should participate, but the involvement of others provides valuable insights because of their views and experiences. The output of the risk workshop should be a fully developed risk register that identifies all potential risks to the project, no matter who carries the responsibility for the resolution of those risks.

## DEFINITION OF RISK TERMS

The Project Management Institute (PMI) defines *project risk* in its *Project Management Body of Knowledge* (the PMBOK™) (PMI, 2013) as "an uncertain event or condition that, if it occurs, has a positive or negative effect on at least one project objective, such as time, cost, scope, or quality. A risk may have one or more causes and, if it occurs, one or more impacts." The PMBOK adds the following: "Risk conditions could include aspects of the project's or organization's environment that may contribute to project risk, such as poor project management practices, or dependency on external participants who cannot be controlled."

**Risk management**: A process designed to examine uncertainties occurring during project delivery and to implement actions dealing with those uncertainties in order to achieve project objectives.

The definition of *risk management* in *PMBOK* (PMI, 2013) is: "systematic process of identifying, analyzing, and responding to project risk."

The definition of *risk* by AACE International Cost Engineering Terminology[4] is: "the degree of dispersion or variability around the expected or 'best' value, which is estimated to exist for the economic variable in question, e.g., a quantitative measure of the upper and lower limits which are considered reasonable for the factor being estimated."

**Time contingency**: An amount of time added to the base estimated duration to allow for unknown impacts to the project schedule or to achieve a certain level of confidence in the estimated duration.

**Probability**: A measure of the likelihood of occurrence of an event.

**Risk register**: A checklist of potential risks developed during the risk identification phase of risk management.

**Risk allocation**: A determination of how to respond to risks, which can include shifting risks, avoiding risks, preventing or eliminating risks, and incorporating risks into the schedule.

**Deterministic**: A calculated approach to estimating a single activity duration using work quantity divided by estimated production rate.

**Probabilistic**: The determination of risk likelihood and consequences to establish duration ranges or risk-adjusted durations that can be used in a schedule in recognition that there are no certainties in estimating future durations.

**Monte Carlo analysis**: A probabilistic approach to determining confidence levels of completion dates for a project schedule by calculating durations as probability distributions.

**Probability distribution**: The spread of durations in a statistically significant population that is used for the range of durations in probabilistic scheduling approaches.

**Confidence level**: A measure of the statistical reliability of the prediction of a project's completion.

**What-if scenario**: A modeling of a risk for use in a CPM schedule in order to predict the ramifications of an identified risk.

**Qualitative analysis**: The determination of the likelihood of a risk occurring on a project, as well as assessing the severity of that risk should it occur and prioritizing the resultant list of risks.

**Quantitative analysis**: The assigning of a probability to the qualitative description of a risk, ranking risks, and calculating the potential impact from both individual risks and the cumulative effect of all risks identified.

**Exculpatory clauses**: Disclaimer verbiage that is designed to shift risk.

[4] Association for the Advancement of Cost Engineering (AACE) International, "Cost Engineering Terminology."

## IMPORTANCE OF GOOD PLANNING FOR RISK MANAGEMENT

The quality of the risk management plan will control the usefulness of the risk analysis. Quality is achieved through developing a good and encompassing master risk register in a brainstorming workshop with experienced attendees, and following that process with analysis and risk allocation. This is combined with a process of continuing risk monitoring during updates as well as continuous cycles of risk management.

Participants in the workshop often comment that they cannot take certain risks into account because they do not have control of the risks or they have no idea if that risk will actually happen. One of the typical issues is repeated cycles of shop drawings, where experience tells us that a complicated design may cause structural steel shop drawings to be rejected, requiring revision and resubmission. Some stakeholders feel that this is beyond their ability to plan for and, therefore, that the schedule should not include it and they should assume that the risk will not happen. Accepting this assumption minimizes the risk identification and analysis process. This type of risk should be identified, and then during the qualitative analysis, either it should be identified and ignored as a low priority or incorporated as a high priority. However, if the risk is has not been included on the risk register, the opportunity to analyze it is lost.

By means of a thorough and organized risk workshop, based on a good master risk register, and participation by the major stakeholders as well as the project management team, the output of the risk analysis will be very useful. The most likely risks will be identified and analyzed, and with the rest of the risk management steps, the schedule will evolve into a risk-adjusted schedule, capable of reasonable analysis and realistic completion predictions.

## IMPORTANCE OF GOOD CPM SCHEDULING PRACTICES FOR RISK ASSESSMENT

Although there are significant benefits in brainstorming and identifying potential risks on a construction project through raising the awareness of those issues, the efficient way to evaluate and analyze those risks is through some computerized risk management approaches. Whether it is modeling specific risk events or running Monte Carlo simulations for duration uncertainties, these approaches depend on the quality of the CPM schedule. If the schedule model does not reflect the complete scope of work, does not utilize a good network that produces accurate calculations, and contains scheduling components used inappropriately, then the results from the risk analysis will not be useful. With risk assessment based on a well-developed CPM schedule, the results will reflect a more probable accounting of those risks.

Good CPM scheduling practices include capturing the full and complete scope of the work in the schedule. This can be achieved by using a work breakdown structure (WBS), which then is reconciled with the chart of accounts or estimate to ensure that all activities carrying cost are included on the lowest level of each column of the WBS. Including the full scope of work also requires some level of consistency in the amount of detail in each trade so that no single trade can control the network calculations because of the number of activities in that trade.

Another important practice is to limit the use of relationships among activities to mostly finish-start relationships, with minimal use of lags.[5] This improves the ability of the Monte Carlo analysis software to provide accurate results from those calculations. Some Monte Carlo software programs do not calculate accurately with negative lags, so those should be minimized in any schedule that is intended to be adjusted for risk through a Monte Carlo analysis.

In addition, the level of detail in the schedule is an important requirement for using risk analysis. There must be enough detail in the schedule to isolate each activity by responsibility. This means that, for a schedule to be used in risk analysis, an activity should only model one trade. A rough-in activity should be broken down into separate activities for mechanical, electrical, plumbing, and fire sprinkler work. The rough-in work should also be separated into wall rough-ins and ceiling rough-ins, and by area designation plans if those areas tend to progress differently. This allows an evaluation of each trade for different assumptions of risk, as well as an evaluation of areas for different risks. For example, if a plumbing subcontractor shows up on the risk register after the workshop as a high risk because of his or her poor reputation, then a different factor for risk or a different spread of duration estimates can be used to account for that risk. On a very simple level, without Monte Carlo analysis, a time contingency could be added to the plumbing activities to allow more time than predicted, especially on those activities that are vital to opening up other significant areas of work.

The use of constraints can affect the validity and accuracy of risk calculations because constraints may sequester float or prevent the network from calculating correctly. It may be necessary in the risk analysis to remove constraints in order to see the impact of those constraints on the project's completion. The fewer constraints there are, the easier it is to incorporate risk management. In addition, the use of mandatory constraints that do not allow the network to calculate float accurately in either direction, delay, or acceleration is problematic and might render the schedule an inappropriate candidate for a risk analysis.

Just as in any analysis of a schedule, the more calendars that exist in the schedule, the harder it is to analyze the schedule, whether it is for delay or risk. Multiple calendars with many shifts from calendar to calendar along critical paths will amplify or reduce the total float values. This can affect the risk analysis and, at the least, can require additional work on the analysis.

The risk management plan is based on CPM network calculations, whether you are using Monte Carlo analysis or what-if scenarios. So, if the network does not calculate correctly, the value from risk management is severely reduced. This means that one of the generally accepted scheduling best practices, the limitation of open-ended activities to the first and last activities, is vital to risk management analysis.

With a Monte Carlo analysis, the iterations are run with multiple values of activity durations, so those durations have to be reasonable, comparable, and ideally limited to

[5] Overlapping activities can be accurately represented by splitting the predecessor. See the discussion in Chapter 5 and Figure 5.8.

one update period or less. The estimated durations, whether they are single estimates or three-point estimates, should be calculated by accurate quantities and appropriate production rates. This means that the durations will be based on reasonable resource planning that reflects the contractor's ability to staff the project. Unusually large durations might artificially skew the results in either Monte Carlo or what-if scenarios. In addition to best practices in duration estimating, logic must be depicted accurately to eliminate any unnecessary or redundant relationships.

Careful examination of the critical path and near-critical paths is vital in developing a CPM schedule for a risk analysis effort. Activities that drive the completion of the project and those that appear critical during updates must be logical and make sense. At this time, a re-examination of all assumptions that were used in the schedule development is important and includes verification that there is no logic missing that might allow activities to inappropriately carry a high float. The validity of the critical path is an essential basis of good CPM scheduling practices, which is reinforced by the needs of risk assessment of the schedule.

## RISK SHIFTING IN CONTRACTS

Contract language may have a significant impact on how much of the risk each party carries. Sometimes called *exculpatory clauses,* this language attempts to shift or apportion undetermined risk. Contracts are often used to control or assign risk to various parties, or to assign it to a party other than the owner. Many owners, developers, and contractors prefer using standard contract forms, such as those developed by organizations such as the American Institute of Architects (AIA), the Construction Management Association of America (CMAA), and the Associated General Contractors (AGC) in the United States and the International Federation of Consulting Engineers (FIDIC) or New Engineering Contract (NEC) in Europe and the Middle East, because such contract forms were written and updated by professionals and are widely known and used. However, many others insist on writing their own contracts or making amendments to the standard forms so that they can change certain conditions, which may—and usually does—affect the risk of the contracting parties.

One example of this risk shifting is the use of clauses stating that geotechnical reports and information are provided to bidders for information only, and the owner is not responsible for any usage or interpretation of the geotechnical information. This is an attempt to limit the owner's exposure to delays because of differing site conditions.

Another example is that of the typical "no damages for delay" language that sometimes shows up in contracts, which does not typically shift the time performance risk but only the costs for the delay. This language attempts to move the risk of the costs of delays from the responsibility of the owner to the contractor so that the sole remedy is a time extension.

Construction manager and contractor insurances are means to handle the shifted risk of contracts and to limit the liability of those parties. These types of insurance

can provide some level of protection against the adverse consequences of unknown problems that might affect the completion of the project. Builder's risk policies provide insurance that will replace materials and provide for damage repair that can be invoked fairly quickly in the event of vandalism or property losses, allowing the project to resume production and minimize risks of delayed completion.

An astute owner realizes that the more a risk is shifted to the contractor, the higher the cost and, sometimes, the longer the performance time of the project will be. A fair risk allocation is essential for a successful and economical project that is completed in a timely manner. Unfair risk allocation results in risks being distributed among members of the construction team, creating disharmony and adversarial relationships among those very team members who are needed to resolve the problems at hand.

As noted in the CMAA's *Capstone: The History of Construction Management Practice and Procedures* (2003):

> *Following the timely identification and assessment of risks, a rational approach to risk allocation can proceed based upon the following general principles*:
>
> - Risk should be assigned to the party who can best control it.
> - Risk should be assigned to the party who can bear the risk at the lowest cost.
> - Risk should be assigned to the Owner when no other party can control the risk or bear the loss.
> - Assumption of risk by the other parties to the construction process results in increases in cost (visible or hidden) to the Owner.

The risk management plan is the means by which the management team can identify all risks and determine how to deal with those risks. It provides much better protection through a fair and objective allocation of risk and produces a clear understanding of the risk objectives by the entire project team.

In some contracts, owners may try to shift some risks to the contractor as part of what they perceive as negotiation. A contractor's profit is usually proportional to the risk taken by the contractor. It is important for any owner to understand that there is always a price for shifting the risk, whether the risk is declared or hidden. Perhaps, in some instances, if the owner knew the real cost of shifting certain risks, the owner would have preferred not to shift them. An example of shifting of risk is when someone is buying a new car or home. A standard warranty usually comes with every new vehicle and covers the manufacturer's defects up to a certain time period (e.g., 36 months) or mileage (e.g., 36,000 miles), whichever comes first. Of course, the salesperson will try to sell the buyer (owner) an "extended warranty" policy that extends most of the original warranty terms in time and mileage and perhaps adds a few attractive items. A buyer who considers himself or herself a good negotiator may manage to obtain this extended warranty policy at "no extra cost." This is a myth! In most cases, the buyer would have received a price discount on the vehicle, roughly equivalent to the dealer's cost on the extended warranty policy, in lieu of the policy itself.

## SCHEDULE RISK MANAGEMENT STEPS

The *Project Management Body of Knowledge* includes a chapter dedicated to project risk management (PMI, 2013). The chapter deals with all aspects of project risks and serves as the basis for schedule risk management. PMI suggests that project risk management include the following:

- Planning, defined as "the process of determining which risks may affect the project and documenting their characteristics"
- Identifying risks, defined as "the process of determining which risks may affect the project and documenting their characteristics"
- Performing qualitative risk analysis, defined as "the process of prioritizing risks for further analysis or action by assessing and combining their probability of occurrence and impact"
- Performing quantitative risk analysis, defined as "the process of numerically analyzing the effect of identified risks on overall project objectives"
- Planning risk responses, defined as "the process of developing options and actions to enhance opportunities and to reduce threats to project objectives"
- Controlling risk, defined as "the process of implementing risk response plans, tracking identified risks, monitoring residual risks, identifying new risks, and evaluating risk process effectiveness throughout the project." (PMI, 2013, chap. 11, p. 309)

Therefore, we can say that schedule risk management for construction includes the following processes:

1. Risk management planning
2. Identification of schedule risks
3. Performing qualitative analysis of the identified risks and establishing priorities
4. Performing quantitative analysis of the qualified risks
5. Responding to and addressing risks by avoiding, shifting, preventing, or accepting risks, and incorporating remaining risks into the schedule and providing mitigation plans where appropriate
6. Monitoring and updating the risk management plan during update cycles, including evaluating existing risks as well as starting the identification cycle for new risks

### 1. Risk Management Planning

Risk management starts with developing a risk management plan. The plan should provide direction to the project management team regarding the use of risk management,

both in the development of the baseline schedule and in creating the schedule updates. This should include determining how the risk management will be carried out as well as developing a master risk register that would serve to facilitate risk identification. The risk management plan development will serve to encourage the project management team to recognize that managing risk is a formal procedure, with a regimented process that should be used as the approach to a standardized plan. This risk management process should be incorporated into the procedures for design and development of the baseline schedule as well as the procedures for each schedule update.

It is important for any company or organization to have a level of risk management incorporated into its work culture. A good way to initiate the use of risk management is through a separate brainstorming session that is designed to develop the master risk register. Development of this master risk register will improve the efficiency of risk identification and should also include a storage place for capturing historical information and lessons learned from the experience of all of the company's project teams.

The organization of the master risk register is important, since it will help categorize and isolate historical risks that have been encountered on previous projects, many of which might still be potential risks for the next project. The development of this master risk register could simply include capturing categories, leading to the development of a more formal structure, such as a risk breakdown structure (RBS), as recommended by PMI. As noted in the *Project Management Body of Knowledge*, "the RBS is a hierarchically organized depiction of the identified project risks arranged by risk category and subcategory that identifies the various areas and causes of potential risks" (PMI, 2013). The RBS example shows the first level of the structure containing the categories "technical," "external," "organizational," and "project management," with each category subdivided into subcategories, such as technology, subcontractors, resources, and communication. Categories might be arranged by project type, even to the point of maintaining separate master risk registers for each project type (e.g., transportation projects and facility projects), which helps maintain relevance in the register. Some typical examples of useful categories might include plans and specifications, quality control, contractors and subcontractors, owner influences, unforeseen conditions, weather, cost and schedule constraints, change management, claims and disputes, project management, safety, political and cultural risks.

Subcategories such as whether a constructability review was performed are particularly important. If it was performed, the plans probably provide much better direction for construction and will result in fewer requests for information that could turn into change orders. The reputation of the designer has an impact on the quality of the drawings, which will affect change orders as well. Physical quality control issues, such as the distance from the nearest concrete batch plant to the project, are important to review for possible risk issues. The author was involved in a large bridge project that was constructed in a remote location with a local batch plant that did not provide the capacity to supply the project. This raised the risk of performance in high concrete placement periods, such as the counterweight fill for the bascule equipment, and as a result of the risk management effort, the project management team was able to look into setting up a batch plant on-site. Limited suppliers for a piece of highly technical

equipment will raise the procurement risk. This makes new technology or specialized technology a higher risk for the project. Even techniques that are common in some parts of the country (or the world) may not be common at the project location or for the project CM or contractor. A wharf constructed in Virginia was designed with roller-compacted concrete, a technique that had only been performed on the West Coast, and the first concrete placement was a disaster. The contractor suffered some inefficiency from a learning curve because of a lack of experience, but fortunately this was identified before the schedule was approved.

Subcategories are used to collect and organize risk factors, such as the stage of completion of the contract documents, the age of subsurface information, the availability of as-built drawings, the water table, the contract type and delivery method, the experience of the project management team and subcontractors, the quality of the schedule, the availability of skilled labor, and many others. In the brainstorming session, the participants, preferably involving all of the project management team members, should list every problem that they have experienced and then attempt to categorize each one. It is useful to identify how and when the problem was solved and how the risk was actually handled at the time.

#### 2. Identifying Schedule Risks

The next step in risk management is to identify risks for the project at hand. Conducting and facilitating a risk workshop is a good way to start the next step in the process. With a good master risk register in hand, and an experienced and knowledgeable facilitator, a short meeting with the specific project management team and other important stakeholders can prove to be efficient and revealing. The discussion should be broken down into the general types of risk discussed earlier in the chapter: general duration uncertainty, specific risk events, and network logic risks.

#### 3. Performing Qualitative Analysis

Once the specific risk events are identified and recorded in the master risk register, the next step in risk management is to analyze the risks qualitatively. This process involves making judgments about the likelihood of occurrence for each risk, as well as prioritizing the risks based on a combination of their likelihood of occurring and the severity of the consequences. Qualitative analysis of risks also includes the determination of the range of durations for the three-point duration estimates that are used in a quantitative probabilistic Monte Carlo analysis.

In deciding on the three-point duration estimates, consider that the pessimistic estimate should provide for the longest duration that is realistically possible, whereas the optimistic estimate should provide for the shortest time that can realistically be imagined for that activity. The most likely estimate of duration is the duration that is most likely to occur, taking into account all known factors of project conditions, resources, and difficulty of performance. These duration ranges will be used in the Monte Carlo analysis, used for duration uncertainties in order to produce a

distribution of project durations with the probability of success, as well as other useful metrics.

The qualitative descriptions for risk generally fall into five categories that range from high to low likelihood: remote, unlikely, likely, highly likely, near certainty.

- *Remote* indicates that it is reasonable to assume that the risk will not happen.
- *Unlikely* indicates a small likelihood that the risk will happen but that a risk is possible, particularly over the lifetime of the project.
- *Likely* carries the expectation that the project probably will see the risk occur at some time during the project.
- *Highly likely* indicates that the risk will occur at least one time, so the priority for this qualitative judgment should be high.
- *Near certainty* indicates that planning should include the expectation that it will occur more than once during the project.

At the beginning of the qualitative analysis portion of the risk workshop, the facilitator should explain the qualitative terms chosen for the program and ensure that the participants have a common understanding of the range and judgments. This will take some discussion to ensure that the stakeholders feel comfortable with providing a description of their qualitative assessment of the risk, whether it is a near certainty or unlikely. The facilitator should remind the participants that this is historically based upon lessons learned. If no one in the risk workshop, for example, has ever run into a specific risk, it should carry a remote likelihood of occurrence. Conversely, a problem that has been witnessed by all participants on almost all projects should be described as a near certainty of showing up on the project.

In conjunction with the likelihood of occurrence is the issue of consequence. This is every bit as important as the likelihood that a risk will happen. The consequences are the ramifications that occur from the effects of the risk if (or when) it happens. So, identifying the risk and the likelihood that the risk will occur does not tell the entire story and is not sufficient for analysis. Qualitative assessment of the consequences of rsisks is an attempt to understand how the risks will affect the project from all aspects, that is, from direct impacts to secondary disruption and inefficiencies.

The descriptions of consequence include the range of impacts, from no impact to disaster: negligible, acceptable, marginal, critical, and catastrophic.

- *Negligible consequence* indicates that there will be minimal or no impact on the schedule.
- *Acceptable consequence* indicates that there will be some slippage of contractual milestones but that there will be float available to recover the overall schedule.
- *Marginal consequence* indicates that the risk will cause some critical path items to be impacted and will result in minor delays that will require recovery efforts.
- *Critical consequence* indicates that there will be major and potentially lengthy delays to a single critical path item.

- *Catastrophic consequence* indicates that there will be multiple delays to critical path items or multiple critical paths, which will result in lengthy delays to the project.

Once these initial qualitative assessments are made, they can be used to determine priorities and consequences during the qualitative analysis stage of risk management. A risk that has a high likelihood of occurring with a serious consequence to the project's success should be considered the highest priority of any risk, just as those with low likelihood and minor consequences are low-priority risks. The output from the qualitative analysis process should be a list of prioritized risks, ordered from the highest to the lowest priority, as well as three-point estimates of durations for activities if the quantitative risk analysis will be probabilistic using Monte Carlo simulation.

One item that bears discussion is a concern about bias in the risk identification process. There are ways that participants in the risk workshop may influence the input from other participants, from group think to confirmation bias. It is important that each participant in the workshop is allowed and encouraged to submit his or her own ideas and assessments without influence from others. One way to minimize this concern is through the use of interviews where the facilitator meets individually with the participants so there is no outside influence on the discussion. See David Hulett's book, "*Practical Schedule Risk Analysis*" (2009), for more information.

#### 4. Performing Quantitative Analysis

The next step after completing the qualitative assessment is to perform a quantitative analysis of the risks. Qualitative descriptions, which can be used to identify the likelihood and consequences of risk, are then aligned with quantitative probabilities in a process that is often called *probability mapping*. The qualitative descriptions are used to make it easier to evaluate risks, and once they are completed, probability mapping converts those descriptions into values that can be used in the software risk calculations. A common probability mapping might correlate the following ranges of quantitative probabilities with these qualitative descriptions: remote, less than or equal to 20%; unlikely, 21% to 40%; likely, 41% to 60%; highly likely, 61% to 80%; near certainty, greater than 80%. During the probability mapping and discussion about each risk, the estimated location in the probability range can be determined and recorded. The output from the quantitative analysis is the prioritized risk register with assigned rankings, sorted by the combination of the probability and the consequence. This enables the start of the next step, responding to the risks, or if using a probabilistic quantitative analysis, factoring the risks into the Monte Carlo or what-if scenario analyses.

#### 5. Responding to and Addressing Risks

Once the risks are listed and analyzed, the next step is to address the risks by various means. These include avoiding, shifting, or preventing all possible risks, and accepting remaining unresolved risks and incorporating them into the schedule, as well as

documenting the decisions that are made. The task of documenting the decisions that are made should include preparing a risk mitigation plan for those unresolved risks and then acting on that plan. The risk mitigation plan might include just monitoring unresolved risks to ensure that they don't become a driver of productivity or delay. The risk mitigation plan might include adding time contingencies to the activities, representing a specific risk on a certain scope of work, like the craft activities mentioned earlier. This risk mitigation plan should include identification of the progress stages that are necessary to investigate new risks in case it is determined unnecessary to do so at each schedule update.

Contractors will often add a cost contingency to cover such risks as the likelihood that they will be unable to complete the project by the contractual completion date. This could include making a judgment about the difference between the contractual completion date and the scheduled completion date, and adding the costs of paying liquidated damages for that difference or accelerating the schedule. Such a risk might encourage the contractor to withdraw from bidding or contracting on a project because of the risk in order to pursue lower-risk projects.

After the risk mitigation plan and resolved risks have been incorporated into the schedule, the risk assessment of the baseline schedule is complete, documentation of the process has been recorded, and the final product is a risk-adjusted schedule. This product is the result of a good plan, with decisions made at every step along the way based on appropriate assumptions and accurate assessment of the risks to the project. This product is not a black-box risk management approach, where the schedule is dumped into proprietary software for risk adjustments, based on unknown assumptions and decisions. A good risk management process should be documented and be able to be duplicated by a reviewer.

#### 6. Monitoring and Updating the Risk Management Plan

With the first schedule update, the next step comes into play: monitoring and updating the risk management plan during updates. This step also includes evaluating existing unresolved risks with each update, as well as starting the identification cycle for new risks again. This new cycle comprises the same steps that were performed for the baseline schedule. New risks are identified qualitatively and then are quantitatively analyzed, prioritized, and responded to or resolved. New risks that cannot be resolved need to be added to the risk mitigation plan in order to determine a plan of action and incorporate them into the schedule. This cycle continues until the completion of the project or the determination that all risks have been actualized or have disappeared.

Some scheduling software programs include ways to monitor and control risk, and offer the ability to perform some level of analysis. An example is Primavera Project Management, which has a directory button that displays risks and allows some level of monitoring of those risks. This type of schedule software package with standardized components can help with the last step in a risk management plan: monitoring and control risks during the schedule update cycle.

## EXPECTED VALUE

Statisticians combine the likelihoods of different outcomes of an event with their corresponding potential consequences in what is known as the *expected value*:

$$E(X) = \sum_i x_i \cdot p(x_i)$$

where

$E(X)$ = the "expected value" of an event, $X$, such as an accident, hurricane, or shop drawing rejection
$i$ = the domain of all possible outcomes, such as catastrophic, severe, significant, mild, light, negligible
$p(x_i)$ = the probability of occurrence of outcome $i$
$x_i$ = the value of consequence of outcome $i$

For example, for a hurricane that may strike the area where a project is located, the following likelihoods and outcomes are estimated:

| Outcome | Likelihood | Impact on Schedule |
|---|---|---|
| Negligible | 20% | No delay |
| Mild | 30% | 5-day delay |
| Significant | 25% | 12-day delay |
| Major | 20% | 20-day delay |
| Catastrophic | 5% | 50-day delay |

The expected value of the hurricane event is

$$E = 0.20 \cdot 0 + 0.30 \cdot 5 + 0.25 \cdot 12 + 0.20 \cdot 20 + 0.05 \cdot 50 = 11 \text{ days}$$

It is important to note that the expected value is a hypothetical, not real, value. It is adjusted by the likelihood of its occurrence. However, the party assuming the risk must account for the possibility of all outcomes and whether or not he can take that risk. In the preceding example, there is a likelihood, albeit small, that a catastrophic hurricane will cause a 50-day delay in the completion of the project. The contractor and owner must bear in mind that such an outcome may happen.

In a different example, a 55-year-old woman is contemplating investing her entire savings in an investment venture with several possible outcomes:

| Outcome | Likelihood |
|---|---|
| Double her money | 20% |
| Make a 50% profit | 30% |
| Break even | 30% |
| Lose her money | 20% |

Assuming the person's capital is $100,000, the expected value is

$$E = -100,000 + 0.20 \cdot 200,000 + 0.30 \cdot 150,000 + 0.30 \cdot 100,000 + 0.20 \cdot 0$$
$$= +15,000.$$

or[6]

$$E = 0.20 \cdot 100,000 + 0.30 \cdot 50,000 + 0.30 \cdot 0 + 0.20 \cdot (-100,000) = +15,000$$

Even though the investment has a positive (attractive) value overall, the investor must bear in mind that there is a 20% chance that her entire savings will be lost. In such case, the investor may not be willing to take such risk.

The contractor, on the other side, should not overreact, perhaps by taking into consideration the event outcome or consequence only without considering the likelihood. This may lead to a situation in which the risk mitigation costs more than the expected value of the event itself.

Companies or investors who diversify their investments or projects generally have a lower risk of suffering a catastrophic loss at the level of the corporation or organization. If the probability of a catastrophic loss (or adverse condition) for each project is low (e.g., 20%), the probability of catastrophic loss at $n$ projects simultaneously is $n \cdot 20\%$ (2% if 10 projects). This is true only if the events in the different projects are independent of each other.

## APPLICATION IN SCHEDULING

Historically, schedule risk management has been reserved mostly for large complex international projects with severe risk events, such as long-lead shipping components, but the scheduling industry has started to recognize that the use of strictly deterministic schedule development has some drawbacks. As noted earlier, risk has been considered for years in the cost-estimating side of project controls, through processes ranging from Monte Carlo analysis to going with a "gut feeling" estimation of contingencies. Few estimators would provide a project cost estimate that did not account for escalation and uncertainties in the estimate; however, schedulers are just now starting to take the same approach with time risk.

Much of the benefit of a schedule risk management program is a result of the risk workshop. Once the project management team has participated in a formal risk workshop, has discussed the project's problems, has thought through the likelihood of encountering those same problems, and has worked out risk allocations, the team

[6] The two equations are equivalent: the first one considers all payments, including the initial investment, which comes in as a negative value. All other payments (profit/loss) are adjusted by the probability. The second equation considers only profit/loss after the initial investment.

will see the benefits of schedule risk management. If the project management team embarks on a second project that is designed by the same architect and engineers, and the first project generated a high volume of requests for information in order to build the project, that team will think twice about how to manage the new project. If the team has participated in a project that had a good constructability review performed and witnessed a small volume of requests for information, then they will recognize the lowered risk of performance because of good quality control of the documents.

The discussion about the three-point duration estimates is useful, since it will enable the project management team to evaluate duration estimates, rather than casually providing the durations or calculating durations strictly from third-party references that may or may not be accurate for a specific project location or condition. This is an important phase of planning: the development of realistic durations and logic relationships driven by a statistical approach to common problems that are historically known to be present on projects.

Risk analysis emphasizes that delays are often caused by near-critical path activities that slip. The author has been involved in many dispute resolution cases in which the schedule analysis exposes a delay that is caused by what is referred to as a *mid-period critical path shift,* meaning that the critical path at the beginning of the period is not the same as the critical path at the end of the period. Often participants in a dispute look at the critical path at the beginning of the period, assess the changes to that path, and never look at other paths that may overtake the current critical path.

With good risk management, parallel critical paths are examined statistically, providing results that are typically realistic across many projects. While individual projects may and can differ, especially because of project management decisions and responses to threats during construction, in the larger project experience, the statistics provide a level of realism for planning and monitoring.

## EXAMPLES OF RISK ADJUSTMENT

Some examples of risk-adjusted schedules include the development of a 3,200-activity baseline schedule for a firing range for a state prison system. This project was a design-bid-build municipal project, and, as such, the project was awarded on a low-bid basis. The contractor for the project used the pricing from an earthwork subcontractor with historical records showing low productivity in excavation. During development of the schedule, while brainstorming specific risks for the master risk register, this risk was identified. The risk was incorporated into the schedule by increasing durations for all work to be done by this subcontractor. During routine updates, the durations of this subcontractor's activities were reviewed in order to examine performance, in case the risk was still not resolved.

Another example of a risk analysis involved a new port project that needed a high volume of sand fill, with multiple ways to supply the sand. After determination of the preferred method of sand supply, a resource-driven analysis schedule was developed and resource loaded. This resource-loaded schedule provided what-if scenario schedules by changing the resources and allowing them to drive the completion date. After

a number of runs with different resources, the best combination of resource quantity and lead time was used to select the method of supply at the least risk to delivery needs.

Another project in which the author provided risk analysis and participated in the schedule review was an airport construction project that required a separate project to build a people-mover facility on the roof of the airport. This people mover was designed to run passenger vehicles from the airport to a remote station that provided central access to a number of other modes of transportation: buses, rental and private car parking, and taxis. During the risk workshop, the construction of this station was identified as under the control of the state Department of Transportation (DOT). The qualitative analysis showed that the timing of the station's completion date was unlikely and the consequence was catastrophic, with the combination impact forcing this risk to the top of the priority list. During the prescheduling session with the contractor, the master risk register was produced and this high-priority risk was discussed. All agreed that steps should be taken to prevent the risk materializing by good communication with the DOT and the contractor, and this was done by holding joint periodic meetings between the project management personnel of both projects. The risk response also required some level of incorporation of the risk into the schedule. The contractor did this very well, ensuring that the sequencing was done so that the start of construction in this station was pushed as late as possible and carried several months of float. The risk workshop and resolution prevented later arguments and potential high risks existing in the baseline schedule, and supported completion of the project on time.

## CONCLUSION

There are many other examples, however, the important point is that the use of a risk management program increases the attention given to risks and provides an objective and scientific approach to risk management that allows for better results in predicting a project's completion. The contractor can plan demobilization and cash flow more accurately, and the owner can plan for opening the facility and assumption of maintenance and operations with a greater level of confidence.

Risk management is another tool in the scheduler's tool chest that will pay dividends and promote more accurate and believable predictions of completion, but it is a process that must start early and then continue until the end of the project. With a commitment to risk management, schedulers who are trained in risk assessment, a good risk management program, and involvement of the project management team, any schedule can be developed into a risk-adjusted schedule that has a higher probability of being completed on the predicted completion date.

## CHAPTER 14 EXERCISES

1. Compare the cost risk and time risk in any typical construction project; include similarities, differences, and means of identifying the risks, and responses to each.

2. Talk to a project manager for a local construction project and ask how risk management is being handled. If no formal risk management plan is being used, discuss how the project is protected against typical project risks. Discuss the benefits of formal risk management.
3. Mention five different risks that may have to be considered in a typical infrastructure construction project consisting of bridges and/or roadways.
4. Pick a random project (any type, not necessarily construction) that you are either leading or involved with. Hold a meeting with the project team members (minimum of four people). Hold a brainstorming session and prepare a risk register for your project.
5. In the previous question, pick two to three risks and estimate the cost and time impact in two different scenarios:
   a. These risks were considered at the early stages of the project (i.e., planning), with a response prepared as part of the risk management plan.
   b. These risks were not considered until they were imminent or after the fact.
6. What are the three major types of schedule risks?
7. Mention at least two risks of each type in question 6.
8. In an excavation for a building foundation in a downtown area, there are many risks. Mention five of them and categorize them into the three groups of schedule risks.
9. A contractor in your locale, while working on a road project, submits a claim for extending the completion date due to "adverse weather." His claim is based on the fact that heavy rain prevented work on the project for 13 days during the months of August and September. How do you respond to such a claim? Assume the following: Case I, you are part of the owner's organization; Case II, you are part of the contractor's organization.
10. From past experience, you believe that the chances for approval of a subcontractor's shop drawings are:
    a. 50% from first submission
    b. 30% from second submission
    c. 20% from third submission

    If estimated durations for shop drawing activities are 45 days for first submission, 14 days for first review, 14 days for each resubmission, and 7 days for each review (after the first), what is the duration that you assign for the entire cycle of the above process, using the expected value equation?
11. What is the duration that you assign for the entire cycle in the previous example, based on a "worst-case scenario"? Do you believe that such a duration is realistic? Why or why not?

12. Arrange a meeting with a project manager for a local construction project. Before the meeting, prepare your own list of risks that would have been identified in the risk register if you were the project manager (PM) providing a risk analysis. During the meeting with the PM, request a copy of the risk register. If such a copy is not available, ask the PM for the risks considered at the planning stage for the project and what management's response was.
13. In the previous question, compare your own risk register for the list given to you by the PM. If you have any risks on your own list that do not exist on the PM's list, ask the PM (in a professional manner) about them and whether they were considered.
14. Choose two activities in the project chosen in question 12. Ask the PM about the durations used in the CPM schedule for these two activities. Ask the PM if these durations represent the "most likely" case. If so, ask for the durations for the "optimistic" and "pessimistic" cases for each activity. Do you believe, considering the optimistic and pessimistic durations, that the most likely durations are reasonable? Why or why not? If not, calculate the "expected duration" using the PERT or three-point formula.
15. From the project chosen in question 12, separate your list of risks into those that can be avoided, shifted, prevented, or accepted as unresolved. Explain how the unresolved risks can be incorporated into the schedule with a mitigation plan.
16. From the project chosen in question 12, perform a risk analysis for one of the routine schedule updates and identify any newly discovered risks.

Chapter **15**

# BIM-Based 4D Modeling and Scheduling

## OVERVIEW OF THE BUILDING INFORMATION MODELING (BIM)

### Definition and Benefits of BIM

The vision of National Building Information Modeling Standard (NBIMS) Committee for Building Information Modeling (BIM) is "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its life cycle" (NBIMS, 2007). Associated General Contractors (AGC) of America defines BIM "as is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and to improve the process of delivering the facility" (AGC, 2005). An example of how the building components are represented in BIM systems is given in Figure 15.1.

BIM is about digital representation of the physical and functional characteristics of a facility/building component that incorporates "knowledge" and "information." BIM can be regarded as a novel technology or a new technique based on the automation of the solid structure of the facilities, sequencing, cost estimation, facility management and life-cycle assessment. It is a new form of knowledge and resource sharing that provides a reliable basis for decision making, dependable assessments of probable clashes, problems and conflicts, more successful project deliveries, and enhanced collaborative culture. Figures 15.2 and 15.3, respectively, show how the information about a column and a wall are captured and stored in BIM.

In short, BIM is a visualization, coordination, communication, and design tool that utilizes 3D models to create 4D, 5D, or even nD models. Some nD models of BIM with its major functions are given in Figure 15.4. BIM enables the user to generate visual prototypes and simulations of projects prior to building them, enhance the quality of products and processes, minimize time and cost overruns, accurately estimate project costs, and effectively share project information with all project stakeholders. BIM supports the various phases of a project by designing, utilizing, and

[1] This chapter was written with contributions from Dr. Onur B. Tokdemir and Acelya E. Yildiz.

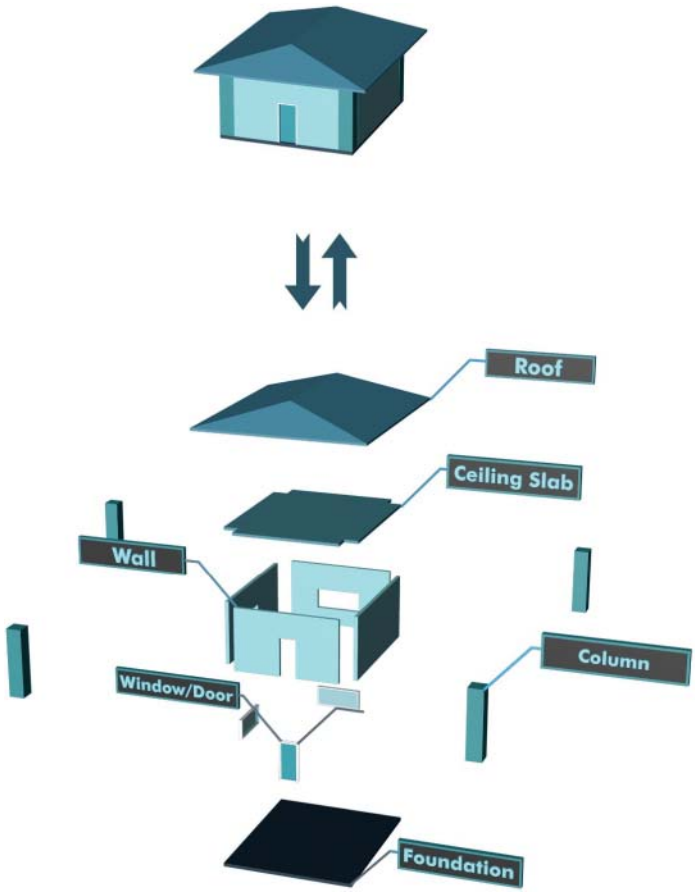



**Figure 15.1 An example of the representation of a building with BIM**

managing building components in the form of intellectual objects. 3D smart models of the projects are created, and all architectural, structural, electrical, and mechanical components of the projects are codified, including information attached to each object. During the codification, all information about the components (i.e., material, labor, equipment codes) are defined in the context of objects and are utilized to extract quantity takeoff and estimate project costs. Thus, with the use of BIM, semantically rich 4D and 5D construction models can be created, and project scheduling and cost estimating can be incorporated into the 3D models of the construction.

### Differences between BIM and CAD

Computer-aided design (CAD) is the use of computer systems in the creation, modification, analysis, documentation, and communication of a design. CAD systems replace manual approaches with automated processes and software-based solutions,

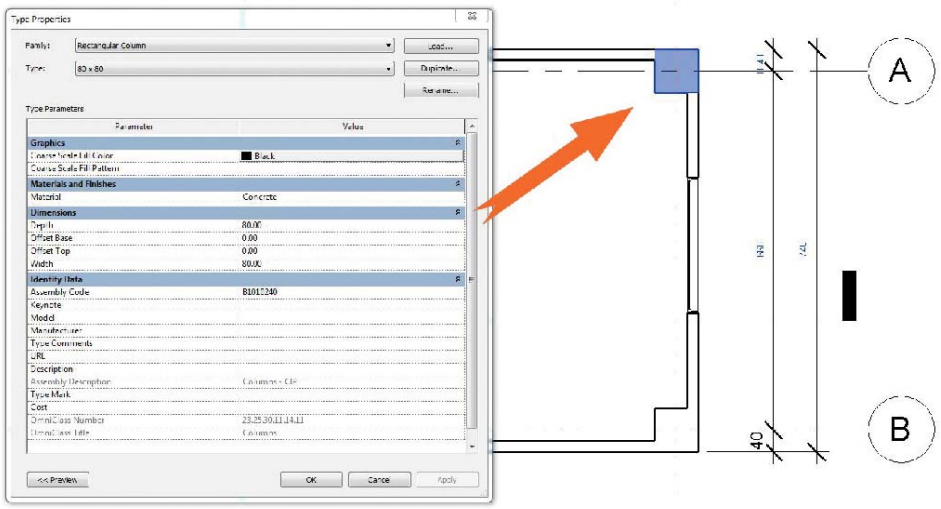



**Figure 15.2 Representation of how information about a building column is stored in a BIM model**

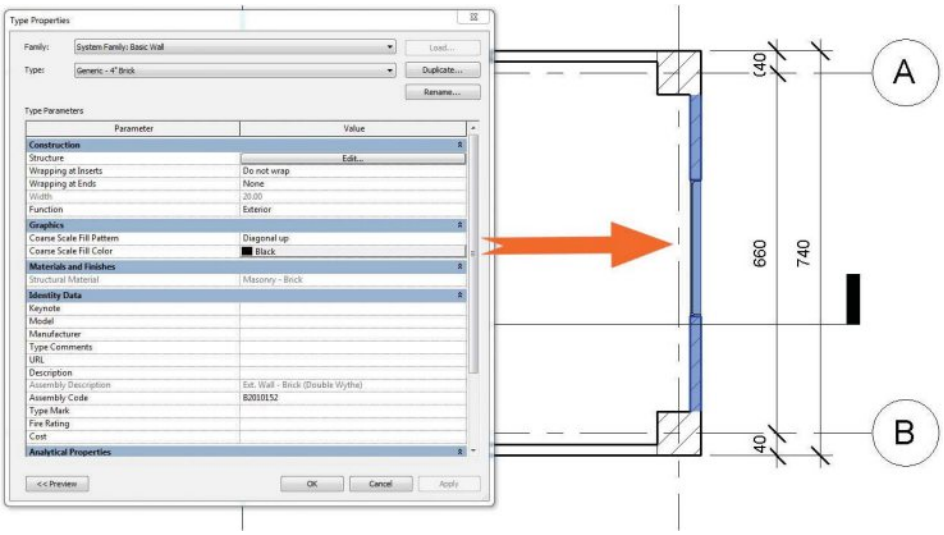



**Figure 15.3 Representation of how information about a building wall is stored in a BIM model**

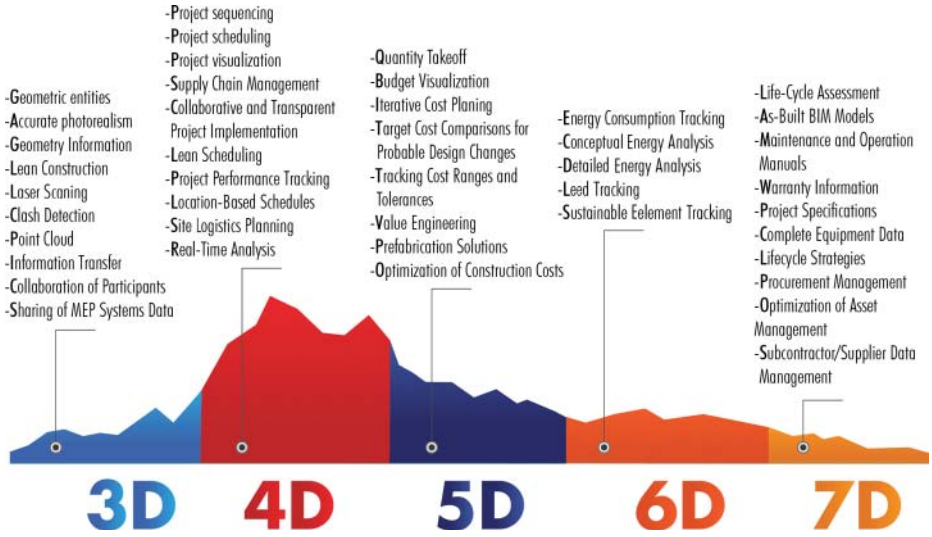



**Figure 15.4 Summary of functions of nD BIM**

with the creation of 2D and 3D soft drawings. 3D CAD drawings can be described as graphical entities that represent physical characteristics of the components in terms of their length, width, and height. These drawings do not incorporate intelligent data parameters about the project, that is, the knowledge about the physical characteristics of the components that makes the major difference between CAD systems and BIM. Although 3D CAD systems provide vast amount of benefits over traditional 2D CAD drawings (i.e., the representation of how a design will perform in practice and the visualization of architectural, structural, mechanical, and electrical drawings in 3D environment), they fail to cover the data information (i.e., material information, supplier information, project life-cycle information) that are assigned to individual component objects. For example, while "an external wall" is just a wall and is described as a three-dimensional object in 3D CAD drawings, "an external wall" in BIM means components such as external brick leaf, internal block leaf, insulation layer, and a protected weatherproof finish. The description of each of these objects allows the estimation of quantity takeoff, activity sequencing, and automatic generation of project schedules. Thus, to work in a BIM environment and create 4D, 5D, and nD models, the "intelligence" of the 3D object-based models should be ensured. In summary, while CAD systems can be regarded as 2D and 3D drawings that are created in a software environment, BIM can be defined in terms of a database of information about a building, a virtual platform for design, construction, maintenance, and construction, and an automated technology for cost estimation and project scheduling.

### Definition and Benefits of 3D Modeling

**Three-dimensional models (3D models)** are digital representations of building components and facilities in terms of spatial dimensions (width, length, and depth) as well

as object information. The incorporation of object information into 3D models adds "smart" characteristics to the building components, which provide information about materials, interconnectivity, the budget code attached to the object, material suppliers, responsible subcontractors, and so on. The physical environment of projects attached with the building characteristics enables project parties to have a better understanding of the architectural, structural, mechanical, and electrical design of the project. Thus, compared with the traditional designs and 2D plans, 3D intelligent models allow the identification of potential conflicts and/or errors, and inconsistencies among different design documents and drawings, and they detect probable project clashes (e.g., HVAC and fire protection clashes). In addition to the visual representation of the project design, 3D models are helpful in processing project data, automating design changes, ensuring collaboration of the project participants, and easy sharing of knowledge and information.

#### Definition and Benefits of 4D Modeling

**4D modeling** is a visualization method that incorporates 3D building model into the project timeline, including the project schedule, resources, quantities, and project phasing. In general, 4D models are defined as 3D models with the addition of time associations. 4D models allow visualization of a sequence of activities in terms of building components and "duration to complete" information that are associated with each component. Thus, they can be regarded as a virtual simulation of the construction process from its beginning to its end, with location, resources, and progress information. 4D models enable project participants to visualize and evaluate how the project will be executed over a predefined project duration. One of the major contributions of the 4D models to the scheduling technology is that they automatically capture the variations between the actual and the planned schedule by simulating its virtual model in case actual site data are captured (i.e., with time-lapsed photographs). Thus, more dependable and reliable assessments can be carried out because of the visual information about which activities are planned to be finished and which activities have actually finished. This can be an invaluable tool in some delay claim cases. The simulation of construction progress, in turn, provides the evaluation of project performance in terms of time and cost.

4D models are widely utilized by contractors, engineers, designers, owners, subcontractors, and suppliers along planning-operation phases of construction projects. When the 4D models are generated and used within the construction value chain and the early involvement of all project participants is ensured, some bottlenecks (such as constructability problems, resource allocation, tower-crane location and selection, etc.) that can delay the success of projects can be avoided. Probable communication and coordination problems that arise due to the highly fragmented nature of the industry can be minimized by sharing project information within a virtual platform, as well as serving as transparency between owners and parties. With the use of 4D models, project information, including architectural, structural, and MEP designs, and site management plans, can be effectively retrieved and shared by diverse participants in

both the design and construction phases. Thus, the probability of having change orders, rework requests, and time and cost overruns during a project is minimized prior to the initiation of the construction. Also, through the generation and utilization of 4D models, project managers and contractors can determine site management facilities (i.e., site layout planning), coordinate subcontractors and suppliers, plan site logistics (i.e., access routing to the construction site), and communicate concerning the completed parts of the projects with the different subcontractors.

#### Steps for Creating 4D Models

The steps for creating the 4D modeling process in BIM are as follows:

- A 3D model of the building should be developed using a design authoring software (such as Autodesk's Revit, Nemetschek's Allplan, etc.) to create the intelligent objects and appropriate groupings of the construction components. Construction components should be created based on hierarchical groupings so that a construction schedule can be easily linked to the 3D model. During the development of the 3D model of the building, the involvement of the contractor is essential, because the contractor can provide rapid and reliable feedback about the sequencing, constructability, and sustainability of the building. The "selection tree" should be developed based on the work breakdown structure (WBS) of the building component and the project schedule.
- A project schedule should be developed using compatible software such as MS Project or Primavera P6, manually keeping track of the project tasks within the Navisworks TimeLiner. The project schedule should be developed based on the consideration of the sequence of activities and the logical relations among them. Refer to the previous chapters for an examination of how to create a project schedule.
- The project schedule and 3D geometry of the building component should be imported to the Navisworks TimeLiner, and the project tasks should be linked to the relevant 3D objects by using "selection tree."
- Once this linkage has been done, a 4D model can be generated that shows a movie of the construction of the building, representing how a building is constructed over time, step by step. The work flow for creating a 4D model of a building component is given in Figure 15.5.

Various BIM tools can be utilized when you are creating a 4D model for a project. The most common commercial BIM tools that have the ability to create 4D models are given in Table 15.1, along with their descriptions. In almost all of them, the way to import the model or a schedule differs, but the concept is the same.

#### Definition and Benefits of 5D Modeling

**5D modeling** is the integration of 3D models of a project with cost and time associations. While 4D models add time- and schedule-related information into the 3D

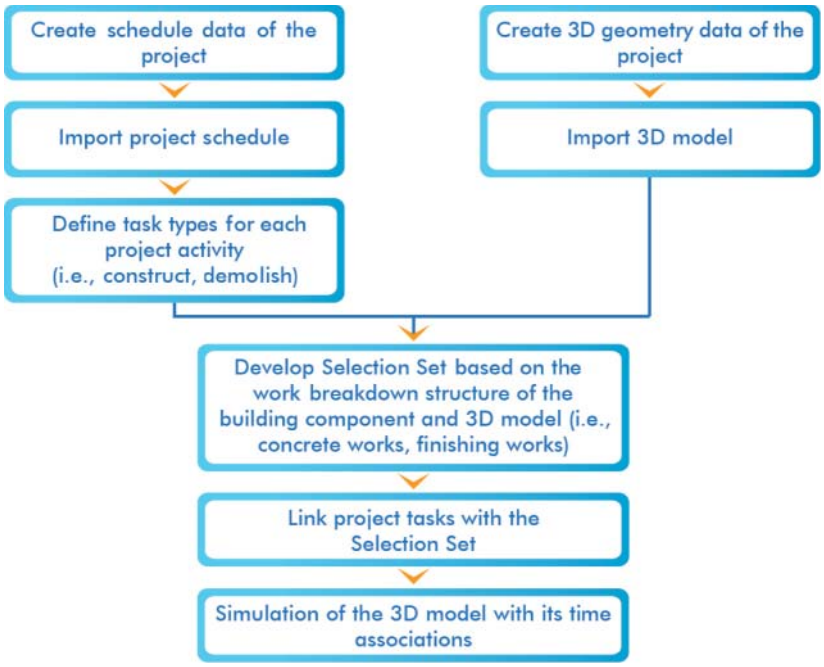



**Figure 15.5 Work flow for creating a 4D model**

model, a 5D model integrates cost information to estimate the final cost of a project. A 5D model estimates the project's cost by utilizing material quantities that are automatically generated from the preconstructed 3D building model. A 5D model uses data stored in the 3D model by retrieving the stored information and incorporating that information into the cost estimation process. A 5D model allows generation of quantity takeoff, estimating of a project's final cost, interactive forecasting of a project's cash flow, comparing of the target and actual costs, and generation of cost-loaded schedules. Also, while a 4D model has the ability to reflect the actual progress of construction works as a project updated-schedule, a 5D model adjusts the cost estimations based on the actual conditions of the project. It enables architects, contractors, and clients to automatically visualize how the cost of the project can change with varying project conditions, that is, with variations in the project's design or reworking of building components. In other words, as the project progresses, any variations in the 3D model can automatically be reflected in the 5D model, and cost estimations can easily be updated.

## CASE STUDY

### Project Information

The project is a nine-story building that consists of nine floors with two apartments on each floor and one basement floor that is used as a parking garage. The building itself

**Table 15.1 Some BIM Tools to Develop 4D Models[a]**

| Company | Product | Product Overview |
|---|---|---|
| Autodesk | Revit Architecture | Each Revit object includes parameters for "phasing" that allow users to assign a "phase" to an object and then use Revit's view properties to view different phases and create 4D snapshots. It is not possible to play back a model, however. Via the API[b], users can link to scheduling applications and exchange data with tools like MS Project to automate 4D entity. |
| Tekla | Tekla Structures | A full-fledged, Gantt chart scheduling interface allows definition of tasks and association of model objects to one or more tasks. The model can be played between dates, and objects can be color coded according to time-dependent attributes. |
| Gehry Technologies | Digital Project | An add-on product, Construction Planning and Coordination, allows users to link 3D components to Primavera or MS Project activities with their associated data and generate 4D simulation analysis. Construction-related objects need to be added (and removed when appropriate) to DP [b]model. Changes to Primavera or MS Project schedule are propagated to linked DP model. |
| Bentley | ProjectWise Navigator V8i | This is a standalone application that provides a series of services for: Importing multiple 2D and 3D design files from many sources (DWG, DGN, DWF[b], etc.) and from Bentley's iModel design system<br>Reviewing 2D drawings and 3D models concurrently<br>Following links between data files and components<br>Reviewing interferences (clashes), and viewing and analyzing schedule simulations |
| Innovaya | Visual Simulation | Links any 3D design data in DWG with either MS Project or Primavera scheduling tasks and shows projects in 4D. Generates simulation of construction process. Synchronizes changes made to either the schedule or 3D objects. Uses color codes to detect potential schedule problems, such as objects assigned to two concurrent activities or not assigned to any activity. |
| Autodesk | Navisworks Simulate | The Simulate module includes all the features of Naviswork's visualization environment and supports the largest number of BIM formats and best overall visualization capabilities. The Simulate module supports automatic and manual linking to imported schedule data from a variety of schedule applications. Manual linking is tedious and not user-friendly, and there are few custom 4D features. |
| Synchro Ltd. | Synchro Professional | This is a powerful, new (since 2007) 4D tool, with the most sophisticated scheduling capabilities of any of the 4D software. The tool requires a deeper knowledge of scheduling and project management than the other tools to take advantage of its risk and resource analysis features. It includes built-in tools to visualize risk, buffering, and resource utilization, in addition to basic 4D visualization. It accepts building model objects and schedule activities from a variety of sources. |

**Table 15.1 (*Continued*)**

| Company | Product | Product Overview |
|---|---|---|
| Vico Software | Virtual Construction | Visual Construction 5D construction planning system consisting of Constructor, Estimating, Control, and 5D Presenter. The building model is developed in Constructor or imported from another BIM-authoring system, and objects are assigned recipes that define the tasks and resources needed to build or fabricate them. Quantities and costs are calculated in Estimator, schedule activities are defined and planned using life-of-balance (LOB or location-based) techniques in Control, and then the 4D construction simulation is visualized in Presenter. As an alternative to using Control, schedule dates can be imported from Primavera or MS Project. Changes in the scheduling system are automatically reflected in the 4D visualization. |

[a]The table was prepared and reported by Chuck Eastman, Paul Teicholz, Rafael Sacks and Kathleen Liston (2011) in their book, *BIM Handbook, a Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. The original name of the table is "Selected BIM Tools with 4D Capability."
[b]API: Application Program Interface, DP: Digital Project, DWG: Drawing (CAD programs file extension), DGN: Design (CAD programs file extension), DWF: Design Web Format

has two staircases: a main staircase and a fire escape, which has fire exit doors to the rear garden. The elevator of the building has a lift capacity of four persons (weighing approximately 320 kg). Each apartment consists of 140 $m^2$ living space with three bedrooms, one living room, and two bathrooms. Since there is a total of 18 apartments in the building, a covered parking area is constructed on the basement floor with a capacity of 23 vehicles. Water tanks and a bunker are located on the basement floor. Also, a green living space is provided for the residents on top of the parking lot. The general view of the building is given in Figure 15.6.

### Creating and Linking the 3D Model

To build a 4D model, firstly a 3D model of the building should be developed, using a modeling software program, in terms of intelligent objects and appropriate groupings of the construction components. Construction components should be created based on hierarchical groupings so that the construction schedule can be easily linked to the model. Once the 3D model of the project is created using the CAD application, the model should be imported into the Navisworks TimeLiner. 3D models can be imported into the Navisworks TimeLiner in two different ways: importing a 3D model file into a new Navisworks file by using "open" command or by adding or merging a new 3D model geometry into an already existing Navisworks file with "append" and "merge" commands. The major difference between the "append" and "merge" commands is that, once the files are merged using the "merge" command, the models are combined and cannot be updated individually. This could be a problem if the models were updated by different people (e.g., architectural and structural engineers). A snapshot of how to import a 3D model into Navisworks is represented in Figure 15.7.



**Figure 15.6 General view of the building**

### Information about the TimeLiner Tab

TimeLiner is one of the main features of Navisworks and contains a series of tabs regarding task creation, task importing from an external project file, configuring and defining a simulation, and simulation export. The Tasks tab enables the user to define and/or manage project tasks that will form the basis of the project schedule. It lists all scheduling tasks (activities) comprising the project, such as excavation works, upper structure construction works, and finishing works, within the rows of the task table. Task columns are the other major components of the task table that represent the scheduling information for predefined tasks. They contain information about planned and actual start and end dates of tasks, types of tasks, and selection sets that are attached to each task. The general view of the Navisworks TimeLiner is depicted in Figure 15.8.

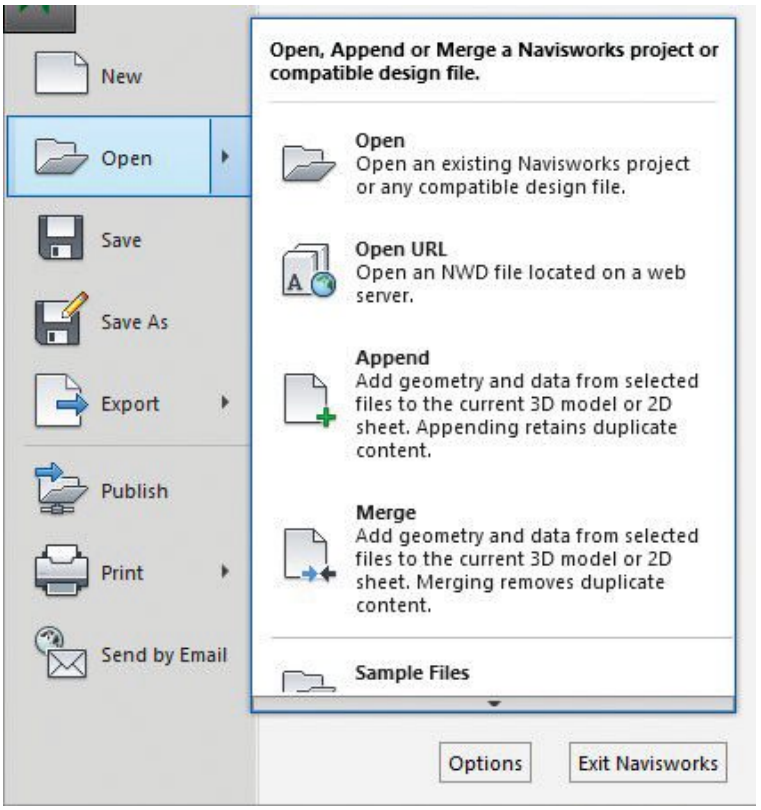



**Figure 15.7 Snapshot of how to import a 3D model into Navisworks**

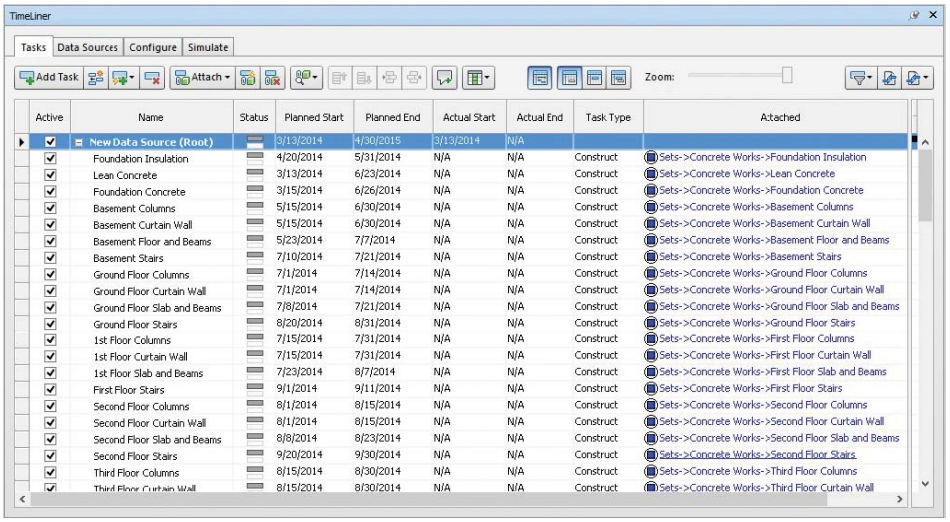



**Figure 15.8 Snapshot of general view of the Navisworks TimeLiner**

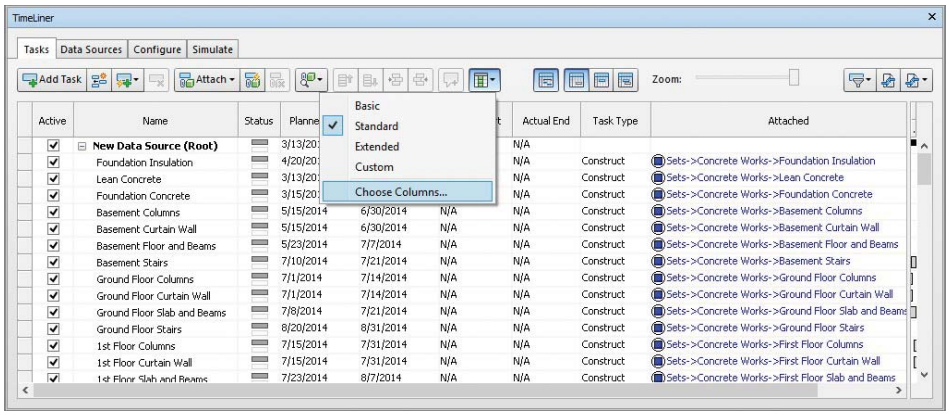



**Figure 15.9 Snapshot of how to define column types**

The tasks columns can be specialized by clicking on the Choose Columns tab, as shown in Figure 15.9. The list of all available column types are given in Figure 15.10. The widely utilized column types are; "Name," "Status," "Planned Start," "Planned End," "Actual Start," "Actual End," "Task Type," and "Total Cost."

The right section of the Tasks tab contains the Gantt chart of the project, which displays colored bars representing the status of the project tasks. Please refer to the previous chapters for an in-depth understanding of Gantt charts.

### Creating and Importing Project Schedules

Schedules can be developed in Navisworks in three alternative ways: by manually creating a project schedule, by adding tasks based on the selection set, or by establishing a link to an external project schedule that was created by scheduling software. In the first method, similar to the scheduling operations undertaken in scheduling software, project tasks are created, task durations are attached, and logical sequences among tasks are identified. In the second method, the "Auto-Add Tasks" command is used to create tasks with the same names that are given in the selection set that have already been defined in the 3D model. Finally, in the third method, an external project schedule can be imported with scheduling software and linked with the 3D model represented in Navisworks. In this case, each task defined in the schedule should be attached to the 3D model components to create a 4D simulation. Schedules can be linked to Navisworks with scheduling software such as Primavera and Microsoft Project or CSV Import. In order to import an external schedule, the Data Sources tab of the TimeLiner should be used.

The Data Sources tab enables the user to import a project schedule with external scheduling software. All data sources imported from a software or application will be listed within the Data Sources tab in a table format, with source and project information. To import a schedule from an external software, click the Data Sources tab from the TimeLiner menu. An external schedule can be imported in the form

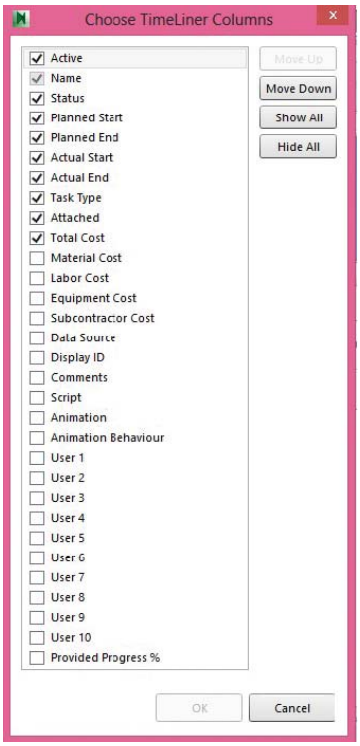



**Figure 15.10 Snapshot of TimeLiner column types**

of CSV Import or from Microsoft Project and Primavera scheduling applications. As the schedule is imported, the source of the data, as well as the system location of the project, are shown in the Data Sources tab. Snapshots of the Data Sources tab of Navisworks TimeLiner and types of external sources available in the TimeLiner are given in Figures 15.11 and 15.12, respectively. Using Microsoft (MS) Project or Oracle Primavera P6 is preferred, because updates to the schedule are kept within the 4D model. If the schedule is manually created, all of the updates must be done by the user.

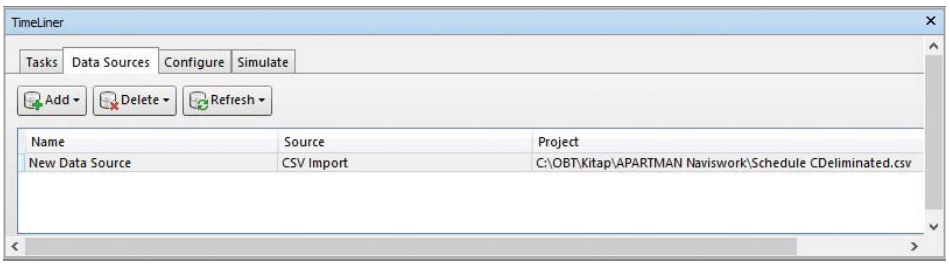



**Figure 15.11 Snapshot of Data Sources tab in Navisworks TimeLiner**

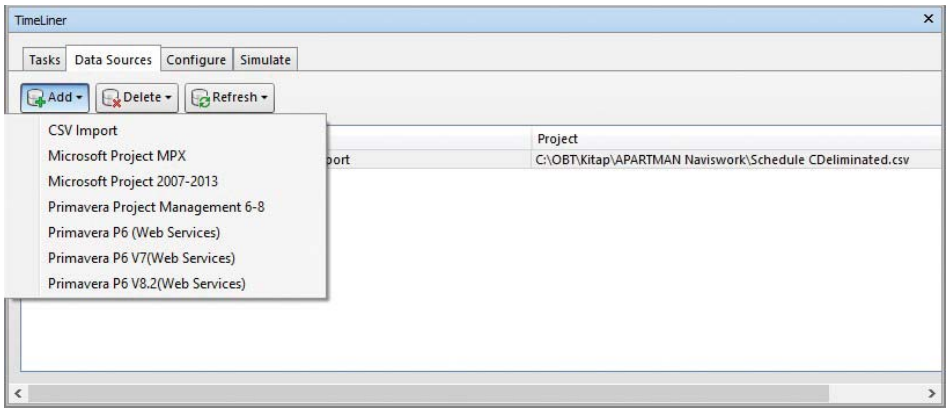



**Figure 15.12 Snapshot of types of external data sources available in Navisworks TimeLiner**

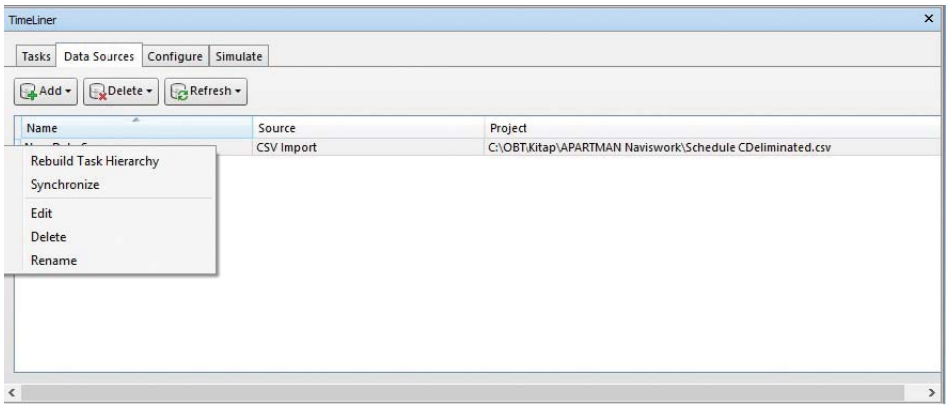



**Figure 15.13 Snapshot of commands in the Data Sources tab**

The added data sources can be managed by right-clicking on the sources listed in the drop-down menu as shown in Figure 15.13. With the use of the "Rebuild Task Hierarchy" command, the activities that have been assigned in the project schedule within the scheduling software (Primavera P6, Microsoft Project, etc.) will be added as a task list in the Tasks tab of the TimeLiner. If any updates or changes are made in the schedule, the "Synchronize" command should be utilized. By clicking on the "Synchronize" command, any updates and changes will be reflected in the tasks that have been listed in the TimeLiner previously.

### Defining Task Types

Each task that is defined in the project schedule should be associated with a task types shown in Figure 15.14. The task type provides the information about how the 3D objects defined in the model geometry will be shown at the start and the end of the task as well as during the execution of the tasks in the 4D simulation of the component.

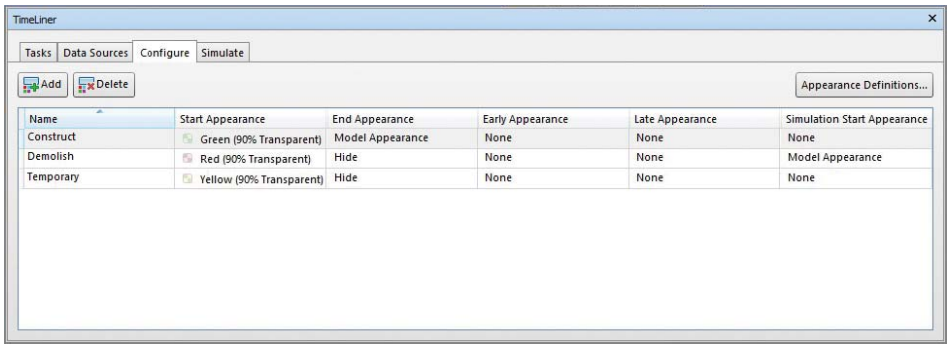



**Figure 15.14 Snapshot of the Configure tab in Navisworks TimeLiner**

The association of each task with a task type shows how 3D objects will be displayed within the 4D simulation, along with their time associations. The available options in the Navisworks TimeLiner for the task type are "Construct," "Demolish," and "Temporary"; however, new task types can be added, or existing types can be renamed. The available options in the Navisworks TimeLiner for visualizing 3D items that are linked with predefined task types are none, hide, and model appearance. "Construct" is mainly used for tasks whose attached 3D objects need to be constructed. The default start appearance of "Construct" is green (90% transparent), and the end appearance is "model appearance." "Demolish" tasks are the ones whose attached 3D objects will be demolished during or after the construction. The default start appearance of "Demolish" is red (90% transparent), and the end appearance is "hide." The final task type, "Temporary," represents the associated objects when the relevant tasks are solely temporary items within the execution of the project. The default start appearance of "Temporary" is yellow (90% transparent), and the end appearance is "hide." Also, new task types can be created by selecting "Add" and entering a new name for the task type, as shown in Figure 15.15.

The "Appearance Definitions" command, as shown in Figure 15.14, enables the selection of predefined or custom-created appearances that can be used to display

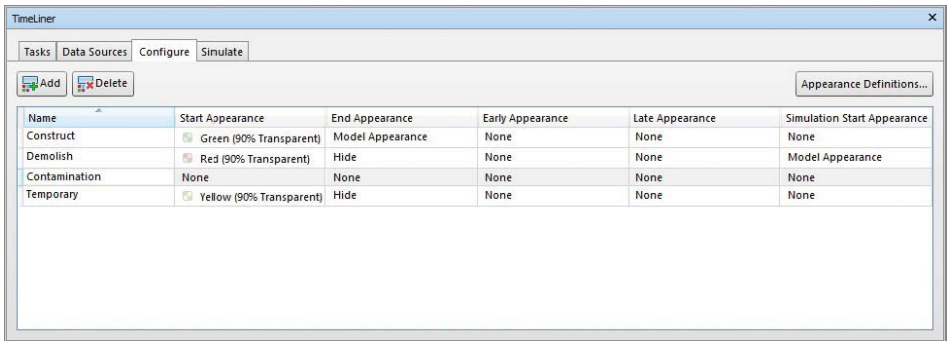



**Figure 15.15 Snapshot of adding a new task type**

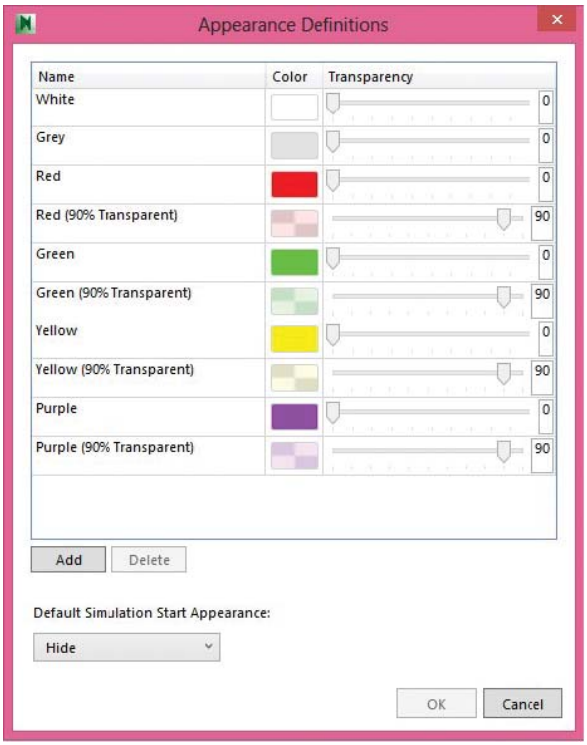



**Figure 15.16 Snapshot of "Appearance Definitions"**

diverse tasks types. For example, diverse construction items, tasks that will be executed by different project participants, or different task types (i.e., construction, demolish) can be displayed with different colors and assigning different appearances to the task types. The available options defined in the "Appearance Definitions" command are given in Figure 15.16. The shortcut for defining appearance of the tasks is also available by clicking the appearance field of the each task type and selecting an appearance theme from the drop-down icons. The shortcut for "Appearance Definitions" is depicted in Figure 15.17.

### Creating Selection Sets

After the 3D geometry of the model and the project schedule are imported into the Navisworks TimeLiner, a "Selection Set" folder structure that lists the work breakdown structure of the "tasks" representing the 3D model should be created. The "Selection Set" folder can be created in two ways: by utilizing the "Selection Tree" or by interactively selecting objects in Scene View. The Autodesk Company defines Selection Tree as "a dockable window, which displays a variety of hierarchical views of the structure of the model, as defined by the CAD application in which the model was created" (The Autodesk Company, 2011, p. 338). There are four available options

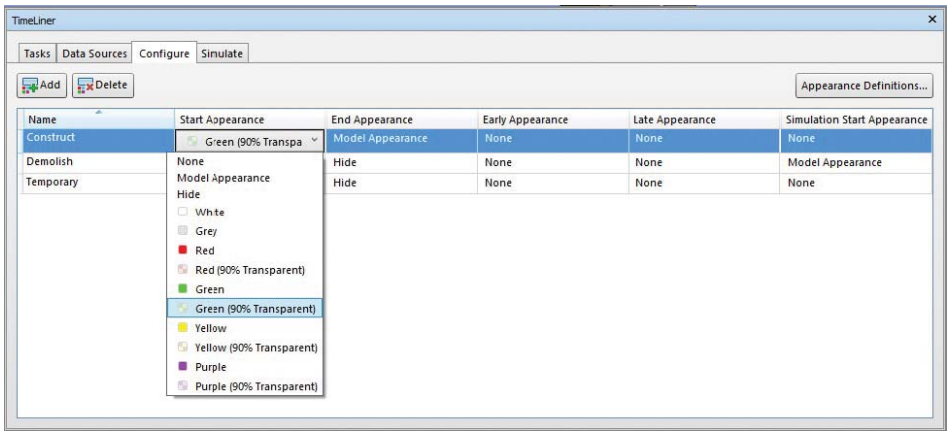



**Figure 15.17 Snapshot of the shortcut for "Appearance Definitions"**

from the drop-down list of "Selection Tree": "Standard," "Compact," "Properties," and "Set". "Standard" displays the default tree hierarchy, "Compact" displays a simplified list given in the "Standard" form, "Properties" is used to display the tree hierarchy where the structure is based on the item's properties, and "Set" displays the hierarchy of selection and search sets. Snapshots of the "Selection Tree" are given in Figures 15.18 and 15.19.

After the "Selection Sets" with 3D geometry information has been created, the defined sets should be linked with the relevant tasks displayed in TimeLiner. If all of the tasks have unique names (no two tasks with the same name) and "Selection Sets" have the same name with their attached tasks, the linking process can be carried out automatically. Also, the "Selection Set" can be linked to the associated tasks by right-clicking a task in the Task tab in the TimeLiner and selecting "Attach Set." The snapshot for how to link "Selection Sets" with the relevant task is depicted in Figure 15.20.

### Creating the 4D Model and Project Animation

Once all of the schedule tasks are linked to the 3D model geometry through the use of "Selection Set," 4D modeling scenarios can be created. 4D model of the building component can be visualized as a dynamic visualization of the component in Navisworks TimeLiner: a movie of the project that displays the construction sequence and also a series of snapshots taken from the movie that represents how the project looks at any point in time.

With the use of "Simulate" tab, the 4D model of the building component can be visualized from the beginning to the end of the project. The date from when the 4D model will be displayed can be managed from the calendar, as shown in Figure 15.21. The simulation can be stopped or paused when needed with the use of relevant buttons (Figure 15.21). The setting of the 4D model animation can be defined by using the "Simulation Settings" command, as shown in Figure 15.22. The "Override Start/End

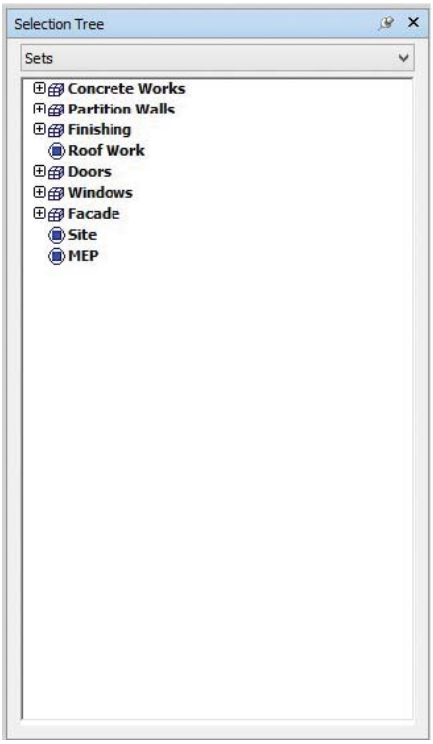



**Figure 15.18 Snapshot of the "Selection Tree"**

Dates" choice enables the user to define the time interval within which the simulation will run. The interval size of the simulation can be defined either as a percentage of the overall simulation or as a number of weeks, days, hours, and so on. Also, the type of simulation can be defined in terms of the planned or actual schedule and will be displayed in the animation. The snapshots of the 4D animation of the building component are shown in Figures 15.23 through 15.29.

### Exporting Snapshots and Animation

In addition to the dynamic visualization of the 4D model described in the previous section, the 4D model also can be visualized as a series of snapshots and a movie showing the construction schedule. The snapshots and/or animation of the model can be exported as an external file by utilizing the "Export Animation" interface of Navisworks. Figure 15.30 shows the "Export Animation" box displayed in the "Simulate" tab of TimeLiner. The animation of the model can also be exported by using the "Animation Export" dialog box given in the File menu. The export settings also can be

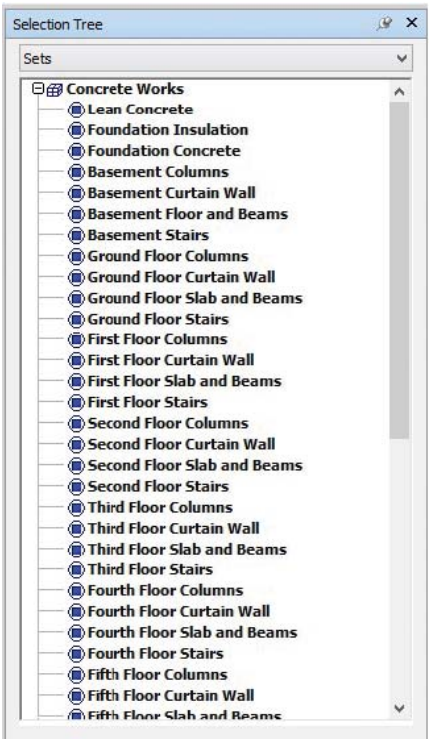



**Figure 15.19 Snapshot of the "Selection Tree" demonstrating details of the concrete works**

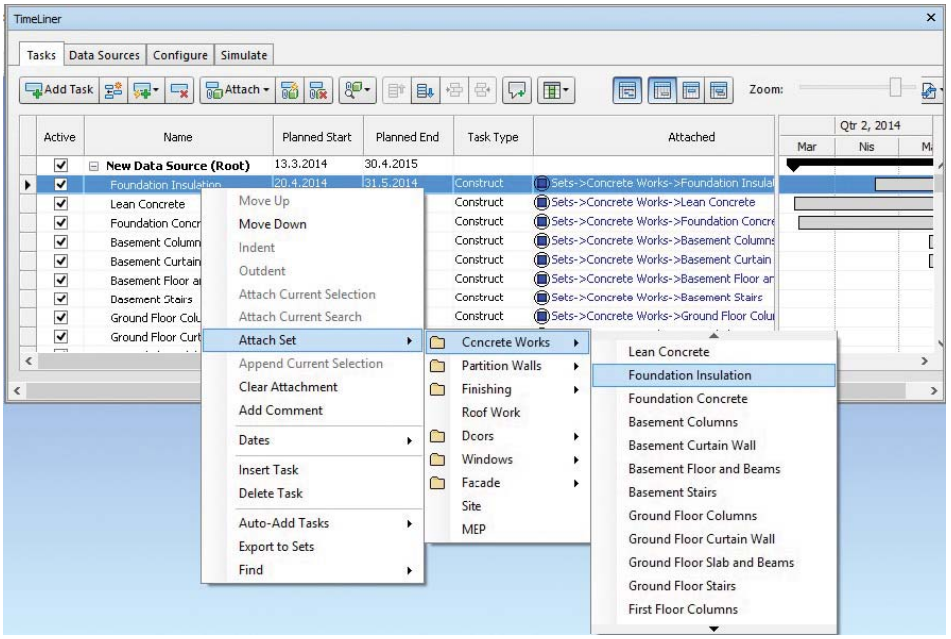



**Figure 15.20 Snapshot of how to link "Selection Sets" and TimeLiner Tasks**

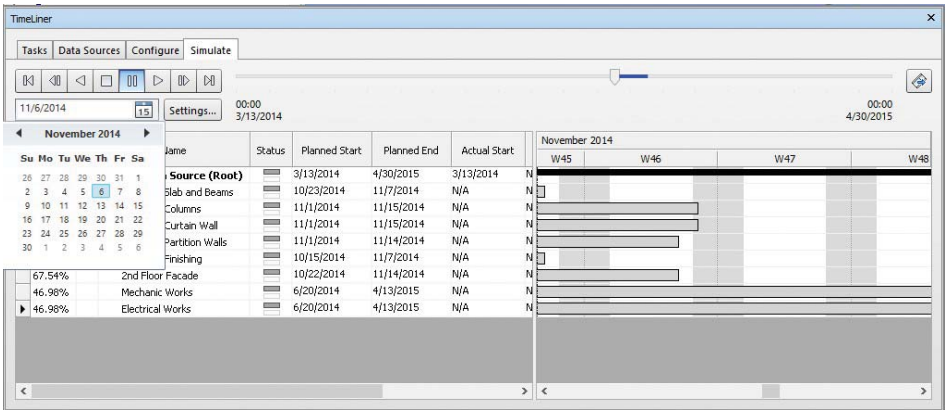



**Figure 15.21 Snapshot of the Simulate tab in TimeLiner**

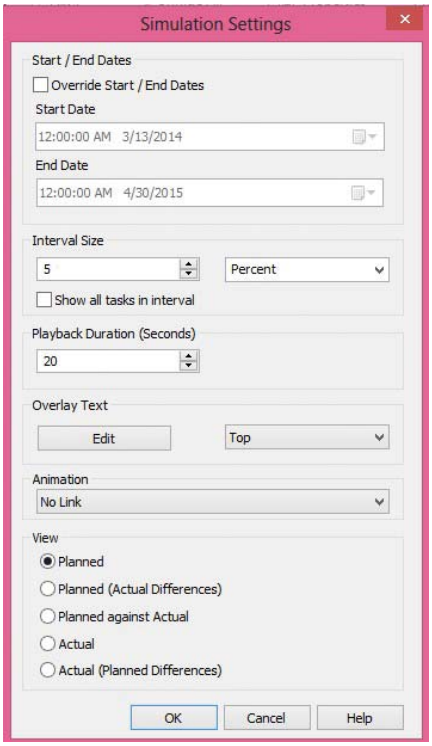



**Figure 15.22 Snapshot of how to define animation settings**

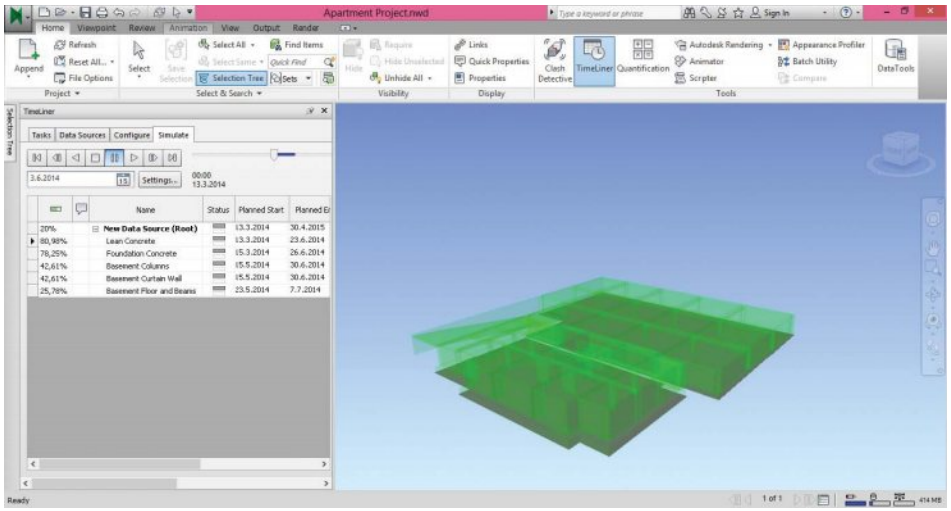



**Figure 15.23 Snapshot of the 4D model of the building, Example 1**

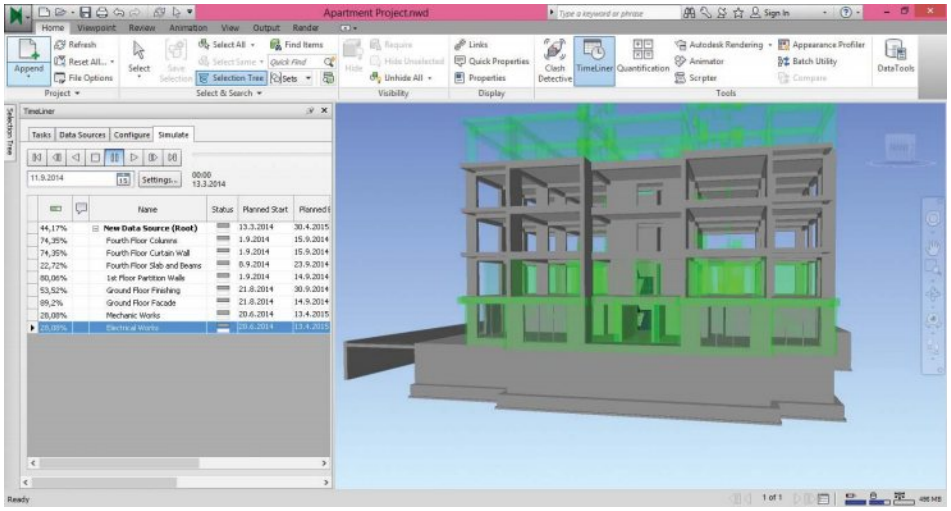



**Figure 15.24 Snapshot of the 4D model of the building, Example 2**

managed with the "Animation Export" interface, as shown in Figure 15.31. The settings such as "Renderer," "Output Format," "Size Type," "Anti-aliasing," and "FPS" should be defined by Navisworks users.

When snapshots are being created, the image formats should be selected in terms of .jpg, .bmp, or .tif formats, and the size of the images should be defined. There are three different size types for the images that will be exported: Explicit, Use Aspect Ratio, and Use View. Explicit is for the custom-selected sizes; that is, users should enter the width and height information for the image. "Use Aspect Ratio"

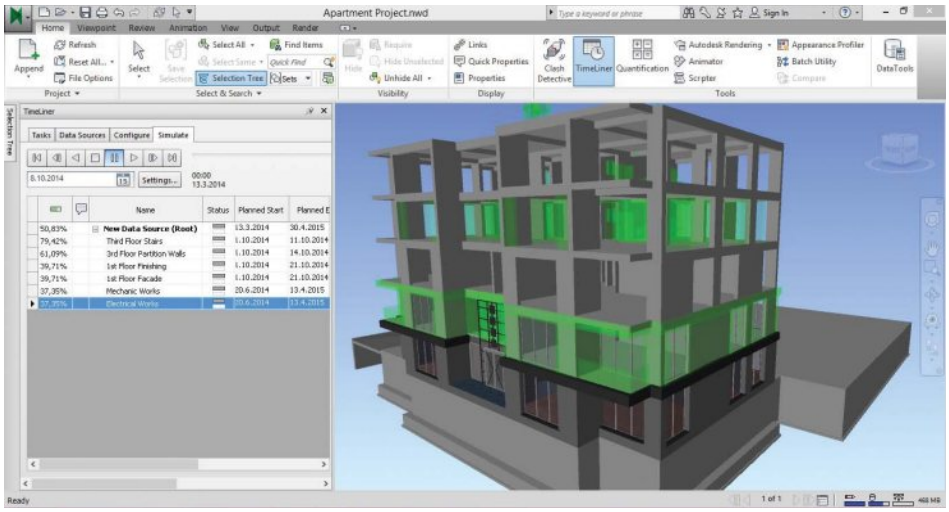



**Figure 15.25 Snapshot of the 4D model of the building, Example 3**

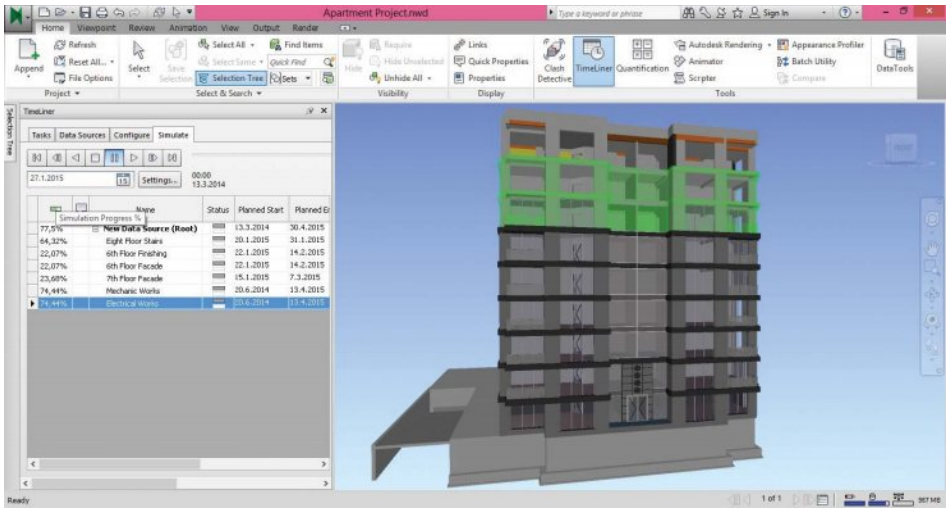



**Figure 15.26 Snapshot of the 4D model of the building, Example 4**

function automatically adjusts the width and length values in terms of a ratio of 2:1 for width:height. The image can also be exported based on the size of the active model in Navisworks by selecting the Use View option.

Navisworks also offers the ability to create and export a 4D AVI movie of the model as an external file. The format of the output should be selected as Windows AVI when creating an external 4D movie file. The size of the animation also should be determined, which will identify the output resolution of the AVI file. The number

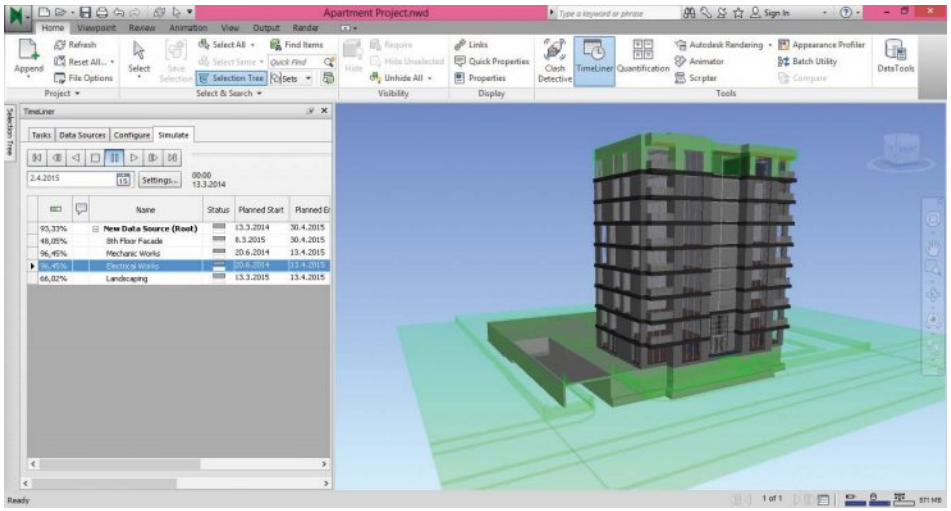



**Figure 15.27 Snapshot of the 4D model of the building, Example 5**

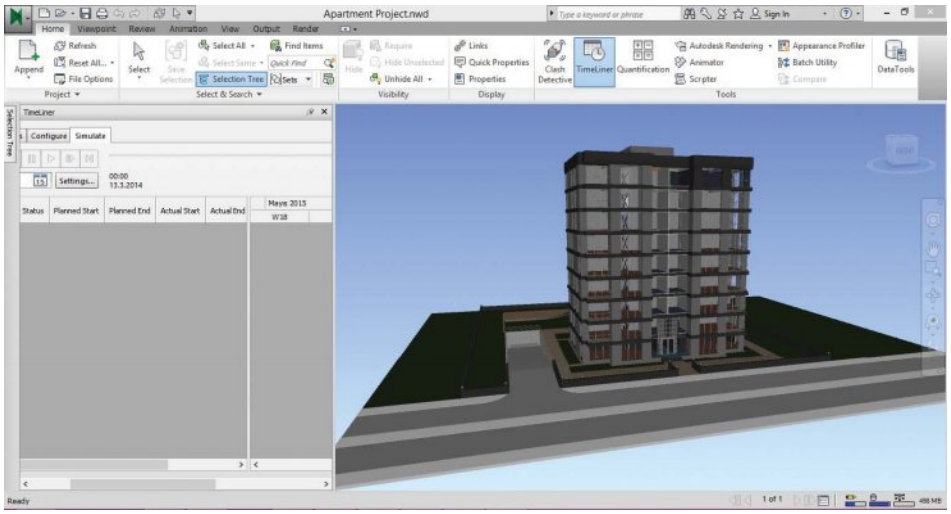



**Figure 15.28 Snapshot of the 4D model of the building, Example 6**

of frames per second (FPS) is another item that should be defined by users. A larger value for FPS enables smoother animation; however, it is needed to generate more images. Generally, a value of 15 FPS is sufficient to demonstrate 4D models in an AVI format. The last item that the user needs to define is anti-aliasing, which is utilized to smooth the edges in the 4D model. A larger value of anti-aliasing results in a smoother image; however, the exporting process will take longer due to the increasing number of frames generated.

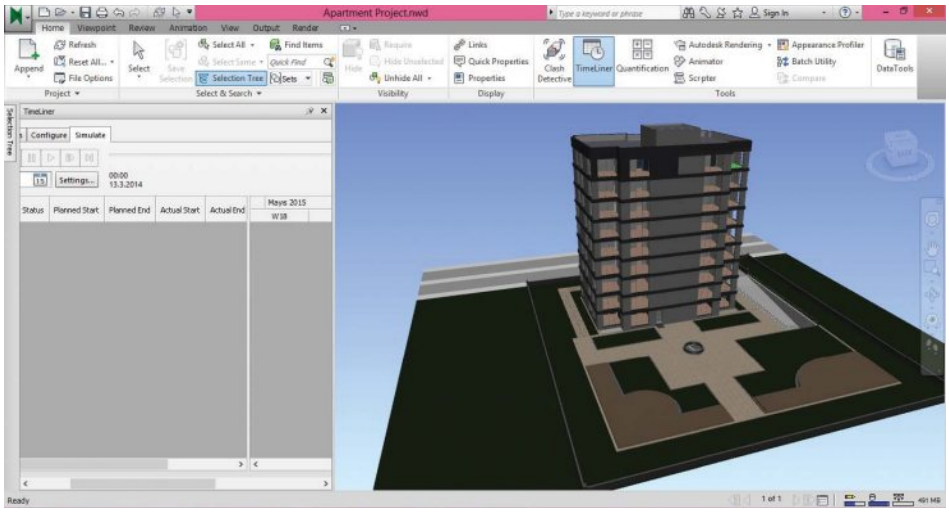



**Figure 15.29 Snapshot of the 4D model of the building, Example 7**

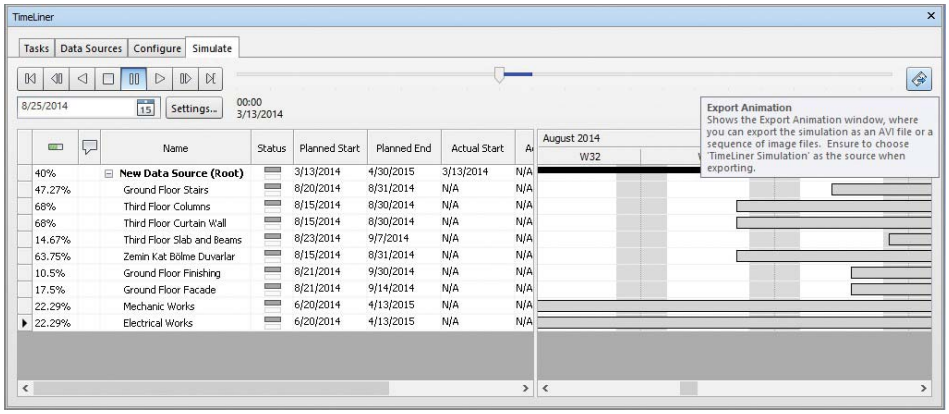



**Figure 15.30 Snapshot of the "Export Animation" command**

### Using Integrated Systems

Using an integrated systems approach allows the execution of projects collaboratively and interactively from planning phase throughout the operation. It provides a collaborative working environment by bringing together key participants, such as clients, designers, engineers, consultants, project developers, operators, and project managers. Integrated systems incorporates ERP (enterprise resource planning) systems with BIM to support the entire life cycle of a project as well as enables services to various project participants. The integration of BIM with ERP systems eliminates traditional data transfer problems (data losses, etc.), conflicts and misunderstandings among project

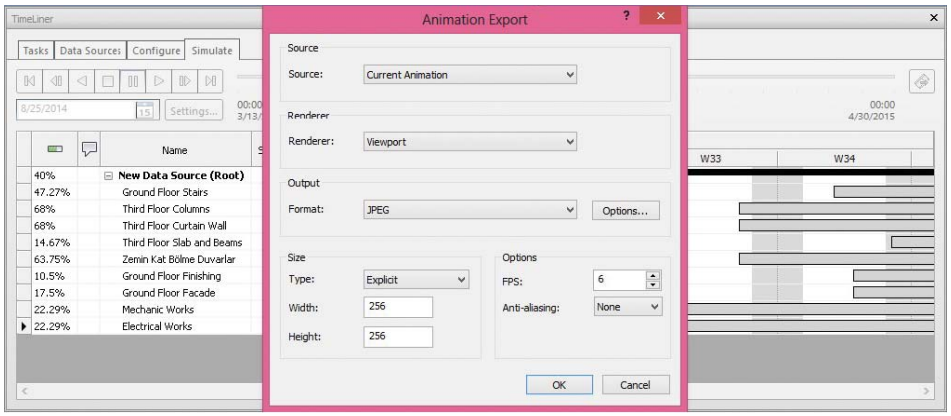



**Figure 15.31 Snapshot of the Animation Export settings**

participants, and probable time delays arising due to working in diverse environments and systems. Traditional ERP services, such as accounting, financing, and human resources management are incorporated into integrated systems to transfer project management activities to the business solutions. Thus, the integrated systems approach generally supports the design, estimating, tendering, execution, and operation phases of projects, and engages designers, estimators, contract managers, procurement officers, project managers, and controllers during the entire life cycle of a project. The most common services provided by integrated systems cover design checking, bill of quantities (BoQ, also called schedule of values), cost estimating, scheduling, material procurement, project controlling, clash detection, resource management, change order management, materials management, contract management, bid analysis, and other services, such as finance, accounting, cash payments tracking, warehouse management, and human resources management. The BIM solutions, along with the life cycle of a project and responsible participants, are depicted in Figure 15.32.

In this regard, the RIB iTwo* BIM ERP 5D system is one of the integrated project delivery systems that successfully supports construction processes in the civil infrastructure, process and energy, manufacturing, and public sectors.[2] The system is compatible with various BIM enablers, such as Graphisoft, Nemetschek, Tekla, Bentley, and Revit, and can be utilized by designers, estimators, contract managers, procurement officers, and project managers. It provides savings in analysis time, the number of change orders received, the cost of materials, the project's lifespan, risk reductions, and improved quality. The operations undertaken in the context of the RIB iTwo BIM ERP 5D system are estimation of quantity takeoff and calculation of billing of quantities, development of the activity models utilizing scheduling software (i.e., Oracle Primavera P6), development of assemblies by using resource catalogs (catalogs

[2] The RIB Group, founded in 1961 with headquarters in Germany, is one of the companies that designs, develops, and offers iTwo technology for the construction industry. Please refer to http://www.rib-software.com/home.html for more detailed information.

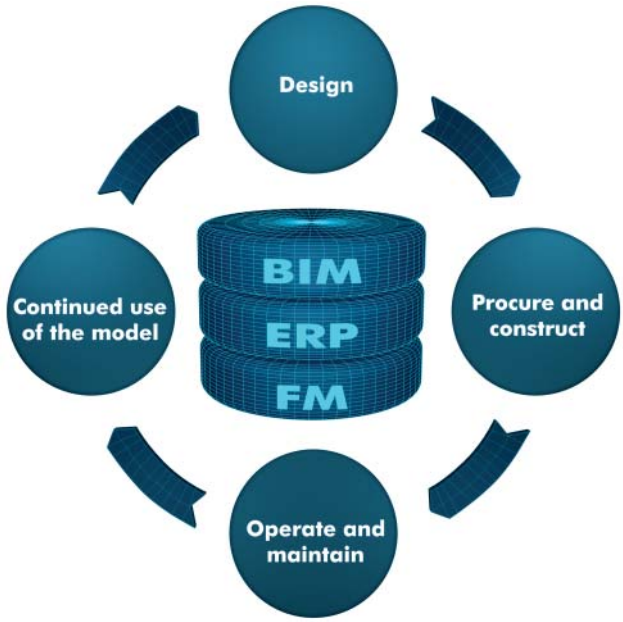



**Figure 15.32 Integrated solutions for building a life cycle using BIM**

that are previously defined for all resources within the ERP system), and incorporation of assemblies into the 5D BIM. In other words, activity models created in scheduling software are linked to BoQ items and assemble catalogs by utilizing iTwo platform, which allows incorporation of project resources to the project schedule automatically.

### Lean Construction

Lean construction is based on the techniques and methodologies offered by the Toyota Production System, which are mainly about minimization of waste throughout the processes that exist in a production (Liker, 2004). During the evolution of lean thinking in the construction industry, some changes and adoptions have been made; however, the main idea remains the same. In this regard, the lean construction technique is one of the novel efforts of the industry's practitioners and researchers that focuses on eliminating waste in projects while maximizing the value of the projects. Continuous improvement (*kaizen* in Japanese), the elimination of waste, and just-in-time are the major principles of the lean construction technique, which increases value, minimizes waste, enhances profitability and quality, and ensures client satisfaction. To clarify the description of "waste" in production process, Taiichi Ohno, one of the creators of the Toyota Production System (Holweg, 2007), classified "waste" into seven types (Liker, 2004): waste of overproduction, waste of waiting, waste of transportation, waste of overprocessing and incorrect process, waste of inventory, waste of unnecessary movement, and waste of making a defective product.

In this sense, the incorporation of BIM is essential to minimize waste that may occur in construction processes while increasing the value to the customer. The major contributions of BIM to the implementation and execution of the lean construction technique are described as follows:

- *BIM reduces waste of overproduction, defective products and rework*: BIM provides collaboration between the various project participants in the early stages of the project and ensures their full involvement, especially in the design phase. It allows parties to communicate and evaluate probable design problems, detect clashes, and integrate architectural, structural, mechanical, and electrical designs in a single information file. The 3D model enables users to physically represent the building component while capturing and storing the "component information." The intelligence of these models is helpful in estimations, material procurement and allocation, subcontractor management, and design analysis.
- *BIM reduces waste of waiting and idle process times*: A 4D model created in a BIM environment provides automated project scheduling and project visualization throughout the life cycle of the project. The simulation of the project enables users to manage and allocate project resources, plan site logistics, and manage subcontractor schedules. The interdependencies among activity packages and sequences of these activities are easily identified so that the working times of the subcontractors are more successfully allocated. Also, the automated generation of project reports allows consistent and reliable information to be provided to the participants, which reduces the risk of loss of information and minimizes the waste of waiting for information. The virtual simulation of the projects improves the stability of the work flow and minimizes the idle times in the construction processes.

As a final remark, if BIM is incorporated into an integrated project delivery system, leaner constructions can be executed. First, the integration of the BIM with a supply chain management application and an ERP system, the delivery of materials, and site logistics and subprocesses among different project phases are more collaboratively and effectively managed. Second, the incorporation of various project participants are ensured so that coordination and communication problems among cross-functional parties are avoided, and waste of waiting for information is eliminated. The fulfillment of a continuous flow of work is another characteristic of a BIM-enabled integrated project delivery system that allows the alignment of all project activities in an effective work flow, minimizing lead times among diverse work packages and eliminating unnecessary steps. The room for improvement always exists; however, the adoptability of novel and innovative systems, tools, and techniques, such as the incorporating of BIM-enabled integrated systems into a company's existing operations, is a sign of a willingness to continuously strive for improvement. The adoption of novel systems as well as the improvement of the processes by using these systems are triggers for continuous improvement, which is one of the major targets of lean construction.

## CHAPTER 15 EXERCISES

1. What are the major functions and benefits of the following?
   a. 3D BIM
   b. 4D BIM
   c. 5D BIM
2. Explain the difference between 4D and 5D BIM.
3. What is the relationship between BIM and LEAN construction?
4. Why are 4D and 5D models important in project management?
5. What is the innovative aspect of BIM?
6. Describe how the use of a BIM system increases collaboration among project participants.
7. If you were an architect, why would you use BIM? (Answer it also as if you were a contractor, a client, or a subcontractor.)
8. How can the nD models of BIM be improved? In your opinion, what will be the next nth model?
9. Explain 6D and 7D BIM models and their major functions.
10. What is the relationship between BIM and sustainability? How would the use of BIM contribute to sustainability?
11. Explain the difference between 3D CAD drawings and 3D intelligent models.
12. How can the use of BIM minimize cost overruns and time delays?
13. What is the integrated project delivery system?
14. How does incorporation of ERP systems with BIM influence project management efforts?
15. List BIM tools that have 4D capability and explain their major functions.
16. Describe the steps for creating a 4D model for a project.
17. How can a project schedule be linked and created using Navisworks?
18. Describe when and for which activities you would use "Construct," "Demolish," and "Temporary" task types.
19. Describe the idea and importance of "Selection Set."
20. What is the difference between merging and appending a model?

Appendix **A**

# Computer Project

You are scheduling a project: a two-story concrete office building with an area of about 4,000 square feet (SF) per floor. The first floor has a slab on a grade (SOG). The second floor is made of a cast-in-place (CIP) concrete slab, carried by both concrete columns and concrete masonry unit (CMU) walls. The roof is made of wood trusses topped with sheathing and asphalt shingles. The schedule logic includes many simplifying assumptions.

## GENERAL GUIDELINES

1. This is an individual project, but group discussion is allowed and encouraged.
2. Your work will be done mainly on the computer. Some written parts may be required. Make sure that your reports are marked clearly with your name, the date, the report's name, the page number, and so forth.
3. Write down any assumptions you make. Submit a written copy with your report.
4. The recommended software is Oracle Primavera P6 or Primavera Contractor. Alternatively, you may use Microsoft (MS) Project, but if you do, remember that combination relationships will not work in this program.
5. The project is composed of no more than 60 activities in case the software (student version) has limitations.
6. The assignments pertain to topics covered in the body of this book. Be sure to keep an electronic copy of each assignment.
7. Make the start date 03-AUG-2015. Leave the finish date open.
8. In all calendars, enter the following as nonworkdays: New Year's Day (January 1), Martin Luther King Day (3rd Monday of January), Memorial Day (last Monday of May), July 4, Labor Day (1st Monday of September), Thanks giving (4th Thursday of November) and the day after, and Christmas (December 25).[1] If a holiday falls on a nonworkday, take the nearest workday

[1] If you live in a country other than the United States, you may assign your country's holidays instead. However, depending on the number of holidays and their distribution, your completion date may slightly differ.

as a holiday. In addition, enter two rain days per month. Try to distribute these rain days as evenly as possible.

9. The general contractor (GC) will be doing mainly the structural work, using his or her own workforce, but the GC will use the following subcontractors for other work:

| Nickname | Full Name | Type of work |
|---|---|---|
| ACAL | All Seasons AC & Heating | HVAC[a] |
| WALL | Wall to Wall | Drywall, Stucco, and Paint |
| MART | Master Art Landscape | Site Work and Landscaping |
| MASE | Mase & Company | Masonry |
| ROSS | Ross Carpentry & Framing | Wood Framing |
| PLMX | Plumbing Experts | Plumbing |
| RABT | Rabbit-the-Roofer | Roofing |
| TACO | Tile and Carpet Co., Inc. | Flooring |
| WINT | Windows & Doors NT | Doors and Windows |
| ZAPP | Zapp Electric Co. | Electrical |

[a]Heating, ventilation, and air-conditioning.

10. Four areas are designated in the project: ALL (for all of the project), 1st (for first-floor activities), 2nd (for second-floor activities), and ROOF (for roof activities).

| Activity ID | Activity Title | Duration (days) | IPA[a] | Rel. Type[b] | Lag (days)[i] | Resp.[c] | Area |
|---|---|---|---|---|---|---|---|
| 1000 | NTP[d] | — | — | | | GC | ALL |
| 1010 | Mobilization | 3 | 1000 | | | GC | ALL |
| 1020 | Clear & grub | 12 | 1010 | | | GC | ALL |
| 1030 | Excavation | 7 | 1020 | SS | 4 | GC | ALL |
| 1040 | Foundation | 15 | 1030 | SS | 3 | GC | ALL |
| | | | 1030 | FF | 1 | | |
| 1050 | Fill, compact, and treat soil | 3 | 1040 | | | GC | ALL |
| 1060 | 1st floor plumbing rough-in | 3 | 1050 | | | PLMX | 1st |
| 1070 | SOG | 4 | 1060 | | | GC | 1st |
| 1080 | 1st floor columns | 7 | 1050 | | | GC | 1st |
| 1090 | 1st floor external CMU walls | 10 | 1070 | | | MASE | 1st |
| 1100 | 1st floor internal CMU walls | 14 | 1070 | | | MASE | 1st |
| 1110 | 2nd floor suspended slab | 8 | 1080, 1090, 1100 | | | GC | 2nd |
| 1120 | 2nd floor plumbing rough-in | 3 | 1110 | SS | 1 | PLMX | 2nd |
| | | | 1110 | FF | −1[e] | | |
| 1130 | 1st floor electrical rough-in | 4 | 1090, 1100, 1280 | SS | 2 | ZAPP | 1st |
| | | | 1090, 1100, 1280 | FF | 2 | | |

| Activity ID | Activity Title | Duration (days) | IPA[a] | Rel. Type[b] | Lag (days)[i] | Resp.[c] | Area |
|---|---|---|---|---|---|---|---|
| 1140 | 1st floor HVAC ductwork\rough-in | 6 | 1110 | | | ACAL | 1st |
| 1150 | 1st floor door & window frames | 5 | 1090, 1100, 1280 | SS | | WINT | 1st |
| | | | 1090, 1100, 1280 | FF | | | |
| 1160 | 2nd floor columns | 7 | 1110 | | 3 | GC | 2nd |
| 1170 | 2nd floor external CMU walls | 12 | 1110 | | | MASE | 2nd |
| 1180 | 2nd floor internal CMU walls | 16 | 1110 | | 2 | MASE | 2nd |
| 1190 | Roof trusses | 8 | 1160, 1170, 1180 | | | ROSS | Roof |
| 1200 | 2nd floor electrical rough-in | 4 | 1170, 1180, 1280 | SS | 2 | ZAPP | 2nd |
| | | | 1170, 1180, 1280 | FF | 2 | | |
| 1210 | 2nd floor HVAC ductwork\rough-in | 6 | 1190 | | | ACAL | 2nd |
| 1220 | 2nd floor door & window frames | 5 | 1170, 1180, 1280 | SS | | WINT | 2nd |
| | | | 1170, 1180, 1280 | FF | | | |
| 1230 | Roof sheathing | 5 | 1190 | | | ROSS | Roof |
| 1240 | Roof felt | 1 | 1230 | | | RABT | Roof |
| 1250 | Building dry-in[f] | — | 1240 | | | GC | ALL |
| 1260 | Soffit & facia | 3 | 1250 | | | ROSS | Roof |
| 1265 | Roof shingles | 6 | 1240 | | | RABT | Roof |
| 1270 | Roof insulation | 2 | 1250 | | | ROSS | Roof |
| 1280 | Internal partition framing | 12 | 1250 | | | ROSS | ALL |
| 1290 | 1st floor: hang doors & windows | 10 | 1150, 1280 | | | WINT | 1st |
| 1300 | 1st floor drywall | 8 | 1280 | | | WALL | 1st |
| 1310 | 1st floor HVAC air handler | 5 | 1140, 1300 | | | ACAL | 1st |
| 1320 | 1st floor suspended ceiling | 8 | 1300 | | | WALL | 1st |
| 1330 | 1st floor plumbing: install fixtures | 2 | 1060, 1300 | | | PLMX | 1st |
| 1340 | 1st floor paint/wall covering | 10 | 1320 1330 | SS | 4 | WALL | 1st |
| 1350 | 1st floor electrical finish | 6 | 1130, 1320 | | | ZAPP | 1st |
| 1360 | 1st floor flooring | 12 | 1340, 1350 | | | TACO | 1st |

(*continued overleaf*)

| Activity ID | Activity Title | Duration (days) | IPA[a] | Rel. Type[b] | Lag (days)[i] | Resp.[c] | Area |
|---|---|---|---|---|---|---|---|
| 1370 | 2nd floor: hang doors & windows | 10 | 1220, 1280 | | | WINT | 2nd |
| 1380 | 2nd floor drywall | 8 | 1300 | | | WALL | 2nd |
| 1390 | 2nd floor HVAC air handler | 5 | 1210, 1380 | | | ACAL | 2nd |
| 1400 | 2nd floor suspended ceiling | 8 | 1270, 1380 | | | WALL | 2nd |
| 1410 | 2nd floor plumbing: install fixtures | 2 | 1120, 1380 | | | PLMX | 2nd |
| 1420 | 2nd floor paint/wall covering | 11 | 1400 1410 | SS | 4 | WALL | 2nd |
| 1430 | 2nd floor electrical finish | 6 | 1200, 1400 | | | ZAPP | 2nd |
| 1440 | HVAC: install equipment | 1 | 1310, 1390 | | | ACAL | ALL |
| 1450 | 2nd floor flooring | 10 | 1420, 1430 | | | TACO | 2nd |
| 1460 | Stucco & paint to ext. walls | 8 | 1260 | | | WALL | ALL |
| 1470 | Site work[g] | 15 | 1020, 1090 | | | MART | ALL |
| 1480 | Plumbing finish | 2 | 1330, 1410 | | | PLMX | ALL |
| 1490 | HVAC thermostat & test | 1 | 1350, 1430, 1440 | | | ACAL | ALL |
| 1500 | Electrical final | 4 | 1340, 1350, 1420, 1430 | | | ZAPP | ALL |
| 1510 | Building cleanup | 2 | 1265, 1290, 1360, 1370, 1450, 1460, 1480, 1490, 1500 | | | GC | ALL |
| 1520 | Final check/CO[h] | 1 | 1470, 1510 | | | GC | ALL |

[a]Immediately preceding activity.
[b]Relationship type: SS, start to start; FF, finish to finish. If blank, the relationship is FS, finish to start.
[c]Responsibility.
[d]Notice to proceed. Make this activity a start milestone.
[e]The negative lag means 2nd-floor plumbing rough-in must finish 1 day before completion of the 2nd-floor slab. Note also that the start of this activity lags 1 day behind the start of the slab activity. This makes the plumbing activity completely contained within the slab activity.
[f]Make this activity a finish milestone.
[g]Insert a constraint so that site work will not finish umtil about 1 week before the end of the entire project.
[h]Certificate of occupancy.
[i]If blank, then the lag is zero.

**Assignment 1**

Do the following:

1. Create the project and call it "Tampa Office Building–01."[2] You may choose the name you like. Enter the specified start date. Enter the nonworkdays in the calendar. Enter the Responsibility and Area codes and values.
2. Enter all of the activities listed in the preceding table, along with their information (duration, relationships, lag, responsibility, and area).
3. Schedule the project. Make sure there are no errors. Check all dates.
4. Determine the calculated finish date. Go back to the site work activity and put in the appropriate constraint.
5. Schedule the project again. Print the scheduling report. As an option for a better-looking report, save the report and then open it in your word processor. Work on improving how it looks.
6. Print the following:
   a. The scheduling report. Record the expected finish date (it should be 18-MAR-2016[3]) for use in the next assignments.
   b. A tabular report listing all activities, ordered by Activity ID. Compare this with the preceding table to make sure that nothing is missing.
   c. A tabular report listing all activities, ordered by ES (early start) and TF (total float). This report should show all early and late dates as well as total float.
   d. A tabular report that is similar to the previous one. Mask late dates and total float. Check if the program automatically renames early dates as scheduled dates. If not, do so yourself.
   e. A tabular report for activities scheduled to start during the month of September 2015.
   f. A bar chart showing all activities, organized by Area, ordered by ES and TF.
   g. A bar chart showing all activities, organized by Responsibility, ordered by ES and TF.
   h. A bar chart showing only critical or near-critical ($TF \leq 3$) activities. Do not organize it. Sort it by ES and TF. Display the relationships.
   i. A logic diagram. In each box (node), show the activity ID, and also show the early dates, the late dates, and the original duration. You may have to work on the size of the box so that the writing inside is legible and the report is not enormous.
   j. A logic diagram for the activities under the electrical subcontractor only.

[2] If you are using Primavera Project Planner (P3), you must select a name with four characters. You may choose TOB0.

[3] The finish date may vary by a day or two, depending on the choice of the rain days in March 2016.

7. Make at least one backup copy of the project on an external medium (e.g., CD, flash drive).

## COST LOADING

In this exercise, the GC is cost loading the schedule but will follow two approaches. For self-performed activities, the GC will resource load them (i.e., assign the proper amount of labor and equipment, plus add the cost of materials, if any).[4] For subcontracted activities, the GC will add only the cost of these activities (no resource loading).

| | | Resources[a] | | | | |
|---|---|---|---|---|---|---|
| Activity ID | Activity Title | Laborer | Forman | Carpenter | Excavator | Cost[b] |
| 1000 | NTP | — | — | — | — | $0 |
| 1010 | Mobilization | 3 | 1 | — | 1 | $2,000 |
| 1020 | Clear & grub | 4 | 1 | — | 2 | $0 |
| 1030 | Excavation | 3 | 1 | — | 1 | $0 |
| 1040 | Foundation | 3 | 1 | 2 | 1 | $5,000 |
| 1050 | Fill, compact, and treat soil | 2 | 1 | — | 1 | $1,000 |
| 1060 | 1st floor plumbing rough-in | — | — | — | — | $2,500 |
| 1070 | SOG | 2 | 1 | 1 | — | $1,500 |
| 1080 | 1st floor columns | 2 | 1 | 2 | — | $1,200 |
| 1090 | 1st floor external CMU walls | — | — | — | — | $9,200 |
| 1100 | 1st floor internal CMU walls | — | — | — | — | $7,800 |
| 1110 | 2nd floor suspended slab | 2 | 1 | 2 | — | $3,000 |
| 1120 | 2nd floor plumbing rough-in | — | — | — | — | $2,500 |
| 1130 | 1st floor electrical rough-in | — | — | — | — | $6,000 |
| 1140 | 1st floor HVAC ductwork\rough-in | — | — | — | — | $7,000 |
| 1150 | 1st floor Door & Window Frames | — | — | — | — | $3,500 |
| 1160 | 2nd floor columns | 2 | 1 | 1 | — | $1,200 |
| 1165 | Roof shingles | — | — | — | — | $8,000 |
| 1170 | 2nd floor external CMU walls | — | — | — | — | $11,500 |
| 1180 | 2nd floor internal CMU walls | — | — | — | — | $8,500 |
| 1190 | Roof trusses | — | — | — | — | $10,000 |
| 1200 | 2nd floor electrical rough-in | — | — | — | — | $6,000 |
| 1210 | 2nd floor HVAC ductwork\rough-in | — | — | — | — | $7,000 |
| 1220 | 2nd floor door & window frames | — | — | — | — | $2,600 |
| 1230 | Roof sheathing | — | — | — | — | $3,500 |
| 1240 | Roof felt | — | — | — | — | $400 |
| 1250 | Building dry-in | — | — | — | — | $0 |
| 1260 | Soffit & facia | — | — | — | — | $2,500 |
| 1270 | Roof insulation | — | — | — | — | $4,000 |
| 1280 | Internal partition framing | — | — | — | — | $4,500 |

[4] In some computer-scheduling programs, this must also be achieved by adding a resource called *lump sum*, which is used for cash amounts only.

| | | Resources[a] | | | | |
|---|---|---|---|---|---|---|
| Activity ID | Activity Title | Laborer | Forman | Carpenter | Excavator | Cost[b] |
| 1290 | 1st floor: hang doors & windows | — | — | — | — | $5,200 |
| 1300 | 1st floor drywall | — | — | — | — | $6,500 |
| 1310 | 1st floor HVAC air handler | — | — | — | — | $4,000 |
| 1320 | 1st floor suspended ceiling | — | — | — | — | $7,500 |
| 1330 | 1st floor plumbing: install fixtures | — | — | — | — | $7,500 |
| 1340 | 1st floor paint/wall covering | — | — | — | — | $5,700 |
| 1350 | 1st floor electrical finish | — | — | — | — | $15,000 |
| 1360 | 1st floor flooring | — | — | — | — | $11,000 |
| 1370 | 2nd floor: hang doors & windows | — | — | — | — | $4,200 |
| 1380 | 2nd floor drywall | — | — | — | — | $7,000 |
| 1390 | 2nd floor HVAC air handler | — | — | — | — | $4,000 |
| 1400 | 2nd floor suspended ceiling | — | — | — | — | $7,500 |
| 1410 | 2nd floor plumbing: install fixtures | — | — | — | — | $7,500 |
| 1420 | 2nd floor paint/wall covering | — | — | — | — | $5,400 |
| 1430 | 2nd floor electrical finish | — | — | — | — | $17,000 |
| 1440 | HVAC: Install equipment | — | — | — | — | $22,000 |
| 1450 | 2nd floor flooring | — | — | — | — | $8,500 |
| 1460 | Stucco & Paint to exterior walls | — | — | — | — | $7,000 |
| 1470 | Site work | — | — | — | — | $30,000 |
| 1480 | Plumbing finish | — | — | — | — | $4,500 |
| 1490 | HVAC thermostat & test | — | — | — | — | $5,000 |
| 1500 | Electrical final | — | — | — | — | $9,500 |
| 1510 | Building cleanup | 3 | 1 | — | — | $200 |
| 1520 | Final check/CO | 1 | 1 | — | — | $0 |

[a]Resources for the general contractor's self-performed activities. The author has used only three labor categories and one equipment category for the sake of simplicity.
[b]When used for self-performed activities, it reflects the general contractor's materials cost only (total cost excluding labor and equipment). For subcontracted work, the cost includes all expenses.

### Assignment 2

Do the following:

1. Make a copy of the Tampa Office Building–01 project. Call it "Tampa Office Building–02." Add all the information mentioned in the preceding table to the schedule.
2. Print the following reports:
   a. A tabular report showing the quantity of each resource used by each activity. You may need to use a filter to select activities with resources (Responsibility = GC).
   b. A tabular report showing the cost (in dollars) for all activities. Organize it by Responsibility.
   c. A tabular report showing the cost (in dollars) for all activities. Summarize it by Responsibility.
   d. A tabular report showing cost per month. Organize it by Responsibility.

## UPDATING THE PROJECT

On 02-SEP-2015, the project manager is creating the first update, with Data date = 01-SEP-2015 and the following information:

Activities 1000 NTP and 1010 Mobilization were finished on time.

Activity 1020 Clear & Grub started on time. It finished on 28-AUG-2015.

Activity 1030 Excavation started on 17-AUG-2015. As a result of unexpectedly hard soil, the contractor had to acquire different equipment. Excavation was finished on 28-AUG-2015.

Activity 1040 Foundation started on 20-AUG-2015. As of the data date, the percent complete for this activity is 44%. The expected remaining duration is 10 days.

Activity 1110 2nd Floor Suspended Slab was modified by the engineer and will require 10 days' duration.

### Assignment 3

Do the following:

1. Make a copy of the Tampa Office Building–01 project. Call it "Tampa Office Building–03."
2. In the new copy, update each activity's progress according to the preceding list. Schedule the project with a new Data date = 01-SEP-2015.
3. Print the following reports:
   a. A tabular report listing all activities, ordered by ES and TF. Note that every finished event has one date (i.e., the actual date) instead of the range (Early – Late) it had before. Also, float disappears from any finished activity.
   b. A bar chart showing all activities, organized by Responsibility, ordered by ES and TF. Note how a new vertical line now separates the completed items from future items. This line represents the Data date.
4. Now go back to the project data (the function name differs depending on your software) and assign a finish date equal to the date you originally obtained in assignment 1.
5. Reprint the tabular report from step 3a. Note the negative float that appeared with many activities. Print this report.
6. Print a report similar to the previous one, but apply a filter to include only activities with negative float.

## CHANGE ORDER

The owner issued a change order to add a vault. The vault will be built on the first floor but will require a thickened SOG and concrete walls. The additional work will include the following new and modified activities.

| Activity ID | Activity Title | Duration (days) | IPA | Rel. Type | Lag (days) | Resp. |
|---|---|---|---|---|---|---|
| 1070 | SOG | 5 | 1060 | | | GC |
| 1080 | 1st floor columns | 7 | 1050 | | | GC |
| 1085 | FRP vault walls | 6 | 1070 | | | GC |
| | | | 1080 | FF | | GC |
| 1087 | Vault door | 2 | 1085 | | | WINT |
| 1110 | 2nd floor suspended slab | 8 | 1080, 1085, 1090, 1100 | | | GC |
| 1300 | 1st floor drywall | 8 | 1087, 1280 | | | WALL |

In addition to the preceding information, the following table provides resources and cost for new and affected activities.

| | | Resources | | | | |
|---|---|---|---|---|---|---|
| Activity ID | Activity Title | Laborer | Foreman | Carpenter | Excavator | Cost |
| 1070 | SOG | 2 | 1 | 1 | – | $2,000 |
| 1080 | 1st floor columns | 2 | 1 | 1 | – | $900 |
| 1085 | FRP Vault walls | 2 | 1 | 1 | – | $800 |
| 1087 | Vault door | – | – | – | – | $3,000 |
| 1110 | 2nd floor suspended slab | 2 | 1 | 2 | – | $3,000 |
| 1300 | 1st floor drywall | | | | | $7,000 |

### Assignment 4

Do the following:

1. Make a copy of the Tampa Office Building–01 project. Call it "Tampa Office Building–04."
2. Add the new activities listed in the previous table and make any needed adjustments to existing activities.

3. Schedule the project and record the calculated finish date; compare it with the date you obtained in assignment 1. The difference, if any, is due to the change order.
4. Print the following:
   a. The scheduling report.
   b. A tabular report listing all activities, ordered by Activity ID.
   c. A tabular report listing all activities, ordered by ES and TF. Make sure that you show all early and late dates, and total float.
   d. A bar chart showing all activities, organized by Responsibility and ordered by ES and TF.
   e. A tabular report showing the quantity of each resource used by each activity.
   f. A tabular report showing the cost (in dollars) for all activities. Organize it by Responsibility. Reschedule the project.

## RESOURCE LEVELING

### Assignment 5

Using the resource information given in assignment 2, do the following:

1. Make a copy of the Tampa Office Building–01 project. Call it "Tampa Office Building–05."
2. Assign resources to the appropriate activities (as mentioned in assignment 2).
3. Apply a filter to include only the GC's activities.
4. Print a resource usage profile for each of the four resources (i.e., units of the resource used per day).
5. Level the Laborer resource to a limit of seven without delaying the project. Print another resource usage profile for Laborer.
6. If the GC has only 6 laborers, what solution would you suggest? (Print a report.)
7. Level the Foreman resource to a limit of two without delaying the project. Print another resource usage profile for Foreman. (Print a report.)
8. On what date do you need to have carpenters on the job site? What is the minimum number of carpenters you can hire without delaying the project?
9. Can you help the contractor find a plan to do the job with only two excavators? Outline your plan. (Print a report.)

## SCHEDULE COMPRESSION

### Assignment 6

Assume the cost of overhead for the project is $500 per day. This cost is not included in the following table, so it must be added manually after you calculate the project duration. Do the following:

1. Make a copy of the Tampa Office Building–01 project. Call it "Tampa Office Building–06."
2. Enter the normal cost for each activity as shown in the following table. Calculate the total cost (with normal duration).

   *Note*: Some of this assignment will force a splitting of some activities (i.e., an interruption and resumption at a later date). In most cases, you must do this manually.

| | | Duration (days) | | Cost $ | |
|---|---|---|---|---|---|
| Activity ID | Activity Title | Normal | Crash | Normal | Crash |
| 1000 | NTP | – | – | – | – |
| 1010 | Mobilization | 3 | 2 | 4,000 | 5,000 |
| 1020 | Clear & grub | 12 | 6 | 12,000 | 16,000 |
| 1030 | Excavation | 7 | 5 | 14,000 | 17,020 |
| 1040 | Foundation | 15 | 11 | 22,000 | 30,000 |
| 1050 | Fill, compact, and treat soil | 3 | 2 | 4,000 | 4,500 |
| 1060 | 1st floor plumbing rough-in | 3 | 2 | 2,500 | 2,800 |
| 1070 | SOG | 4 | 3 | 10,000 | 11,000 |
| 1080 | 1st floor columns | 7 | 5 | 7,000 | 7,800 |
| 1090 | 1st floor external CMU walls | 10 | 6 | 9,200 | 11,800 |
| 1100 | 1st floor internal CMU walls | 14 | 8 | 7,800 | 9,200 |
| 1110 | 2nd floor suspended slab | 8 | 6 | 12,000 | 13,600 |
| 1120 | 2nd floor plumbing rough-in | 3 | 2 | 2,500 | 2,800 |
| 1130 | 1st floor electrical rough-in | 4 | 2 | 6,000 | 7,400 |
| 1140 | 1st floor HVAC ductwork\rough-in | 6 | 4 | 7,000 | 7,500 |
| 1150 | 1st floor door & window frames | 5 | 3 | 3,500 | 4,100 |
| 1160 | 2nd floor columns | 7 | 5 | 7,000 | 7,800 |
| 1170 | 2nd floor external CUM walls | 12 | 7 | 11,500 | 13,300 |
| 1180 | 2nd floor internal CMU walls | 16 | 9 | 8,500 | 10,100 |
| 1190 | Roof trusses | 8 | 6 | 10,000 | 11,000 |
| 1200 | 2nd floor electrical rough-in | 4 | 3 | 6,000 | 6,200 |
| 1210 | 2nd floor HVAC ductwork\rough-in | 6 | 4 | 7,000 | 7,500 |
| 1220 | 2nd floor door & window frames | 5 | 3 | 2,600 | 3,000 |
| 1230 | Roof sheathing | 5 | 3 | 3,500 | 4,100 |
| 1240 | Roof felt | 1 | 1 | 400 | 400 |
| 1260 | Soffit & facia | 3 | 2 | 2,500 | 3,000 |
| 1265 | Roof shingles | 6 | 4 | 8,000 | 10,000 |
| 1270 | Roof insulation | 2 | 1 | 4,000 | 4,200 |

(*continued overleaf*)

| | | Duration (days) | | Cost $ | |
|---|---|---|---|---|---|
| Activity ID | Activity Title | Normal | Crash | Normal | Crash |
| 1280 | Internal partition framing | 12 | 9 | 4,500 | 5,300 |
| 1290 | 1st floor: hang doors & windows | 10 | 5 | 5,200 | 6,100 |
| 1300 | 1st floor drywall | 8 | 6 | 6,500 | 6,900 |
| 1310 | 1st floor HVAC air handler | 5 | 3 | 4,000 | 4,400 |
| 1320 | 1st floor suspended ceiling | 8 | 5 | 7,500 | 8,000 |
| 1330 | 1st floor plumbing: install fixtures | 2 | 2 | 7,500 | 7,500 |
| 1340 | 1st floor paint/wall covering | 10 | 6 | 5,700 | 6,300 |
| 1350 | 1st floor electrical finish | 6 | 4 | 15,000 | 15,800 |
| 1360 | 1st floor flooring | 12 | 8 | 11,000 | 12,000 |
| 1370 | 2nd floor: hang doors & windows | 10 | 5 | 4,200 | 4,800 |
| 1380 | 2nd floor drywall | 8 | 6 | 7,000 | 7,600 |
| 1390 | 2nd floor HVAC air handler | 5 | 3 | 4,000 | 4,400 |
| 1400 | 2nd floor suspended ceiling | 8 | 5 | 7,500 | 8,000 |
| 1410 | 2nd floor plumbing: install fixtures | 2 | 2 | 7,500 | 7,500 |
| 1420 | 2nd floor paint/wall covering | 11 | 7 | 5,400 | 6,000 |
| 1430 | 2nd floor electrical finish | 6 | 4 | 17,000 | 17,400 |
| 1440 | HVAC: Install equipment | 1 | 1 | 22,000 | 22,000 |
| 1450 | 2nd floor flooring | 10 | 7 | 8,500 | 9,100 |
| 1460 | Stucco & paint to exterior walls | 8 | 6 | 7,000 | 7, 800 |
| 1470 | Site work | 15 | 11 | 30,000 | 32,000 |
| 1480 | Plumbing finish | 2 | 2 | 4,500 | 4,500 |
| 1490 | HVAC thermostat & test | 1 | 1 | 5,000 | 5,000 |
| 1500 | Electrical final | 4 | 3 | 9,500 | 9,700 |
| 1510 | Building cleanup | 2 | 1 | 1,000 | 1,400 |
| 1520 | Final check/CO | 1 | 1 | 400 | 400 |

3. Accelerate the project by 2 days; you may have to do so 1 day at a time. Record the total cost. When compressing an activity, reflect the increase in its direct cost as an extra cost (acceleration cost) in its budget in the scheduling program. You may have to create an Excel spreadsheet to calculate the total cost.
4. Accelerate the project by an additional 2 days. Record the total cost.
5. Accelerate the project 1 extra day at a time. Determine the least cost and least-cost duration. Print a tabular report and a bar chart displaying all activities, along with their durations, organized by Responsibility.
6. Keep accelerating the project until it is completely crashed. Determine the crash duration and the associated crash cost.
7. On a separate page, record the following:
   a. Normal duration (number of days and date) and normal cost
   b. Least-cost duration and least cost
   c. Crash duration and crash cost

## SCHEDULE COMPRESSION 2

### Assignment 7

The GC is trying to accelerate the schedule by requiring certain crews to work on Saturdays. Most likely, this will increase the indirect cost—because of overtime pay—but we will not calculate cost in this exercise. Do the following:

1. Make a copy of the Tampa Office Building–01 project. Call it "Tampa Office Building–07."
2. Create a new calendar called "Six-Workday Week." Maintain the same holidays and rain days as on a regular calendar.
3. Choose certain activities to switch to the "Six-Workday Week" calendar. Start with critical activities. Make sure that this change will contribute to an earlier project completion date. This process will start simple but will become more complicated as you accelerate the schedule.
4. Keep accelerating the schedule until the project calculated finish date is no later than 04-MAR-2016.
5. Print a tabular report and a bar chart. Add a column in each report showing the calendar.

## DELAY CLAIM 1: UNFORESEEN CONDITIONS

While excavating, the contractor discovered contaminated soil that forced the contractor to change plans. The contractor incurred extra costs because of the hauling and disposal of the contaminated soil. In addition, excavation took 12 workdays rather than 7 workdays. The contractor issued a claim to the owner, requesting the following:

1. A 1-week (5 workdays) time extension
2. An extra $23,600 (to cover the extra costs for excavating, hauling, and disposing of the contaminated soil, plus the GC's overhead for the extra week of duration)

### Assignment 8

Do you think the contractor's claims are legitimate? Analyze both the contractor's claims (time and cost) separately. Explain your answers.

## DELAY CLAIM 2: CHANGE IN THE OWNER'S REQUIREMENTS

(*Note*: This delay claim is independent of delay claim 1.)

The owner decided to add an awning at the building's entrance. It will require the following three activities.

| Activity ID | Activity Title | Duration | IPA | Rel. Type | Lag[a] | Resp. | Cost |
|---|---|---|---|---|---|---|---|
| 1103 | Embed awning attachments to wall | 1 | 1090 | FF | | MASE | $500 |
| 1105 | Decorative posts (to support awning) | 1 | 1070 | | | AWNE | $2,000 |
| 1107 | Hang awning | 1 | 1103, 1105, 1460 | | | AWNE | $7,500 |

[a]If blank, then the lag is zero.

### Assignment 9

Do the following:

1. Make a copy of the Tampa Office Building–01 project. Call it "Tampa Office Building–09."
2. Add the preceding activities to the project. You must add AWNE as a new Responsibility code with the description "Annie's Awnings." Make activity 1510, Building cleanup, a successor to activity 1107. Also, activity 1107 becomes an additional predecessor to activity 1470, Site work.

   The GC is requesting, in addition to the cost of the change order ($10,000), a 3-day extension because the change order "disrupted his plans and affected other activities." The owner disputed the time extension.
3. Argue from the contractor's viewpoint: why is this a legitimate request? What supporting argument would you present? Make any necessary assumptions to support your point (e.g., contract language, timing of the change order).
4. Argue from the owner's viewpoint: why is this request unacceptable? What supporting argument would you present? Make any necessary assumptions to support your point.

Appendix **B**

# Sample Reports

The sample reports in this appendix were produced by using Primavera Project Manager P6 and Primavera Project Planner P3 software. In these reports, an asterisk next to a date indicates a constraint.

## TABULAR REPORTS

**Report 1**: Report 1 (Table B.1) is a list of activities with information such as the original duration, remaining duration, percent complete, early start, early finish, late start, late finish, and total float. For new projects that have not started yet, the remaining duration and percent complete may be omitted. Note that when an event (start or finish) happens, the early and late dates for the event are replaced with the actual date (followed by *A* in the report). Obviously, total float disappears from completed activities. Milestones are represented by a single date: start or finish. Activity codes may be used to group (organize) activities. In this case, we grouped them by Responsibility. When grouping activities, you may use the software's Subtotal function, which provides summary information per grouping code at the top of the group (or you may choose the bottom of the group). Note, however, that you must read these subtotals with caution. They include only what you see and exclude any activities that were filtered out. This applies to their attributes, such as duration and cost.

**Report 2**: Report 2 (Table B.2) is a list of activities such as those in report 1, but we hide the late start, late finish, and total float. Note that the early start and early finish have been renamed just "Start" and "Finish." We group activities by department (with a subtotal at the bottom) and list the activity code Responsibility and the calendar that each activity will follow.

**Report 3:** Report 3 (Table B.3) is a list of activities with their predecessors and successors. Note that the list does not specify the type of relationship or the lag (if any). Other information may be listed, such as Activity Status.

**Report 4:** Report 4 (Table B.4) is an earned value report that shows earned value versus actual and planned costs. Also note the totals.

**Report 5:** Report 5 (Table B.5) is a resource analysis showing budgeted units, actual units, and other data per resource.

**Table B.1 Tampa Office Building—Update as of 31-Aug-2010**

| Responsibility / Activity ID | Activity Name | Original Duration | Remaining Duration | Activity % Complete | Start | Finish | Late Start | Late Finish | Total Float |
|---|---|---|---|---|---|---|---|---|---|
| **General Contractor** | | **169** | **148** | | **02-Aug-10 A** | **25-Mar-11** | **23-Aug-10** | **17-Mar-11** | **–5** |
| 1000 | NTP | 0 | 0 | 100 | 02-Aug-10 A | | 23-Aug-10 | | |
| 1010 | Mobilization | 3 | 0 | 100 | 02-Aug-10 A | 04-Aug-10 A | 23-Aug-10 | 23-Aug-10 | |
| 1020 | Clear & grub | 12 | 0 | 100 | 05-Aug-10 A | 27-Aug-10 A | 23-Aug-10 | 23-Aug-10 | |
| 1030 | Excavation | 7 | 0 | 100 | 16-Aug-10 A | 27-Aug-10 A | 23-Aug-10 | 23-Aug-10 | |
| 1040 | Foundation | 15 | 8 | 44 | 19-Aug-10 A | 15-Sep-10 | 23-Aug-10 | 02-Sep-10 | –5 |
| 1050 | Fill, compact, and soil treatment | 3 | 3 | 0 | 15-Sep-10 | 20-Sep-10 | 03-Sep-10 | 08-Sep-10 | –5 |
| 1080 | 1st floor columns | 7 | 7 | 0 | 20-Sep-10 | 29-Sep-10 | 01-Oct-10 | 12-Oct-10 | 9 |
| 1070 | SOG | 4 | 4 | 0 | 23-Sep-10 | 29-Sep-10 | 16-Sep-10 | 21-Sep-10 | –5 |
| 1110 | 2nd floor suspended slab | 10 | 10 | 0 | 21-Oct-10 | 04-Nov-10 | 13-Oct-10 | 27-Oct-10 | –5 |
| 1160 | 2nd floor columns | 7 | 7 | 0 | 04-Nov-10 | 16-Nov-10 | 11-Nov-10 | 19-Nov-10 | 4 |
| 1250 | Building Dry-in | 1 | 1 | 0 | 27-Dec-10 | 28-Dec-10 | 17-Dec-10 | 17-Dec-10 | –5 |
| 1510 | Building clean-up | 2 | 2 | 0 | 22-Mar-11 | 24-Mar-11 | 15-Mar-11 | 16-Mar-11 | –5 |
| 1520 | Final check/CO | 1 | 1 | 0 | 24-Mar-11 | 25-Mar-11 | 17-Mar-11 | 17-Mar-11 | –5 |
| **All Seasons AC & Heating** | | **86** | **86** | | **04-Nov-10** | **04-Mar-11** | **22-Feb-11** | **14-Mar-11** | **7** |
| 1140 | 1st floor HVAC ductwork/ rough-in | 6 | 6 | 0 | 04-Nov-10 | 15-Nov-10 | 22-Feb-11 | 01-Mar-11 | 66 |
| 1210 | 2nd floor HVAC ductwork/ rough-in | 6 | 6 | 0 | 16-Dec-10 | 27-Dec-10 | 22-Feb-11 | 01-Mar-11 | 42 |
| 1310 | 1st floor HVAC air handler | 5 | 5 | 0 | 28-Jan-11 | 04-Feb-11 | 02-Mar-11 | 08-Mar-11 | 21 |
| 1390 | 2nd floor HVAC air handler | 5 | 5 | 0 | 11-Feb-11 | 18-Feb-11 | 02-Mar-11 | 08-Mar-11 | 13 |
| 1440 | HVAC: Install equipment | 1 | 1 | 0 | 18-Feb-11 | 21-Feb-11 | 11-Mar-11 | 11-Mar-11 | 13 |
| 1490 | HVAC thermostat & test | 1 | 1 | 0 | 03-Mar-11 | 04-Mar-11 | 14-Mar-11 | 14-Mar-11 | 5 |

**Table B.1 (*Continued*)**

| Responsibility / Activity ID | Activity Name | Original Duration | Remaining Duration | Activity % Complete | Start | Finish | Late Start | Late Finish | Total Float |
|---|---|---|---|---|---|---|---|---|---|
| **Wall to Wall** | | **44** | **44** | | **03-Jan-11** | **04-Mar-11** | **11-Jan-11** | **14-Mar-11** | **7** |
| 1460 | Stucco & paint to ext. walls | 8 | 8 | 0 | 03-Jan-11 | 17-Jan-11 | 01-Mar-11 | 14-Mar-11 | 37 |
| 1300 | 1st floor drywall | 8 | 8 | 0 | 18-Jan-11 | 28-Jan-11 | 11-Jan-11 | 20-Jan-11 | –5 |
| 1380 | 2nd floor drywall | 8 | 8 | 0 | 28-Jan-11 | 11-Feb-11 | 21-Jan-11 | 01-Feb-11 | –5 |
| 1320 | 1st floor suspended ceiling | 8 | 8 | 0 | 28-Jan-11 | 11-Feb-11 | 01-Feb-11 | 14-Feb-11 | 2 |
| 1340 | 1st floor paint/wall covering | 10 | 10 | 0 | 03-Feb-11 | 21-Feb-11 | 07-Feb-11 | 22-Feb-11 | 2 |
| 1400 | 2nd floor suspended ceiling | 8 | 8 | 0 | 11-Feb-11 | 23-Feb-11 | 02-Feb-11 | 15-Feb-11 | –5 |
| 1420 | 2nd floor paint/wall covering | 11 | 11 | 0 | 17-Feb-11 | 04-Mar-11 | 08-Feb-11 | 24-Feb-11 | –5 |
| **Master Art Landscape** | | **16** | **16** | | **14-Oct-10** | **05-Nov-10** | **22-Feb-11** | **16-Mar-11** | **94** |
| 1470 | Site work | 15 | 15 | 0 | 14-Oct-10 | 05-Nov-10* | 22-Feb-11 | 16-Mar-11 | 80 |
| **Mase & Company** | | **46** | **46** | | **29-Sep-10** | **02-Dec-10** | **22-Sep-10** | **19-Nov-10** | **–8** |
| 1100 | 1st floor internal CMU walls | 14 | 14 | 0 | 29-Sep-10 | 21-Oct-10 | 22-Sep-10 | 12-Oct-10 | –5 |
| 1090 | 1st floor external CMU walls | 10 | 10 | 0 | 29-Sep-10 | 14-Oct-10 | 28-Sep-10 | 12-Oct-10 | –1 |
| 1180 | 2nd floor internal CMU walls | 16 | 16 | 0 | 04-Nov-10 | 02-Dec-10 | 28-Oct-10 | 19-Nov-10 | –5 |
| 1170 | 2nd floor external CMU walls | 12 | 12 | 0 | 04-Nov-10 | 23-Nov-10 | 03-Nov-10 | 19-Nov-10 | –1 |
| **Ross Carpentry & Framing** | | **33** | **33** | | **02-Dec-10** | **18-Jan-11** | **22-Nov-10** | **28-Feb-11** | **30** |
| 1190 | Roof trusses | 8 | 8 | 0 | 02-Dec-10 | 16-Dec-10 | 22-Nov-10 | 06-Dec-10 | –5 |
| 1230 | Roof sheathing | 5 | 5 | 0 | 16-Dec-10 | 23-Dec-10 | 08-Dec-10 | 14-Dec-10 | –5 |
| 1280 | Internal partition framing | 12 | 12 | 0 | 28-Dec-10 | 18-Jan-11 | 20-Dec-10 | 10-Jan-11 | –5 |
| 1270 | Roof insulation | 2 | 2 | 0 | 28-Dec-10 | 30-Dec-10 | 31-Jan-11 | 01-Feb-11 | 21 |
| 1260 | Soffit & facia | 3 | 3 | 0 | 28-Dec-10 | 03-Jan-11 | 24-Feb-11 | 28-Feb-11 | 37 |

(*continued overleaf*)

**Table B.1 (*Continued*)**

| Responsibility / Activity ID | Activity Name | Original Duration | Remaining Duration | Activity % Complete | Start | Finish | Late Start | Late Finish | Total Float |
|---|---|---|---|---|---|---|---|---|---|
| **Plumbing Experts** | | **108** | **108** | | **20-Sep-10** | **17-Feb-11** | **09-Sep-10** | **14-Mar-11** | **18** |
| 1060 | 1st floor plumbing rough-in | 3 | 3 | 0 | 20-Sep-10 | 23-Sep-10 | 09-Sep-10 | 15-Sep-10 | –5 |
| 1120 | 2nd floor plumbing rough-in | 1 | 1 | 0 | 02-Nov-10 | 03-Nov-10 | 03-Feb-11 | 03-Feb-11 | 57 |
| 1330 | 1st floor plumbing: install fixtures | 2 | 2 | 0 | 28-Jan-11 | 01-Feb-11 | 03-Feb-11 | 04-Feb-11 | 4 |
| 1410 | 2nd floor plumbing: install fixtures | 2 | 2 | 0 | 11-Feb-11 | 15-Feb-11 | 04-Feb-11 | 07-Feb-11 | –3 |
| 1480 | Plumbing finish | 2 | 2 | 0 | 15-Feb-11 | 17-Feb-11 | 11-Mar-11 | 14-Mar-11 | 16 |
| **Rabbit-the-Roofer** | | **11** | **11** | | **23-Dec-10** | **07-Jan-11** | **16-Dec-10** | **14-Mar-11** | **47** |
| 1240 | Roof felt | 1 | 1 | 0 | 23-Dec-10 | 27-Dec-10 | 16-Dec-10 | 16-Dec-10 | –5 |
| 1265 | Roof shingles | 6 | 6 | 0 | 27-Dec-10 | 07-Jan-11 | 03-Mar-11 | 14-Mar-11 | 43 |
| **Tile and Carpet Co., Inc.** | | **21** | **21** | | **21-Feb-11** | **22-Mar-11** | **23-Feb-11** | **14-Mar-11** | **–5** |
| 1360 | 1st floor flooring | 12 | 12 | 0 | 21-Feb-11 | 11-Mar-11 | 23-Feb-11 | 14-Mar-11 | 2 |
| 1450 | 2nd floor flooring | 10 | 10 | 0 | 04-Mar-11 | 22-Mar-11 | 25-Feb-11 | 14-Mar-11 | –5 |
| **Windows & Doors NT** | | **20** | **20** | | **11-Jan-11** | **08-Feb-11** | **18-Feb-11** | **14-Mar-11** | **25** |
| 1220 | 2nd floor door & window frames | 5 | 5 | 0 | 11-Jan-11 | 18-Jan-11 | 18-Feb-11 | 24-Feb-11 | 26 |
| 1150 | 1st floor door & window frames | 5 | 5 | 0 | 18-Jan-11 | 25-Jan-11 | 18-Feb-11 | 24-Feb-11 | 21 |
| 1370 | 2nd floor: hang doors & windows | 10 | 10 | 0 | 18-Jan-11 | 01-Feb-11 | 25-Feb-11 | 14-Mar-11 | 26 |
| 1290 | 1st floor: hang doors & windows | 10 | 10 | 0 | 25-Jan-11 | 08-Feb-11 | 25-Feb-11 | 14-Mar-11 | 21 |
| **Zapp Electric Co.** | | **41** | **41** | | **14-Jan-11** | **14-Mar-11** | **07-Feb-11** | **14-Mar-11** | **1** |
| 1130 | 1st floor electrical rough-in | 4 | 4 | 0 | 14-Jan-11 | 20-Jan-11 | 07-Feb-11 | 14-Feb-11 | 16 |
| 1200 | 2nd floor electrical rough-in | 4 | 4 | 0 | 18-Jan-11 | 24-Jan-11 | 11-Feb-11 | 16-Feb-11 | 16 |
| 1350 | 1st floor electrical finish | 6 | 6 | 0 | 11-Feb-11 | 21-Feb-11 | 15-Feb-11 | 22-Feb-11 | 2 |
| 1430 | 2nd floor electrical finish | 6 | 6 | 0 | 23-Feb-11 | 03-Mar-11 | 17-Feb-11 | 24-Feb-11 | –4 |
| 1500 | Electrical final | 4 | 4 | 0 | 04-Mar-11 | 14-Mar-11 | 07-Mar-11 | 14-Mar-11 | 1 |
| **Total** | | **169** | **148** | | **02-Aug-10 A** | **25-Mar-11** | **23-Aug-10** | **17-Mar-11** | **–5** |

*Source*: © Primavera Systems, Inc.

**Table B.2 Apex Project—List of Activities (an asterisk indicates a constraint on the activity)**

| Department Activity ID | Activity Name | Orig Dur | Rem Dur | % | Calendar | Resp | Start | Finish |
|---|---|---|---|---|---|---|---|---|
| **Engineering Department** | | | | | | | | |
| CS300 | System design | 30 | 30 | 0 | Conveyor System Calendar 1 | MF | 01-Apr-03* | 12-May-03 |
| CS310 | Review and approve design | 8 | 8 | 0 | Conveyor System Calendar 1 | MF | 13-May-03 | 22-May-03 |
| CS430 | Prepare drawings for conveyors | 10 | 10 | 0 | Conveyor System Calendar 1 | MF | 23-May-03 | 05-Jun-03 |
| CS440 | Review and approve drawings for conveyors | 7 | 7 | 0 | Conveyor System Calendar 1 | MF | 06-Jun-03 | 17-Jun-03 |
| BA400 | Design building addition | 23 | 0 | 100 | Office Building Addition Calendar 1 | GG | 04-Jun-02 A | 04-Jul-02 A |
| BA469 | Assemble technical data for heat pump | 3 | 0 | 100 | Office Building Addition Calendar 1 | GG | 18-Jul-02 A | 22-Jul-02 A |
| BA470 | Review technical data on heat pumps | 10 | 0 | 100 | Office Building Addition Calendar 1 | GG | 23-Jul-02 A | 05-Aug-02 A |
| BA501 | Review and approve designs | 9 | 0 | 100 | Office Building Addition Calendar 1 | GG | 05-Jul-02 A | 17-Jul-02 A |
| BA530 | Review and approve brick samples | 10 | 0 | 100 | Office Building Addition Calendar 1 | JN | 23-Jul-02 A | 05-Aug-02 A |
| BA560 | Review and approve flooring | 10 | 0 | 100 | Office Building Addition Calendar 1 | LH | 30-Jul-02 A | 12-Aug-02 A |
| AS100 | Define system requirements | 14 | 0 | 100 | Automated System Calendar 1 | KL | 04-Jun-02 A | 21-Jun-02 A |
| AS101 | System design | 30 | 0 | 100 | Automated System Calendar 1 | KL | 24-Jun-02 A | 02-Aug-02 A |
| AS102 | Approve system design | 5 | 0 | 100 | Automated System Calendar 1 | KL | 05-Aug-02 A | 09-Aug-02 A |
| AS204 | Prepare drawings for temperature control equipment | 14 | 0 | 100 | Automated System Calendar 1 | KL | 22-Jul-02 A | 08-Aug-02 A |
| AS205 | Review and approve temperature control equipment | 5 | 0 | 100 | Automated System Calendar 1 | KL | 09-Aug-02 A | 15-Aug-02 A |
| AS216 | Prepare drawings for system controller | 4 | 0 | 100 | Automated System Calendar 1 | KL | 22-Jul-02 A | 25-Jul-02 A |
| AS217 | Review and approve system controller | 5 | 0 | 100 | Automated System Calendar 1 | KL | 26-Jul-02 A | 02-Aug-02 A |
| **Subtotal** | | 270 | 55 | | | | 04-Jun-02 A | 17-Jun-03 A |

(*continued overleaf*)

**Table B.2 (*Continued*)**

| Department<br>Activity ID | Activity Name | Orig Dur | Rem Dur | % | Calendar | Resp | Start | Finish |
|---|---|---|---|---|---|---|---|---|
| **Purchasing Department** | | | | | | | | |
| CS400 | Prepare and solicit bids for conveyors | 12 | 12 | 0 | Conveyor System Calendar 1 | KL | 17-Jun-03 | 03-Jul-03 |
| CS410 | Review bids for conveyors | 2 | 2 | 0 | Conveyor System Calendar 1 | KL | 03-Jul-03 | 07-Jul-03 |
| CS420 | Award contract | 1 | 1 | 0 | Conveyor System Calendar 1 | KL | 07-Jul-03 | 08-Jul-03 |
| CS450 | Fabricate and deliver conveyors | 34 | 34 | 0 | Conveyor System Calendar 1 | KL | 08-Jul-03 | 25-Aug-03 |
| BA407 | Prepare and solicit bids for flooring | 5 | 0 | 100 | Office Building Addition Calendar 1 | LH | 13-Aug-02 A | 19-Aug-02 A |
| BA408 | Review bids for flooring | 3 | 0 | 100 | Office Building Addition Calendar 1 | LH | 20-Aug-02 A | 22-Aug-02 A |
| BA409 | Award contract for flooring | 1 | 0 | 100 | Office Building Addition Calendar 1 | LH | 23-Aug-02 A | 23-Aug-02 A |
| BA411 | Prepare and solicit bids for heat pump | 3 | 0 | 100 | Office Building Addition Calendar 1 | JN | 06-Aug-02 A | 08-Aug-02 A |
| BA412 | Review bids for heat pump | 2 | 0 | 100 | Office Building Addition Calendar 1 | JN | 09-Aug-02 A | 12-Aug-02 A |
| BA413 | Award contract for heat pump | 1 | 0 | 100 | Office Building Addition Calendar 1 | JN | 13-Aug-02 A | 13-Aug-02 A |
| BA421 | Prepare and solicit bids for brick exterior | 3 | 0 | 100 | Office Building Addition Calendar 1 | JN | 06-Aug-02 A | 08-Aug-02 A |
| BA422 | Review bids for brick | 3 | 0 | 100 | Office Building Addition Calendar 1 | JN | 09-Aug-02 A | 13-Aug-02 A |
| BA423 | Award contract for brick | 1 | 0 | 100 | Office Building Addition Calendar 1 | JN | 14-Aug-02 A | 14-Aug-02 A |
| BA450 | Assemble brick samples | 3 | 0 | 100 | Office Building Addition Calendar 1 | JN | 18-Jul-02 A | 22-Jul-02 A |
| BA480 | Assemble and submit flooring samples | 8 | 0 | 100 | Office Building Addition Calendar 1 | LH | 18-Jul-02 A | 29-Jul-02 A |
| BA550 | Fabricate and deliver heat pump and controls | 88 | 0 | 100 | Office Building Addition Calendar 1 | JN | 14-Aug-02 A | 13-Dec-02 A |
| BA600 | Deliver brick | 58 | 0 | 100 | Office Building Addition Calendar 1 | JN | 15-Aug-02 A | 05-Nov-02 A |
| BA620 | Fabricate and deliver flooring | 58 | 0 | 100 | Office Building Addition Calendar 1 | LH | 26-Aug-02 A | 13-Nov-02 A |
| AS200 | Prepare and solicit bids for temperature control equipment | 3 | 0 | 100 | Automated System Calendar 1 | MF | 16-Aug-02 A | 21-Aug-02 A |

**Table B.2 (*Continued*)**

| Department<br>Activity ID | Activity Name | Orig Dur | Rem Dur | % | Calendar | Resp | Start | Finish |
|---|---|---|---|---|---|---|---|---|
| AS201 | Review bids for temperature control equipment | 5 | 0 | 100 | Automated System Calendar 1 | MF | 21-Aug-02 A | 27-Aug-02 A |
| AS202 | Award contract for temperature control equipment | 0 | 0 | 100 | Automated System Calendar 1 | MF | 28-Aug-02 A | 28-Aug-02 A |
| AS213 | Prepare and solicit bids for system controller | 7 | 0 | 100 | Automated System Calendar 1 | KL | 02-Aug-02 A | 13-Aug-02 A |
| AS214 | Review bids for system controller | 4 | 0 | 100 | Automated System Calendar 1 | KL | 13-Aug-02 A | 19-Aug-02 A |
| AS215 | Award contract for system controller | 1 | 0 | 100 | Automated System Calendar 1 | KL | 19-Aug-02 A | 20-Aug-02 A |
| AS218 | Fabricate and deliver system controller | 24 | 0 | 100 | Automated System Calendar 1 | KL | 20-Aug-02 A | 23-Sep-02 A |
| AS206 | Fabricate & deliver temperature control equipment | 17 | 0 | 100 | Automated System Calendar 1 | MF | 28-Aug-02 A | 19-Sep-02 A |
| **Subtotal** | | 287 | 49 | | | | 18-Jul-02 A | 25-Aug-03 A |
| **Construction Department** | | | | | | | | |
| BA750 | Brick exterior walls | 7 | 7 | 0 | Standard 5-Day Workweek | JN | 24-Jan-03 | 03-Feb-03 |
| BA840 | Rough-in plumbing/piping | 1 | 1 | 0 | Office Building Addition Calendar 1 | JN | 24-Jan-03 | 24-Jan-03 |
| BA860 | Install elevator rails and equipment | 1 | 1 | 0 | Office Building Addition Calendar 1 | JN | 24-Jan-03 | 24-Jan-03 |
| BA770 | Install door and window frames | 1 | 1 | 0 | Office Building Addition Calendar 1 | JN | 31-Jan-03 | 31-Jan-03 |
| BA790 | Install exterior doors and windows | 2 | 2 | 0 | Office Building Addition Calendar 1 | JN | 03-Feb-03 | 04-Feb-03 |
| BA780 | Insulation and built-up roofing | 10 | 10 | 0 | Office Building Addition Calendar 1 | JN | 04-Feb-03 | 17-Feb-03 |
| BA741 | Close-in phase begins | 0 | 0 | 0 | Office Building Addition Calendar 1 | JN | 04-Feb-03 | |
| BA800 | Building enclosed | 0 | 0 | 0 | Office Building Addition Calendar 1 | JN | | 17-Feb-03 |
| BA850 | Install wiring and cable | 15 | 15 | 0 | Office Building Addition Calendar 1 | JN | 18-Feb-03 | 10-Mar-03 |
| BA830 | Insulate ducts | 2 | 2 | 0 | Office Building Addition Calendar 1 | JN | 18-Feb-03 | 19-Feb-03 |

(*continued overleaf*)

**Table B.2 (*Continued*)**

| Department Activity ID | Activity Name | Orig Dur | Rem Dur | % | Calendar | Resp | Start | Finish |
|---|---|---|---|---|---|---|---|---|
| BA831 | Set heat pump | 5 | 5 | 0 | Office Building Addition Calendar 1 | JN | 20-Feb-03 | 26-Feb-03 |
| BA983 | Relocate HVAC chiller | 3 | 3 | 0 | Standard 5-Day Workweek | JN | 27-Feb-03 | 03-Mar-03 |
| BA870 | Connect equipment | 3 | 3 | 0 | Office Building Addition Calendar 1 | JN | 11-Mar-03 | 13-Mar-03 |
| BA871 | Start up and test HVAC | 1 | 1 | 0 | Office Building Addition Calendar 1 | JN | 14-Mar-03 | 14-Mar-03 |
| BA880 | Rough-in complete | 0 | 0 | 0 | Office Building Addition Calendar 1 | JN | | 14-Mar-03 |
| BA890 | Drywall in offices | 15 | 15 | 0 | Office Building Addition Calendar 1 | LH | 17-Mar-03 | 04-Apr-03 |
| BA913 | Install elevator cab and finishes | 2 | 2 | 0 | Office Building Addition Calendar 1 | JN | 17-Mar-03 | 18-Mar-03 |
| BA930 | Paint building interior | 15 | 15 | 0 | Office Building Addition Calendar 1 | LH | 26-Mar-03 | 15-Apr-03 |
| BA900 | Install ceiling grid | 15 | 15 | 0 | Office Building Addition Calendar 1 | LH | 07-Apr-03 | 25-Apr-03 |
| BA899 | Finishes phase begins | 1 | 1 | 0 | Office Building Addition Calendar 1 | LH | 07-Apr-03 | 07-Apr-03 |
| BA902 | Install AC grills and registers | 5 | 5 | 0 | Office Building Addition Calendar 1 | JN | 17-Apr-03 | 23-Apr-03 |
| BA901 | Install lighting fixtures | 3 | 3 | 0 | Office Building Addition Calendar 1 | LH | 17-Apr-03 | 21-Apr-03 |
| BA910 | Install floor and carpeting | 5 | 5 | 0 | Office Building Addition Calendar 1 | LH | 28-Apr-03 | 02-May-03 |
| BA911 | Finish carpentry and millwork | 5 | 5 | 0 | Office Building Addition Calendar 1 | LH | 05-May-03 | 09-May-03 |
| BA912 | Install plumbing fixtures | 2 | 2 | 0 | Office Building Addition Calendar 1 | LH | 05-May-03 | 06-May-03 |
| BA940 | Touch-up and cleanup | 1 | 1 | 0 | Office Building Addition Calendar 1 | LH | 12-May-03 | 12-May-03 |
| BA941 | Test and balance HVAC equipment | 1 | 1 | 0 | Office Building Addition Calendar 1 | JN | 13-May-03 | 13-May-03 |
| BA950 | Finishes milestone | 0 | 0 | 0 | Office Building Addition Calendar 1 | LH | 14-May-03 | 14-May-03 |
| BA960 | Punch list | 2 | 2 | 0 | Office Building Addition Calendar 1 | LH | 14-May-03 | 15-May-03 |
| BA970 | Building addition complete | 0 | 0 | 0 | Office Building Addition Calendar 1 | LH | 16-May-03 | 16-May-03 |
| CS305 | Start up & debug system | 9 | 9 | 0 | Conveyor System Calendar 1 | JN | 11-Dec-03 | 24-Dec-03 |

**Table B.2 (*Continued*)**

| Department Activity ID | Activity Name | Orig Dur | Rem Dur | % | Calendar | Resp | Start | Finish |
|---|---|---|---|---|---|---|---|---|
| BA630 | Begin building construction | 0 | 0 | 100 | Office Building Addition Calendar 1 | KL | 18-Jul-02 A | |
| BA640 | Site preparation | 18 | 0 | 100 | Office Building Addition Calendar 1 | KL | 18-Jul-02 A | 12-Aug-02 A |
| BA650 | Excavation | 10 | 0 | 100 | Office Building Addition Calendar 1 | KL | 13-Aug-02 A | 26-Aug-02 A |
| BA660 | Install underground water lines | 5 | 0 | 100 | Office Building Addition Calendar 1 | KL | 27-Aug-02 A | 02-Sep-02 A |
| BA670 | Install underground electric conduit | 5 | 0 | 100 | Office Building Addition Calendar 1 | KL | 27-Aug-02 A | 02-Sep-02 A |
| BA680 | Form/pour concrete footings | 10 | 0 | 100 | Office Building Addition Calendar 1 | KL | 03-Sep-02 A | 16-Sep-02 A |
| BA681 | Concrete foundation walls | 10 | 0 | 100 | Office Building Addition Calendar 1 | KL | 17-Sep-02 A | 30-Sep-02 A |
| BA690 | Form and pour slab | 5 | 0 | 100 | Office Building Addition Calendar 1 | KL | 01-Oct-02 A | 07-Oct-02 A |
| BA700 | Backfill and compact walls | 2 | 0 | 100 | Office Building Addition Calendar 1 | KL | 08-Oct-02 A | 09-Oct-02 A |
| BA701 | Foundation phase complete | 0 | 0 | 100 | Office Building Addition Calendar 1 | KL | | 09-Oct-02 A |
| BA702 | Begin structural phase | 0 | 0 | 100 | Office Building Addition Calendar 1 | KL | 07-Nov-02 A | |
| BA710 | Erect structural frame | 20 | 0 | 100 | Office Building Addition Calendar 1 | KL | 10-Oct-02 A | 06-Nov-02 A |
| BA712 | Floor decking | 14 | 0 | 100 | Office Building Addition Calendar 1 | KL | 07-Nov-02 A | 26-Nov-02 A |
| BA720 | Erect stairwell and elevator walls | 10 | 0 | 100 | Office Building Addition Calendar 1 | KL | 18-Dec-02 A | 31-Dec-02 A |
| BA730 | Concrete first floor | 15 | 0 | 100 | Office Building Addition Calendar 1 | KL | 27-Nov-02 A | 17-Dec-02 A |
| BA731 | Concrete basement slab | 10 | 0 | 100 | Office Building Addition Calendar 1 | KL | 18-Dec-02 A | 31-Dec-02 A |
| BA732 | Structure complete | 0 | 0 | 100 | Office Building Addition Calendar 1 | KL | 01-Jan-03 A | 01-Jan-03 A |
| BA809 | Rough-in phase begins | 0 | 0 | 100 | Office Building Addition Calendar 1 | JN | 27-Dec-02 A | |
| BA810 | Set mechanical and electrical equipment | 15 | 0 | 100 | Office Building Addition Calendar 1 | JN | 06-Dec-02 A | 26-Dec-02 A |
| BA820 | Install HVAC ducts | 10 | 0 | 100 | Office Building Addition Calendar 1 | JN | 27-Dec-02 A | 09-Jan-03 A |
| BA735 | Concrete second floor | 15 | 0 | 100 | Office Building Addition Calendar 1 | KL | 18-Dec-02 A | 07-Jan-03 A |
| **Subtotal** | | 374 | 238 | | | | 18-Jul-02 A | 24-Dec-03 A |

(*continued overleaf*)

**Table B.2 (*Continued*)**

| Department Activity ID | Activity Name | Orig Dur | Rem Dur | % | Calendar | Resp | Start | Finish |
|---|---|---|---|---|---|---|---|---|
| **Information Systems Department** | | | | | | | | |
| AS110 | Test & debug line B | 19 | 5 | 74.17 | Automated System Calendar 1 | JM | 02-Dec-02 A | 16-Dec-02 |
| AS109 | Test & debug line A | 19 | 5 | 74.17 | Automated System Calendar 1 | JM | 02-Dec-02 A | 16-Dec-02 |
| AS108 | Install system controller | 13 | 7 | 47.62 | Automated System Calendar 1 | KL | 02-Dec-02 A | 18-Dec-02 |
| AS250 | Install bar rails | 4 | 3 | 23.8 | Automated System Calendar 1 | KL | 09-Dec-02 A | 13-Dec-02 |
| AS270 | Trim robot paths line B | 2 | 2 | 0 | Automated System Calendar 1 | KL | 13-Dec-02 | 16-Dec-02 |
| AS260 | Trim robot paths line A | 2 | 2 | 0 | Automated System Calendar 1 | KL | 13-Dec-02 | 16-Dec-02 |
| AS112 | Start-up line B | 8 | 8 | 0 | Automated System Calendar 1 | JM | 17-Dec-02 | 26-Dec-02 |
| AS111 | Pilot start line A | 2 | 2 | 0 | Automated System Calendar 1 | JM | 17-Dec-02 | 18-Dec-02 |
| AS265 | Path refinement and shakedownline A | 4 | 4 | 0 | Automated System Calendar 1 | JM | 19-Dec-02 | 24-Dec-02 |
| AS275 | Path refinement and shakedownline B | 4 | 4 | 0 | Automated System Calendar 1 | JM | 27-Dec-02 | 01-Jan-03 |
| AS113 | Install proces-sor/software/data tapes | 3 | 3 | 0 | Automated System Calendar 1 | LH | 02-Jan-03 | 06-Jan-03 |
| AS150 | Production start | 0 | 0 | 0 | Automated System Calendar 1 | LH | 02-Jan-03 | |
| AS114 | Calibrate robot controller & power up | 1 | 1 | 0 | Automated System Calendar 1 | KL | 07-Jan-03 | 07-Jan-03 |
| AS115 | Load system software | 1 | 1 | 0 | Automated System Calendar 1 | LH | 08-Jan-03 | 08-Jan-03 |
| AS116 | Program | 14 | 14 | 0 | Automated System Calendar 1 | LH | 09-Jan-03 | 28-Jan-03 |
| AS600 | Manual operation ready | 0 | 0 | 0 | Automated System Calendar 1 | LH | 09-Jan-03 | 09-Jan-03 |
| AS280 | Test software | 4 | 4 | 0 | Automated System Calendar 1 | LH | 29-Jan-03 | 03-Feb-03 |
| AS285 | Debug software | 6 | 6 | 0 | Automated System Calendar 1 | LH | 04-Feb-03 | 11-Feb-03 |
| AS117 | Start-up procedure development | 2 | 2 | 0 | Automated System Calendar 1 | LH | 12-Feb-03 | 13-Feb-03 |
| AS500 | Automatic operation ready | 0 | 0 | 0 | Automated System Calendar 1 | LH | 12-Feb-03 | 12-Feb-03 |

**Table B.2 (*Continued*)**

| Department Activity ID | Activity Name | Orig Dur | Rem Dur | % | Calendar | Resp | Start | Finish |
|---|---|---|---|---|---|---|---|---|
| AS118 | Training manuals/system operation | 7 | 7 | 0 | Automated System Calendar 1 | JM | 14-Feb-03 | 24-Feb-03 |
| AS900 | System buyoff | 0 | 0 | 0 | Standard 5-Day Workweek | KL | | 24-Feb-03 |
| CS311 | Start conveyor installation | 0 | 0 | 0 | Conveyor System Calendar 1 | JN | 01-Apr-03 | ] |
| CS315 | Site preparation | 18 | 18 | 0 | Conveyor System Calendar 1 | JN | 01-Apr-03 | 24-Apr-03 |
| CS700 | Install conveyor 211 | 12 | 12 | 0 | Conveyor System Calendar 1 | JN | 25-Aug-03 | 10-Sep-03 |
| CS770 | Operation manuals | 18 | 18 | 0 | Conveyor System Calendar 1 | KL | 25-Aug-03 | 18-Sep-03 |
| CS710 | Install conveyor 212 | 8 | 8 | 0 | Conveyor System Calendar 1 | JN | 10-Sep-03 | 22-Sep-03 |
| CS720 | Install conveyor 213 | 9 | 9 | 0 | Conveyor System Calendar 1 | JN | 22-Sep-03 | 03-Oct-03 |
| CS730 | Install conveyor 214 | 10 | 10 | 0 | Conveyor System Calendar 1 | JN | 03-Oct-03 | 17-Oct-03 |
| CS740 | Field piping | 10 | 10 | 0 | Conveyor System Calendar 1 | JN | 07-Nov-03 | 20-Nov-03 |
| CS750 | Field wiring | 10 | 10 | 0 | Conveyor System Calendar 1 | JN | 07-Nov-03 | 20-Nov-03 |
| CS760 | Field painting | 4 | 4 | 0 | Conveyor System Calendar 1 | JN | 05-Dec-03 | 11-Dec-03 |
| CS800 | Conveyor system complete | 0 | 0 | 0 | Conveyor System Calendar 1 | JN | | 24-Dec-03 |
| AS103 | Install robot base | 14 | 0 | 100 | Automated System Calendar 1 | KL | 15-Aug-02 A | 04-Sep-02 A |
| AS104 | Run sealant, air, & water piping | 13 | 0 | 100 | Automated System Calendar 1 | KL | 15-Aug-02 A | 02-Sep-02 A |
| AS105 | Install temperature control equipment | 29 | 0 | 100 | Automated System Calendar 1 | MF | 20-Sep-02 A | 30-Oct-02 A |
| AS106 | Set & connect robots | 3 | 0 | 100 | Automated System Calendar 1 | KL | 30-Oct-02 A | 05-Nov-02 A |
| AS219 | Install system & miscellaneous components | 19 | 0 | 100 | Automated System Calendar 1 | KL | 05-Nov-02 A | 02-Dec-02 A |
| AS240 | Installation begins | 0 | 0 | 100 | Automated System Calendar 1 | PR | 15-Aug-02 A | |
| AS310 | Site preparation | 3 | 0 | 100 | Automated System Calendar 1 | GG | 12-Aug-02 A | 14-Aug-02 A |
| AS315 | Install electrical power | 14 | 0 | 100 | Automated System Calendar 1 | JM | 15-Aug-02 A | 04-Sep-02 A |
| **Subtotal** | | 357 | 271 | | | | 12-Aug-02 A | 24-Dec-03 A |

**Table B.3 List of Activities with Predecessors and Successors**

| Activity ID | Activity Name | Original Duration | Activity Status | Predecessors | Successors |
|---|---|---|---|---|---|
| BA702 | Begin structural phase | 0 | Completed | BA710 | |
| BA712 | Floor decking | 14 | Completed | BA710 | BA730 |
| BA720 | Erect stairwell and elevator walls | 10 | Completed | BA730 | BA732, BA860 |
| BA730 | Concrete first floor | 15 | Completed | BA712 | BA720, BA731, BA810, BA735 |
| BA731 | Concrete basement slab | 10 | Completed | BA730 | BA732 |
| BA732 | Structure complete | 0 | Completed | BA720, BA731 | BA750 |
| BA735 | Concrete second floor | 15 | Completed | BA730 | |
| BA741 | Close-in phase begins | 0 | Not Started | BA750 | |
| BA750 | Brick exterior walls | 7 | Not Started | BA600, BA732 | BA741, BA770, BA780 |
| BA770 | Install door and window frames | 1 | Not Started | BA750 | BA790 |
| BA780 | Insulation and built-up roofing | 10 | Not Started | BA750, BA790 | BA800 |
| BA790 | Install exterior doors and windows | 2 | Not Started | BA770 | BA780, BA800 |
| BA800 | Building enclosed | 0 | Not Started | BA780, BA790 | BA830, BA831, BA850, BA890, BA913 |
| BA809 | Rough-in phase begins | 0 | Completed | BA810 | |
| BA810 | Set mechanical and electrical equipment | 15 | Completed | BA730 | BA809, BA820 |
| BA820 | Install HVAC ducts | 10 | Completed | BA810 | BA830, BA840 |
| BA830 | Insulate ducts | 2 | Not Started | BA800, BA820 | BA831 |
| BA831 | Set heat pump | 5 | Not Started | BA550, BA800, BA830 | BA870, BA983 |
| BA840 | Rough-in plumbing/piping | 1 | Not Started | BA820 | BA850 |
| BA850 | Install wiring and cable | 15 | Not Started | BA800, BA840 | BA870 |
| BA860 | Install elevator rails and equipment | 1 | Not Started | BA720 | BA880 |
| BA870 | Connect equipment | 3 | Not Started | BA831, BA850 | BA871 |
| BA871 | Start up and test HVAC | 1 | Not Started | BA870, BA983 | BA880 |
| BA880 | Rough-in complete | 0 | Not Started | BA860, BA871 | BA890, BA913 |
| BA890 | Drywall in offices | 15 | Not Started | BA800, BA880 | BA899, BA900, BA930 |
| BA899 | Finishes phase begins | 1 | Not Started | BA890 | |
| BA900 | Install ceiling grid | 15 | Not Started | BA890 | BA901, BA902, BA910 |
| BA901 | Install lighting fixtures | 3 | Not Started | BA900 | BA910 |
| BA902 | Install AC grills and registers | 5 | Not Started | BA900 | BA910 |
| BA910 | Install floor and carpeting | 5 | Not Started | BA620, BA900, BA901, BA902 | BA911, BA912 |

**Table B.3 (*Continued*)**

| Activity ID | Activity Name | Original Duration | Activity Status | Predecessors | Successors |
|---|---|---|---|---|---|
| BA911 | Finish carpentry and millwork | 5 | Not Started | BA910 | BA940 |
| BA912 | Install plumbing fixtures | 2 | Not Started | BA910 | BA940 |
| BA913 | Install elevator cab and finishes | 2 | Not Started | BA800, BA880 | BA940 |
| BA930 | Paint building interior | 15 | Not Started | BA890 | BA940 |
| BA940 | Touch-up and cleanup | 1 | Not Started | BA911, BA912, BA913, BA930 | BA941 |
| BA941 | Test and balance HVAC equipment | 1 | Not Started | BA940 | BA950 |
| BA950 | Finishes milestone | 0 | Not Started | BA941 | BA960 |
| BA960 | Punch list | 2 | Not Started | BA950 | BA970 |
| BA970 | Building addition complete | 0 | Not Started | BA960 | |
| BA983 | Relocate HVAC chiller | 3 | Not Started | BA831 | BA871 |
| CS305 | Start up and debug system | 9 | Not Started | CS730, CS740, CS750, CS760 | CS800 |

**Table B.4 Earned Value Report**

| WBS Activity ID | Activity Name | Activity Status | Planned Cost (BCWS) | Actual Cost (ACWP) | Earned Value (BCWS) | Cost Variance | Variance at Completion |
|---|---|---|---|---|---|---|---|
| Caprini Corporation | | | | | | | |
| Apex Project | | | | | | | |
| Apex Construction | | | | | | | |
| Office Building Addition | | | | | | | |
| Design and Engineering | | | | | | | |
| BA400 | Design building addition | Completed | $5,520.00 | $5,520.00 | $5,520.00 | $0.00 | $0.00 |
| BA469 | Assemble technical data for heat pump | Completed | $720.00 | $720.00 | $720.00 | $0.00 | $0.00 |
| BA470 | Review technical data on heat pumps | Completed | $2,400.00 | $2,400.00 | $2,400.00 | $0.00 | $0.00 |
| BA501 | Review and approve designs | Completed | $0.00 | $1,800.00 | $0.00 | ($1,800.00) | ($1,800.00) |
| **Subtotal** | | | **$8,640.00** | **$10,440.00** | **$8,640.00** | **($1,800.00)** | **($1,800.00)** |

(*continued overleaf*)

**Table B.4 (*Continued*)**

| WBS Activity ID | Activity Name | Activity Status | Planned Cost (BCWS) | Actual Cost (ACWP) | Earned Value (BCWS) | Cost Variance | Variance at Completion |
|---|---|---|---|---|---|---|---|
| **Foundation** | | | | | | | |
| BA630 | Begin building construction | Completed | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA640 | Site preparation | Completed | $3,096.00 | $532.69 | $3,096.00 | $2,563.31 | $2,563.31 |
| BA650 | excavation | Completed | $1,720.00 | $14.58 | $1,720.00 | $1,705.42 | $1,705.42 |
| BA660 | Install underground water lines | Completed | $1,320.00 | $6.11 | $1,320.00 | $1,313.89 | $1,313.89 |
| BA670 | Install underground electric conduit | Completed | $1,280.00 | $5.93 | $1,280.00 | $1,274.07 | $1,274.07 |
| BA680 | Form/pour concrete footings | Completed | $13,160.00 | $394.95 | $13,160.00 | $12,765.05 | $11,965.05 |
| BA681 | Concrete foundation walls | Completed | $9,960.00 | $409.33 | $9,960.00 | $9,550.67 | $8,750.67 |
| BA690 | Form and pour slab | Completed | $5,940.00 | $147.59 | $5,940.00 | $5,792.41 | $5,392.41 |
| BA700 | Backfill and compact walls | Completed | $728.00 | $1.87 | $728.00 | $726.13 | $726.13 |
| BA701 | Foundation phase complete | Completed | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$37,204.00** | **$1,513.05** | **$37,204.00** | **$35,690.95** | **$33,690.95** |
| **Structure** | | | | | | | |
| BA702 | Begin structural phase | Completed | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA710 | Erect structural frame | Completed | $11,600.00 | $470.74 | $11,600.00 | $11,129.26 | $9,529.26 |
| BA712 | Floor decking | Completed | $8,120.00 | $291.20 | $8,120.00 | $7,828.80 | $6,708.80 |
| BA720 | Erect stairwell and elevator walls | Completed | $1,600.00 | $360.89 | $1,600.00 | $1,239.11 | $1,239.11 |
| BA730 | Concrete first floor | Completed | $9,510.00 | $1,888.80 | $9,510.00 | $7,621.20 | $6,421.20 |
| BA731 | Concrete basement slab | Completed | $14,600.00 | $3,591.36 | $14,600.00 | $11,008.64 | $9,408.64 |
| BA732 | Structure complete | Completed | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA735 | Concrete second floor | Completed | $9,510.00 | $3,957.50 | $9,510.00 | $5,552.50 | $4,352.50 |
| **Subtotal** | | | **$54,940.00** | **$10,560.49** | **$54,940.00** | **$44,379.51** | **$37,659.51** |

**Table B.4 (*Continued*)**

| WBS Activity ID | Activity Name | Activity Status | Planned Cost (BCWS) | Actual Cost (ACWP) | Earned Value (BCWS) | Cost Variance | Variance at Completion |
|---|---|---|---|---|---|---|---|
| **Mechanical/Electrical Systems** | | | | | | | |
| BA809 | Rough-in phase begins | Completed | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA880 | Rough-in complete | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Elevator** | | | | | | | |
| BA860 | Install elevator rails and equipment | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA913 | Install elevator cab and finishes | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$0.00** | **$0.00** | **$0.00** | **$0.00** | **$0.00** |
| **HVAC** | | | | | | | |
| BA411 | Prepare and solicit bids for heat pump | Completed | $384.00 | $384.00 | $384.00 | $0.00 | $0.00 |
| BA412 | Review bids for heat pump | Completed | $256.00 | $256.00 | $256.00 | $0.00 | $0.00 |
| BA413 | Award contract for heat pump | Completed | $128.00 | $128.00 | $128.00 | $0.00 | $0.00 |
| BA550 | Fabricate and deliver heat pump and controls | Completed | $21,120.00 | $14,314.67 | $21,120.00 | $6,805.33 | $6,805.33 |
| BA820 | Install HVAC ducts | Completed | $1,260.00 | $630.00 | $1,260.00 | $630.00 | $630.00 |
| BA830 | Insulate ducts | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA831 | Set heat pump | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA871 | Start up and test HVAC | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA902 | Install AC grills and registers | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA941 | Test and balance HVAC equipment | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA983 | Relocate HVAC chiller | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$23,148.00** | **$15,712.67** | **$23,148.00** | **$7,435.33** | **$7,435.33** |
| **Plumbing and Electrical** | | | | | | | |
| BA810 | Set mechanical and electrical equipment | Completed | $7,200.00 | $7,200.00 | $7,200.00 | $0.00 | $0.00 |
| BA840 | Rough-in plumbing/piping | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA850 | Install wiring and cable | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA870 | Connect equipment | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$7,200.00** | **$7,200.00** | **$7,200.00** | **$0.00** | **$0.00** |
| **Subtotal** | | | **$30,348.00** | **$22,912.67** | **$30,348.00** | **$7,435.33** | **$7,435.33** |

(*continued overleaf*)

**Table B.4 (*Continued*)**

| WBS Activity ID | Activity Name | Activity Status | Planned Cost (BCWS) | Actual Cost (ACWP) | Earned Value (BCWS) | Cost Variance | Variance at Completion |
|---|---|---|---|---|---|---|---|
| **Exterior Finishes** | | | | | | | |
| BA741 | Close-in phase begins | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA800 | Building enclosed | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Brick** | | | | | | | |
| BA421 | Prepare and solicit bids for brick exterior | Completed | $384.00 | $384.00 | $384.00 | $0.00 | $0.00 |
| BA422 | Review bids for brick exterior | Completed | $384.00 | $384.00 | $384.00 | $0.00 | $0.00 |
| BA423 | Award contract for brick exterior | Completed | $128.00 | $128.00 | $128.00 | $0.00 | $0.00 |
| BA450 | Assemble brick samples | Completed | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA530 | Review and approve brick samples | Completed | $2,400.00 | $2,400.00 | $2,400.00 | $0.00 | $0.00 |
| BA600 | Deliver brick | Completed | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA750 | Brick exterior walls | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$3,296.00** | **$3,296.00** | **$3,296.00** | **$0.00** | **$0.00** |
| **Roof** | | | | | | | |
| BA780 | Insulation and built-up roofing | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$0.00** | **$0.00** | **$0.00** | **$0.00** | **$0.00** |
| **Doors and Windows** | | | | | | | |
| BA770 | Install door and window frames | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA790 | Install exterior doors and windows | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$0.00** | **$0.00** | **$0.00** | **$0.00** | **$0.00** |
| **Subtotal** | | | **$3,296.00** | **$3,296.00** | **$3,296.00** | **$0.00** | **$0.00** |
| **Interior Finishes** | | | | | | | |
| BA890 | Drywall in offices | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA899 | Finishes phase begins | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA940 | Touch-up and cleanup | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA950 | Finishes milestone | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA960 | Punch list | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA970 | Building addition complete | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |

**Table B.4 (*Continued*)**

| WBS Activity ID | Activity Name | Activity Status | Planned Cost (BCWS) | Actual Cost (ACWP) | Earned Value (BCWS) | Cost Variance | Variance at Completion |
|---|---|---|---|---|---|---|---|
| **Plumbing and Lighting Fixtures** | | | | | | | |
| BA901 | Install lighting fixtures | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA912 | Install plumbing fixtures | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$0.00** | **$0.00** | **$0.00** | **$0.00** | **$0.00** |
| **Floor and Carpeting** | | | | | | | |
| BA407 | Prepare and solicit bids for flooring | Completed | $640.00 | $640.00 | $640.00 | $0.00 | $0.00 |
| BA408 | Review bids for flooring | Completed | $384.00 | $384.00 | $384.00 | $0.00 | $0.00 |
| BA409 | Award contract for flooring | Completed | $128.00 | $128.00 | $128.00 | $0.00 | $0.00 |
| BA480 | Assemble and submit flooring samples | Completed | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA560 | Review and approve flooring | Completed | $2,400.00 | $2,400.00 | $2,400.00 | $0.00 | $0.00 |
| BA620 | Fabricate and deliver flooring | Completed | $13,920.00 | $5,453.06 | $13,920.00 | $8,466.94 | $8,466.94 |
| BA910 | Install floor and carpeting | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$17,472.00** | **$9,005.06** | **$17,472.00** | **$8,466.94** | **$8,466.94** |
| **Carpentry** | | | | | | | |
| BA900 | Install ceiling grid | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| BA911 | Finish carpentry and millwork | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Paint** | | | | | | | |
| BA930 | Paint building interior | Not Started | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| **Subtotal** | | | **$0.00** | **$0.00** | **$0.00** | **$0.00** | **$0.00** |
| **Subtotal** | | | **$17,472.00** | **$9,005.06** | **$17,472.00** | **$8,466.94** | **$8,466.94** |
| **Subtotal** | | | **$151,900.00** | **$57,727.27** | **$151,900.00** | **$94,172.73** | **$85,452.73** |
| **Subtotal** | | | **$151,900.00** | **$57,727.27** | **$151,900.00** | **$94,172.73** | **$85,452.73** |
| **Subtotal** | | | **$151,900.00** | **$57,727.27** | **$151,900.00** | **$94,172.73** | **$85,452.73** |
| **Subtotal** | | | **$151,900.00** | **$57,727.27** | **$151,900.00** | **$94,172.73** | **$85,452.73** |
| **Total** | | | **$151,900.00** | **$57,727.27** | **$151,900.00** | **$94,172.73** | **$85,452.73** |

**Table B.5 Apex Project—Resource Control—Summary by Resource**

| Resource ID | Budgeted Units | Units % Complete | Actual Units | Actual This Period Units | Remaining Units | At-Completion Units |
|---|---|---|---|---|---|---|
| Jeff Young | 121.00 | 100.00% | 121.00 | –203.00 | 0.00 | 121.00 |
| Wendy Resner | 562.00 | 38.71% | 200.74 | –287.26 | 317.83 | 518.57 |
| Paul Kim | 600.00 | 86.67% | 520.00 | –60.00 | 80.00 | 600.00 |
| Ed Wood | 308.00 | 10.39% | 32.00 | –65.00 | 276.00 | 308.00 |
| Oliver Rock | 260.00 | 98.46% | 256.00 | 203.00 | 4.00 | 260.00 |
| Ace Corp | 1,768.00 | 84.62% | 1,496.00 | 1,496.00 | 272.00 | 1,768.00 |
| Field Engineer—Senior | 744.00 | 22.38% | 166.47 | 166.47 | 577.53 | 744.00 |
| Field Engineer | 439.00 | 43.41% | 190.23 | 190.23 | 248.00 | 438.23 |
| Field Engineer—Assistant | 136.00 | 23.25% | 31.62 | –0.38 | 104.38 | 136.00 |
| Hardware Specialist | 223.00 | 81.89% | 182.62 | 182.62 | 40.38 | 223.00 |
| Programmer | 168.00 | 0% | 0.00 | 0.00 | 168.00 | 168.00 |
| Software Engineer | 40.00 | 0% | 0.00 | 0.00 | 40.00 | 40.00 |
| Elevator Installer | 24.00 | 0% | 0.00 | 0.00 | 24.00 | 24.00 |
| Electrician | 403.00 | 58.31% | 235.00 | 235.00 | 168.00 | 403.00 |
| Excavator | 240.00 | 100% | 240.00 | 144.00 | 0.00 | 240.00 |
| Floor and Carpet Layer | 40.00 | 0% | 0.00 | 0.00 | 40.00 | 40.00 |
| Finisher | 256.00 | 100% | 256.00 | 256.00 | 0.00 | 256.00 |
| Finishes Carpenter | 328.00 | 0% | 0.00 | 0.00 | 328.00 | 328.00 |
| Ironworker | 672.00 | 100% | 672.00 | 672.00 | 0.00 | 672.00 |
| Laborer—Construction | 504.00 | 79.37% | 400.00 | 400.00 | 104.00 | 504.00 |
| Mason | 136.00 | 58.82% | 80.00 | 80.00 | 56.00 | 136.00 |
| Operating Engineer | 264.00 | 75.76% | 200.00 | 200.00 | 64.00 | 264.00 |
| Plumber | 168.00 | 85.71% | 144.00 | 144.00 | 24.00 | 168.00 |
| Painter | 144.00 | 0% | 0.00 | 0.00 | 144.00 | 144.00 |
| Rough Carpenter | 400.00 | 100% | 400.00 | 400.00 | 0.00 | 400.00 |
| Heating Ventilation & AC Technician | 120.00 | 66.67% | 80.00 | 80.00 | 40.00 | 120.00 |
| Machinist | 48.00 | 100% | 48.00 | 48.00 | 0.00 | 48.00 |
| 100-ft Crane | 8.00 | 0% | 0.00 | 0.00 | 8.00 | 8.00 |
| Piping Material | 40.00 | 80% | 32.00 | 32.00 | 8.00 | 40.00 |
| No Resource ID Name | 128.00 | 0% | 0.00 | 0.00 | 128.00 | 128.00 |
| **Total** | — | **64.7%** | — | — | — | — |

## GRAPHIC REPORTS

**Report 6:** Report 6 (Figure B.1) is a bar (Gantt) chart that shows the original duration, early dates, late dates, and total float in the tabular section. The bar chart shows the float bar. The user may opt to hide it. The report is grouped by primary code (phase) and secondary code (department).

**Report 7:** Similar to report 6, report 7 (Figure B.2) has an addition and a deletion. We added the remaining duration and percent complete (since the project has already started), and omitted the late dates and total float. We also hid the float bar in the bar chart section. In both reports 6 and 7, relationship lines may be displayed in the bar chart section.

**Report 8:** Report 8 (Figure B.3) is a logic diagram grouped by phase. Note that completed activities are shown as boxes with two diagonal lines. Boxes representing in-progress activities are designated with one diagonal line. Activities that have not started do not have diagonal lines.

**Report 9:** Report 9 (Figure B.4) looks like a tabular report, since the bar chart was hidden. The report shows activity status and budget information.

**Report 10:** Similarly to report 9, report 10 (Figure B.5) shows a bar chart. Such a report should be printed on wider paper or the font size will be too small.

**Report 11:** Report 11 (Figure B.6) is a bar chart that contains a resource usage profile.

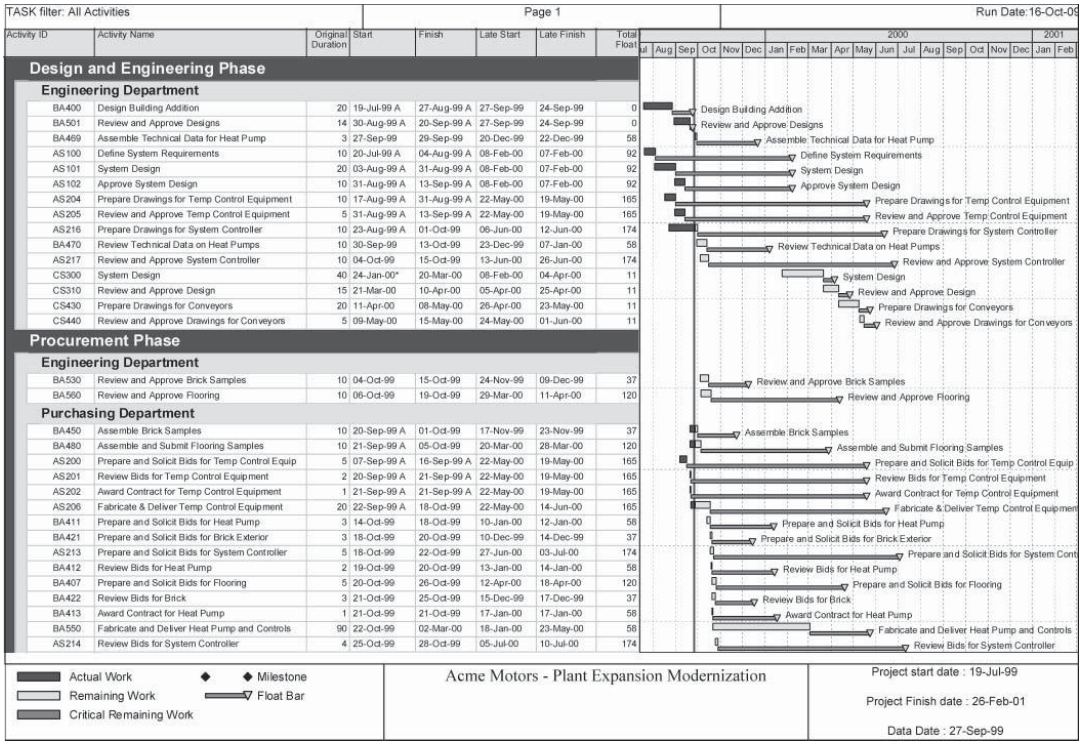



**Figure B.1 Report 6. An asterisk indicates a constraint on the activity. (Reprinted with permission from Primavera Systems, Inc. Primavera® and P6 are either trademarks or registered trademarks of Primavera Systems, Inc.)**

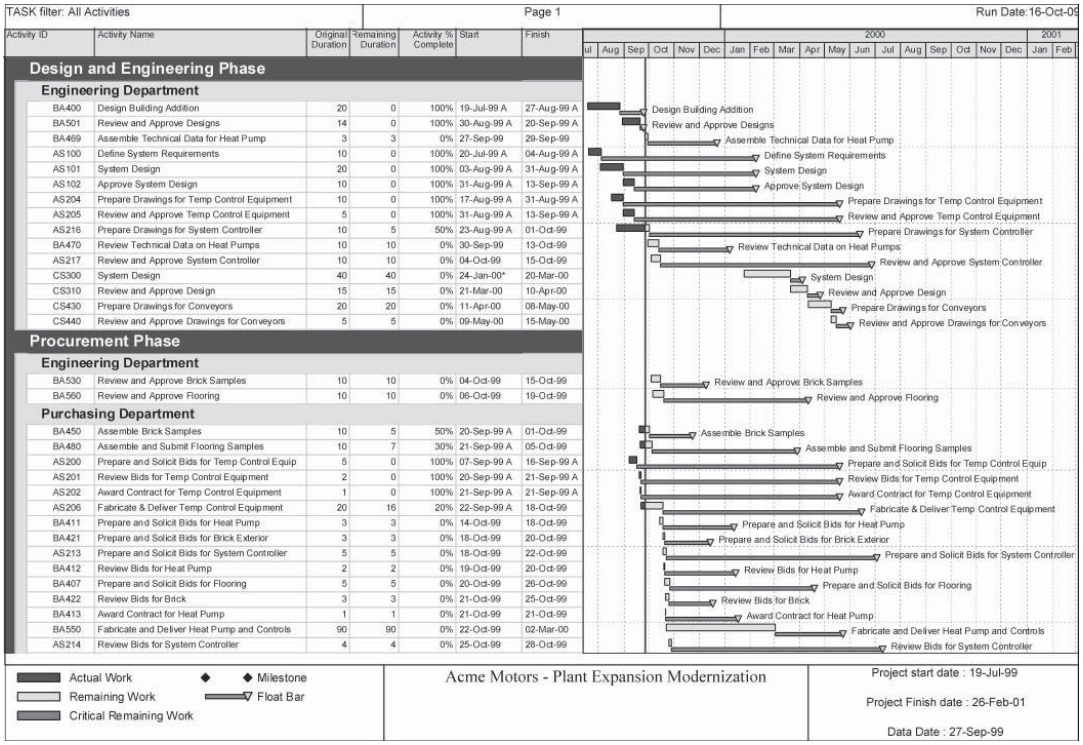



**Figure B.2a Report 7. (Reprinted with permission from Primavera Systems, Inc. Primavera® and P6 are either trademarks or registered trademarks of Primavera Systems, Inc.)**

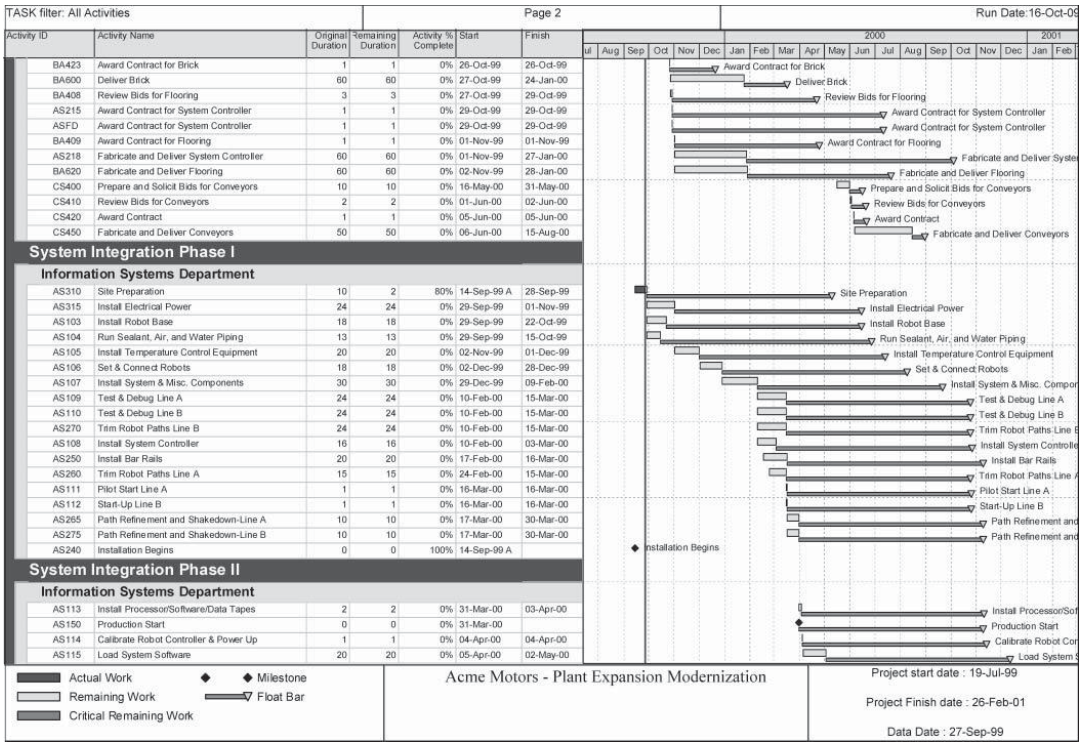



**Figure B.2b (*Continued*)**

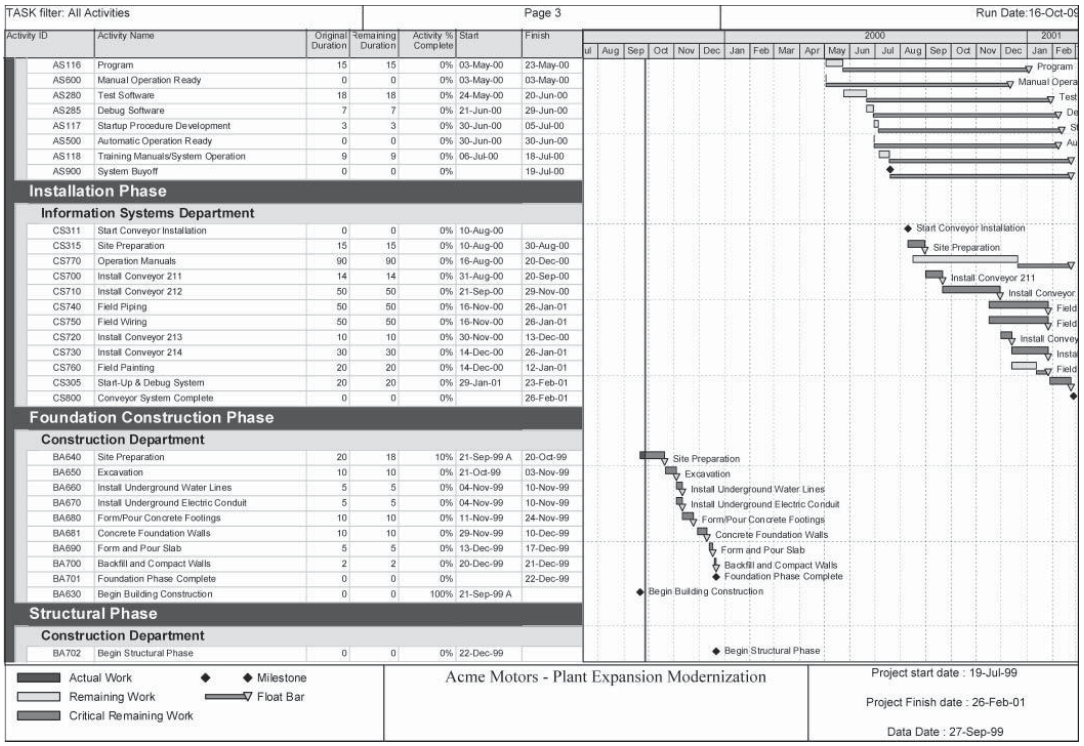



**Figure B.2c (*Continued*)**

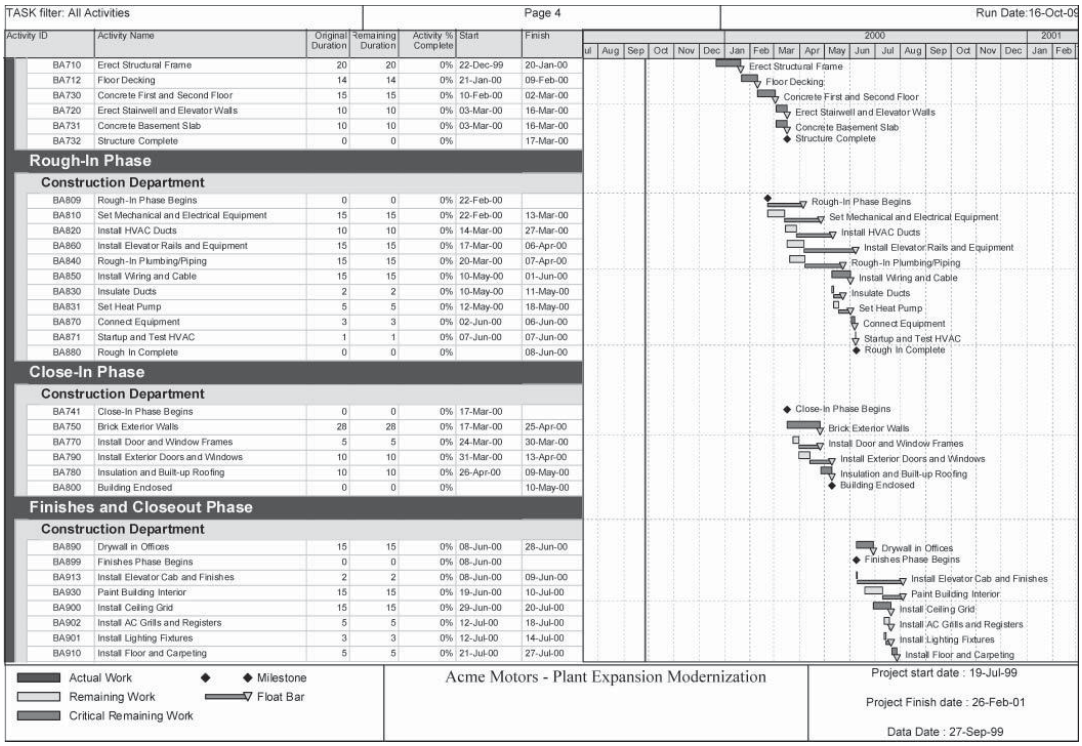



**Figure B.2d (*Continued*)**

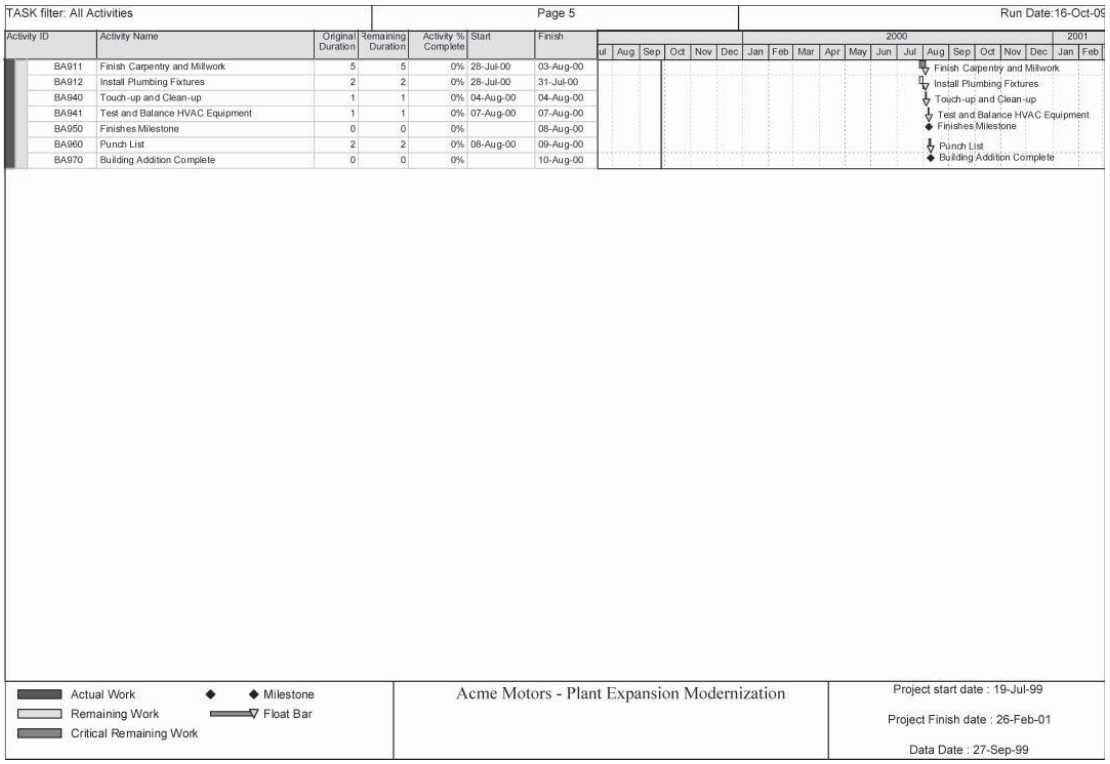



**Figure B.2e (*Continued*)**

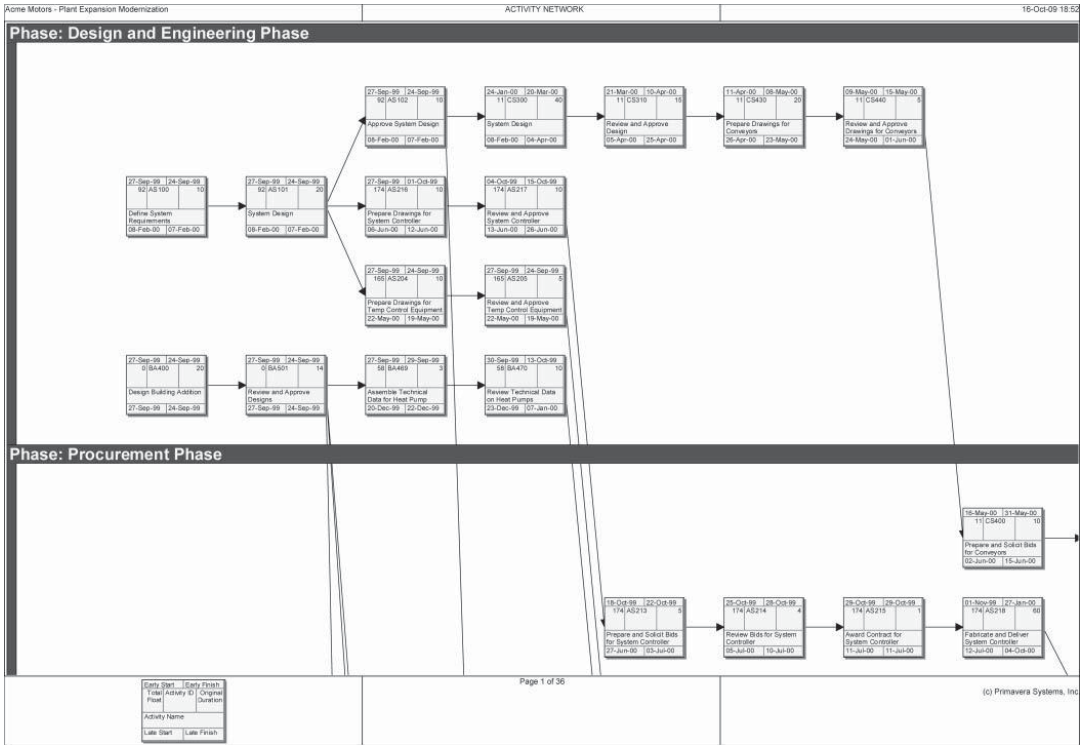



**Figure B.3 Report 8. (Reprinted with permission from Primavera Systems, Inc. Primavera® and P6 are either trademarks or registered trademarks of Primavera Systems, Inc.)**

| Act ID | Description | Orig Dur | Rem Dur | % Compl | Early Start | Early Finish | Late Start | Late Finish | Total Float | Budg Cost | Act Cost to Date | Cost at Compl | Cost Var |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Plant Expansion and Modernization** | | | | | | | | | | | | | |
| BA400 | Design Building Addition | 20 | 0 | 100 | 19JUL99 A | 27AUG99 A | 19JUL99 A | 27AUG99 A | | 9,600.00 | 9,600.00 | 9,600.00 | 0.00 |
| AS100 | Define System Requirements | 10 | 0 | 100 | 20JUL99 A | 04AUG99 A | 20JUL99 A | 04AUG99 A | | 2,960.00 | 3,300.00 | 3,300.00 | -340.00 |
| AS101 | System Design | 20 | 0 | 100 | 03AUG99 A | 31AUG99 A | 03AUG99 A | 31AUG99 A | | 16,640.00 | 16,640.00 | 16,640.00 | 0.00 |
| BA469 | Assemble Technical Data for Heat Pump | 3 | 3 | 0 | 13AUG99 | 17AUG99 | 04NOV99 | 08NOV99 | 58d | 540.00 | 0.00 | 540.00 | 0.00 |
| AS103 | Install Robot Base | 18 | 18 | 0 | 17AUG99 | 10SEP99 | 25AUG99 | 20SEP99 | 6d | 4,824.00 | 0.00 | 4,824.00 | 0.00 |
| AS104 | Run Sealant, Air, and Water Piping | 13 | 13 | 0 | 17AUG99 | 02SEP99 | 14SEP99 | 30SEP99 | 19d | 3,432.00 | 0.00 | 3,432.00 | 0.00 |
| AS204 | Prepare Drawings for Temp Control Equipment | 10 | 0 | 100 | 17AUG99 A | 31AUG99 A | 17AUG99 A | 31AUG99 A | | 1,760.00 | 1,936.00 | 1,936.00 | -176.00 |
| AS315 | Install Electrical Power | 24 | 24 | 0 | 17AUG99 | 20SEP99 | 17AUG99 | 20SEP99 | 0 | 12,288.00 | 0.00 | 12,288.00 | 0.00 |
| BA470 | Review Technical Data on Heat Pumps | 10 | 10 | 0 | 18AUG99 | 31AUG99 | 09NOV99 | 22NOV99 | 58d | 600.00 | 0.00 | 600.00 | 0.00 |
| AS217 | Review and Approve System Controller | 10 | 10 | 0 | 20AUG99 | 02SEP99 | 17SEP99 | 30SEP99 | 19d | 3,426.00 | 0.00 | 3,426.00 | 0.00 |
| BA530 | Review and Approve Brick Samples | 10 | 10 | 0 | 20AUG99 | 02SEP99 | 13OCT99 | 26OCT99 | 37d | 240.00 | 0.00 | 240.00 | 0.00 |
| AS216 | Prepare Drawings for System Controller | 10 | 5 | 50 | 23AUG99 A | 19AUG99 | 23AUG99 A | 16SEP99 | 19d | 1,760.00 | 880.00 | 1,760.00 | 0.00 |
| BA560 | Review and Approve Flooring | 10 | 10 | 0 | 24AUG99 | 07SEP99 | 11FEB00 | 25FEB00 | 120d | 240.00 | 0.00 | 240.00 | 0.00 |
| BA501 | Review and Approve Designs | 14 | 0 | 100 | 30AUG99 A | 20SEP99 A | 30AUG99 A | 20SEP99 A | | 1,680.00 | 1,500.00 | 1,500.00 | 180.00 |
| AS102 | Approve System Design | 10 | 0 | 100 | 31AUG99 A | 13SEP99 A | 31AUG99 A | 13SEP99 A | | 2,546.00 | 2,546.00 | 2,546.00 | 0.00 |
| AS205 | Review and Approve Temp Control Equipment | 5 | 0 | 100 | 31AUG99 A | 13SEP99 A | 31AUG99 A | 13SEP99 A | | 2,826.00 | 2,930.00 | 2,930.00 | -104.00 |
| BA411 | Prepare and Solicit Bids for Heat Pump | 3 | 3 | 0 | 01SEP99 | 03SEP99 | 23NOV99 | 29NOV99 | 58d | 384.00 | 0.00 | 384.00 | 0.00 |
| AS213 | Prepare and Solicit Bids for System Controller | 5 | 5 | 0 | 03SEP99 | 10SEP99 | 01OCT99 | 07OCT99 | 19d | 784.00 | 0.00 | 784.00 | 0.00 |
| BA421 | Prepare and Solicit Bids for Brick Exterior | 3 | 3 | 0 | 03SEP99 | 08SEP99 | 27OCT99 | 29OCT99 | 37d | 384.00 | 0.00 | 384.00 | 0.00 |
| AS200 | Prepare and Solicit Bids for Temp Control Equip | 5 | 0 | 100 | 07SEP99 A | 16SEP99 A | 07SEP99 A | 16SEP99 A | | 1,080.00 | 1,080.00 | 1,080.00 | 0.00 |
| BA412 | Review Bids for Heat Pump | 2 | 2 | 0 | 07SEP99 | 08SEP99 | 30NOV99 | 01DEC99 | 58d | 128.00 | 0.00 | 128.00 | 0.00 |
| BA407 | Prepare and Solicit Bids for Flooring | 5 | 5 | 0 | 08SEP99 | 14SEP99 | 28FEB00 | 03MAR00 | 120d | 640.00 | 0.00 | 640.00 | 0.00 |
| BA413 | Award Contract for Heat Pump | 1 | 1 | 0 | 09SEP99 | 09SEP99 | 02DEC99 | 02DEC99 | 58d | 32.00 | 0.00 | 32.00 | 0.00 |
| BA422 | Review Bids for Brick | 3 | 3 | 0 | 09SEP99 | 13SEP99 | 01NOV99 | 03NOV99 | 37d | 96.00 | 0.00 | 96.00 | 0.00 |
| BA550 | Excavation | 10 | 10 | 0 | 09SEP99 | 22SEP99 | 09SEP99 | 22SEP99 | 0 | 13,760.00 | 0.00 | 13,760.00 | 0.00 |
| BA550 | Fabricate and Deliver Heat Pump and Controls | 90 | 90 | 0 | 10SEP99 | 17JAN00 | 03DEC99 | 07APR00 | 58d | 2,300.00 | 0.00 | 2,300.00 | 0.00 |
| AS214 | Review Bids for System Controller | 4 | 4 | 0 | 13SEP99 | 16SEP99 | 08OCT99 | 13OCT99 | 19d | 659.80 | 0.00 | 659.80 | 0.00 |
| AS240 | Installation Begins | 0 | 0 | 100 | 14SEP99 A | | 14SEP99 A | | | 0.00 | 0.00 | 0.00 | 0.00 |

| | |
|---|---|
| Start date | 15JUL99 |
| Finish date | 08FEB01 |
| Data date | 13AUG99 |
| Run date | 22JUN04 |
| Page number | 1A |
| © Primavera Systems, Inc. | |

**Acme Motors**
**Plant Expansion and Modernization**

| Date | Revision | Checked | Approved |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

**Figure B.4 Report 9. (Reprinted with permission from Primavera Systems, Inc. Primavera® and P6 are either trademarks or registered trademarks of Primavera Systems, Inc.)**

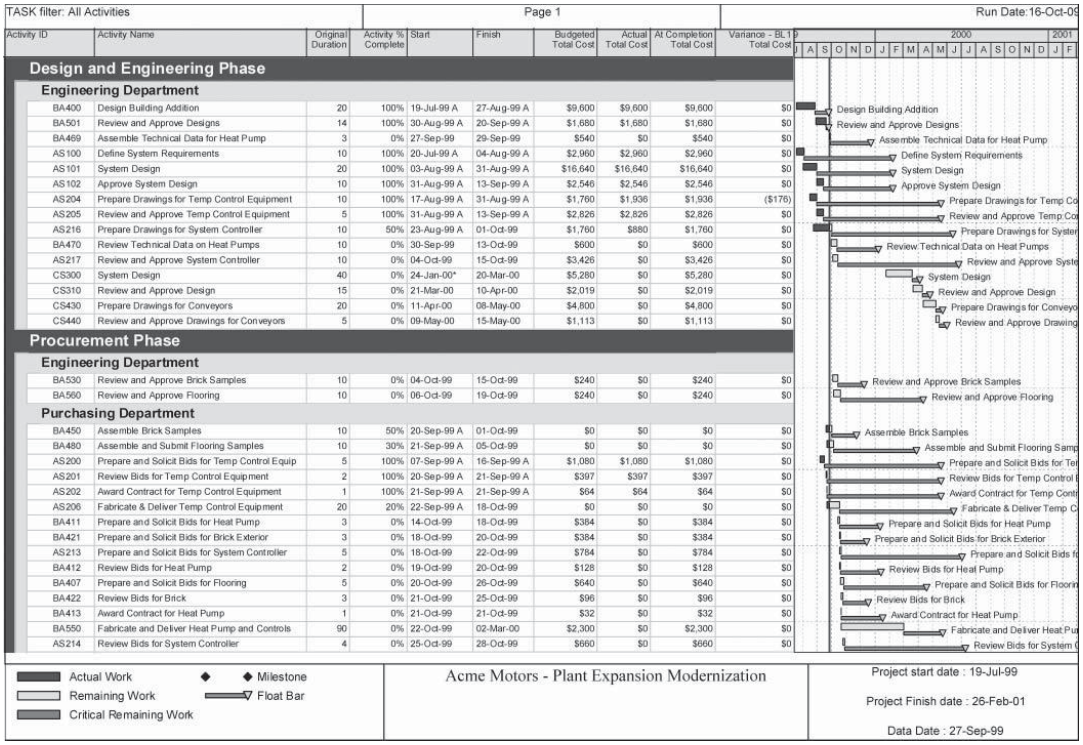



**Figure B.5 Report 10. (Reprinted with permission from Primavera Systems, Inc. Primavera® and P6 are either trademarks or registered trademarks of Primavera Systems, Inc.)**

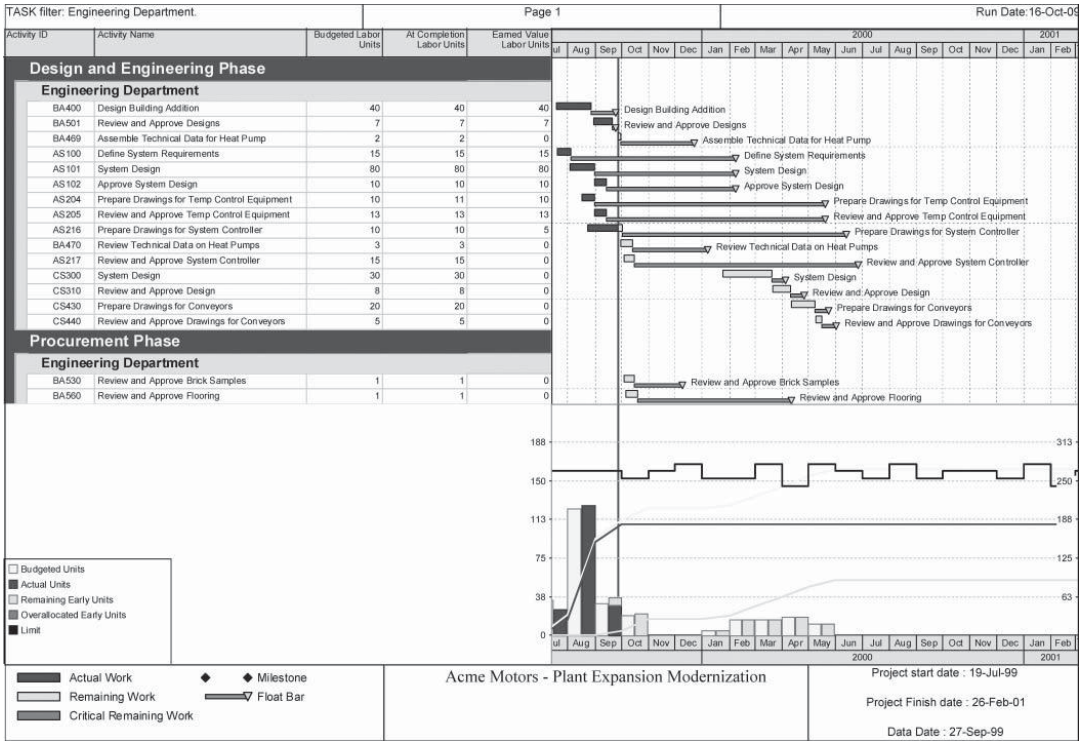



**Figure B.6 Report 11. (Reprinted with permission from Primavera Systems, Inc. Primavera® and P6 are either trademarks or registered trademarks of Primavera Systems, Inc.)**

# Abbreviations

**Important Note:** Many of the following abbreviations are subject specific. In this book, they are used within the context of the construction industry. One abbreviation or acronym may mean one thing in one discipline and something entirely different in another discipline.

| | |
|---|---|
| **AAA** | American Arbitration Association |
| **AACEI** | AACE International (formerly known as the American Association for Cost Engineers), http://www.aacei.org/ |
| **AASHTO** | American Association of State and Highway Transportation Officials, http://transportational.org.aashtonew/ |
| **ABA** | American Bar Association, http://www.abanet.org/ |
| **ABC** | Associated Builders and Contractors, Inc., http://www.abc.org/; or Activity-Based Costing |
| **AC** | actual cost, air conditioning (mechanical), or alternating current (electrical) |
| **ACI** | American Concrete Institute, http://www.aci-net.org/ |
| **ACWP** | actual cost for worked performed |
| **ADM** | arrow diagramming method |
| **ADR** | alternate dispute resolution |
| **A/E** | architect or engineer |
| **AFL-CIO** | American Federation of Labor-Congress of Industrial Organizations, http://www.aflcio.org/ |
| **AGC** | Associated General Contractors of America, http://www.agc.org/ |
| **AIA** | The American Institute of Architects, http://www.aia.org/ |
| **ANSI** | American National Standards Institute, http:www.ansi.org/ |
| **AOA** | activity on arrow |
| **AON** | activity on node |

**ASAP** as soon as possible, a term that should be avoided in contracts and construction agreements (rather, a specific date should be specified); also, a type of constraint in Microsoft Project software
**ASCE** American Society of Civil Engineers, http://www.asce.org/
**ASME** American Society of Mechanical Engineers, http://www.asme.org/
**ASTM** American Society for Testing and Materials, http://www.astm.org/
**AUCA** American Underground Construction Association
**BAC** budget at completion
**B/C ratio** benefit-cost ratio
**BCWP** budgeted cost for work performed
**BCWS** budgeted cost for work scheduled
**BF** board foot, a measuring unit for rough carpentry; 1 BF = 1 ft × 1 ft × 1 in.
**BIM** building information modeling
**BIS** building information system
**BoQ** bill of quantities
**BOT** build-operate-transfer, or board of trustees
**CAD** computer-aided design
**CC** crash cost
**CD** crash duration (in scheduling), compact disc (in information technology), or certificate of deposit (in banking)
**CII** Construction Industry Institute, http://www.construction-institute.org/
**CIP** cast-in-place (adj.)
**CM** construction manager, or construction management (firm)
**CMAA** Construction Management Association of America, http://cmaanet.org/
**CMU** concrete masonry unit
**CO** change order
**CPI** cost performance index
**CPM** critical path method
**C/SCSC** cost/schedule control systems criteria
**CSI** Construction Specifications Institute, http://www.csinet.org/; or Cost-Schedule Index
**CV** cost variance
**cwt** centum weight or hundredweight, a unit of measurement of weight equivalent to 100 lb in the United States, used mostly for steel
**CY** cubic yards
**D/B** design-build
**DCMA** U.S. Defense Contract Management Agency
**DD##** design development (## is the percent complete; e.g., DD30 means the design development is 30% complete)
**DML** dynamic minimum lag; a new type of logic relationship in critical path method (CPM) scheduling
**DoD** Department of Defense

| | |
|---|---|
| **DOE** | Department of Energy |
| **DOT** | Department of Transportation |
| **DRB** | dispute review board |
| **DRF** | double-restricted float |
| **EA** | each |
| **EAC** | estimate at completion |
| **EBS** | enterprise breakdown structure |
| **EF** | early finish time (or date) |
| **EJCDC** | Engineers Joint Contract Documents Committee |
| ***ENR*** | *Engineering News-Record* magazine, http://enr.construction.com/Default.asp |
| **EPC** | engineer-procure-construct |
| **ERP:** | enterprise resource planning |
| **ES** | early start time (or date) |
| **ETC** | estimate to complete |
| **EV** | earned value |
| **EVA** | earned value analysis |
| **EVM** | earned value management |
| **FCV** | forecasted cost variance |
| **FF** | finish-to-finish (relationship), or free float |
| **FF&E** | Furniture, Furnishings and Equipment (architecture); field fabricate & erect (structural steel); or furniture, fixtures & equipment (real estate) |
| **FICA** | Federal Insurance Contributions Act |
| **FIDIC** | The International Federation of Consulting Engineers (the acronym stands for the French version of the name), http://www.fidic.org/ |
| **FPS:** | frames per second |
| **FRP** | formwork, rebar, place (for concrete members) |
| **FS** | finish-to-start (relationship) |
| **FSV** | forecasted schedule variance |
| **GC** | general contractor |
| **GERT** | graphical evaluation and review technique |
| **GPM** | graphical path method |
| **HSE** | health, safety, and the environment |
| **HVAC** | heating, ventilation, and air-conditioning |
| **IAI** | International Alliance for Interoperability, http://www.iai-na.org/ |
| **ID** | identity |
| **IEEE** | Institute of Electrical and Electronics Engineers, http://www.ieee.org/ |
| **Ind. F** | independent float |
| **Int. F** | interfering float |
| **IPA** | immediately preceding activity |
| **IPD** | integrated project delivery |
| **IROR** | internal rate of return (on an investment) |
| **IRR** | internal rate of return (on an investment) |
| **ISA** | immediately succeeding activity |

| | |
|---|---|
| **ISO** | International Organization for Standardization (ISO 9000, ISO 14000), http://www.iso.ch/iso/en/ISOOnline.frontpage |
| **IT** | information technology |
| **LC** | least cost |
| **LCD** | least-cost duration |
| **LD** | liquidated damages (usually written as plural: LDs) |
| **LEED** | leadership in energy and environmental design |
| **LF** | late finish time (or date) or linear feet |
| **LLI** | long lead item |
| **LOB** | line of balance method |
| **LS** | late start time (or date) |
| **LSM** | linear scheduling method |
| **MARR** | minimum attractive rate of return |
| **MBF** | 1,000 board feet |
| **MEP** | mechanical, electrical, and plumbing |
| **MGD** | million gallons per day |
| **MSDS** | materials safety data sheet |
| **NAHB** | National Association of Home Builders, http://www.nahb.org/ |
| **NASA** | National Aeronautics and Space Administration, http://www.nasa.gov/home/index.html |
| **NC** | normal cost |
| **ND** | normal duration |
| **NEC** | new engineering contract |
| **NLT** | no less than |
| **NSPE** | National Society of Professional Engineers, http://www.nspe.org/ |
| **NTP** | notice to proceed |
| **NTS** | not to scale |
| **OBS** | organizational breakdown structure |
| **OSHA** | Occupational Safety and Health Administration, http://www.osha.gov/ |
| **P3** | Primavera Project Planner: the original software developed by Primavera Systems in 1983, which was followed by the enterprise version P3e, which later was named after its version P5, P6 |
| **P6** | Primavera Project Management: the enterprise version of Primavera P3, introduced in the late 1990s as P3e (Primavera Project Planner for the Enterprise); versions and names changed, and then took on version number P5 for version 5.*x* and P6 for version 6.*x* acquired by Oracle Systems in 2008 |
| **PC** | percent complete; has many interpretations, depending on the context in which it is used |
| **PCA** | Portland Cement Association, http://www.portcement.org/ |
| **PCM** | pure agency construction management |
| **PDM** | precedence diagramming method |
| **PE** | professional engineer |
| **PEP** | program evaluation procedure |

| | |
|---|---|
| **PERT** | program evaluation and review technique |
| **PF** | project finish |
| **PM** | project manager, or project management |
| **PMC** | project management consultant |
| **PMI** | Project Management Institute, http://www.pmi.org/ |
| **PMI-COS** | Project Management Institute-College of Scheduling, http://www.pmicos.org/ |
| **PMO** | poject management office |
| **PMP** | professional project manager (certified by PMI); also used sometimes to indicate Project Management Plan |
| **PPP** | **public-private partnership** |
| **PS** | project start |
| **PV** | planned value |
| **QA/QC** | quality assurance/quality control |
| **QS** | quantity surveyor |
| **R&D** | research and development |
| **RDM** | relationship diagramming method |
| **RFA** | request for approval |
| **RFI** | request for information |
| **RFP** | request for proposal |
| **RFQ** | request for quotation |
| **ROR** | rate of return (on an investment) |
| **SC** | substantial completion |
| **SD** | standard deviation |
| **SDK** | software development kit |
| **SF** | start-to-finish (relationship), or square foot |
| **SFCA** | square-foot contact area (unit of measure for concrete formwork) |
| **SOG** | slab on grade |
| **SPI** | schedule performance index |
| **SQ** | square (unit of measure for roofs; equal to 100 square feet) |
| **SRF** | single-restricted float |
| **SS** | start-to-start (relationship) |
| **SV** | schedule variance |
| **TB** | total (planned) budget |
| **TCM** | total cost management, or time couplings method |
| **TF** | total float |
| **TIA** | time impact analysis |
| **TQM** | total quality management |
| **URF** | unrestricted float |
| **VAR** | variance |
| **VE** | value engineering |
| **VPM** | vertical production method |
| **WBS** | work breakdown structure |
| **ZFF** | zero free float (constraint) |
| **ZTF** | zero total float (constraint) |

# Glossary

**3D Modeling**—The digital representations of building components and facilities in terms of spatial dimensions (width, length, and depth) and object information.

**4D Modeling**—A visualization method that incorporates 3D models with time associations.

**5D Modeling**—The integration of 3D models of projects with cost and time associations.

**nD Modeling**—The integration of 3D models of projects with several dimensions (attributes) of the design elements such as cost, time, energy performance, carbon footprint, structural analysis, whole life cost, whole life performance, location (GIS), and/or specifications.

**Accelerated Schedule**—A schedule that is usually submitted by the contractor, implementing adjustments to the original project schedule to accelerate the completion date, without changing the project scope, in order to meet the contract/owner's stipulated finish date, achieve financial gains, and/or avoid losses.

**Accelerating a Project**—See *schedule compression*.

**Acquisition**—The obtaining of supplies, services, or property to meet the needs of a project. Also see *Procurement*.

**Act of God**—See *Force Majeure*.

**Activity**—A basic unit of work as part of the total project that is easily measured and controlled. It is time- and resource-consuming. Also called *Task*.

**Activity Description**—A short phrase or label that is used in a project schedule describing the type of work in the activity. In many cases, it also references the location of work and/or other information pertaining to the work in the activity (e.g., "Concrete placement, suspended slab, 16th floor").

**Activity Duration**—The number of time units (weeks, days, hours, etc.) required to complete an activity. There are four types of duration: *original* (or *planned*) *duration*, *actual duration*, *remaining duration*, and *at completion duration*.

**Activity ID**—A unique identity given—by the scheduler or the scheduling program—to each activity in the schedule. It is usually made of numerical, alphabetic, or combination characters, for example, ASD4230.

**Activity on Arrow (AOA) Network**—A network diagram showing a sequence of activities, in which each activity is represented by an arrow connecting two nodes (circles), each of which represents an event.

**Activity on Node (AON) Network**—A network diagram in which activities are represented by a node (box) connected with arrows (or lines) that represent logic dependencies.

**Activity Percent Complete**—A completion percentage of the work in an activity based on a chosen method of measuring work progress.

**Actual Cost (AC)**—See *Actual Cost for Work Performed (ACWP)*.

**Actual Cost at Completion**—See *At Completion Total Cost.*

**Actual Cost for Work Performed (ACWP)**—Total costs (direct and indirect) incurred in performing work during a given time period.

**Actual Cost This Period**—Actual costs incurred from the previous *Data Date* to the current *Data Date*.

**Actual Cost to Date**—Actual costs incurred from the start of work throughout the current *Data Date*.

**Actual Duration**—The number of time units consumed to complete an activity, if completed, or consumed on the activity so far, if not completed.

**Addenda**—Plural of *Addendum*.

**Addendum**—A document describing an addition, change, correction, or modification to the contract documents. An addendum is issued by the design professional or owner to all bidders during the bidding period but prior to the awarding of the contract. The addenda become part of the contract documents.

**Adjudication**—***A*** statutory alternative dispute resolution forum for resolving construction disputes in the United Kingdom. Adjudication provides a speedy (less than 42 days) and cost-effective method of resolving disputes on an interim basis, allowing decisions to be enforced pending final determination. The procedure can be invoked during the course of construction to address payment disputes, performance problems, time extensions, delays, change order valuations, and other claims related to the construction contract. In most cases, the adjudicator's decision is final and binding and may be implemented immediately.

**Alternate Dispute Resolution (ADR)**—Any procedure or combination of procedures that are voluntarily used to resolve a dispute without going to court. These procedures may include, but are not limited to, assisted settlement negotiations, conciliation, facilitation, mediation, fact-finding, mini-trials, and arbitration.

**A + B Contracting Method**—A bidding/contracting method that factors time plus cost in order to determine the low bid. Under the A + B contracting method, each submitted bid has two components: "A," dollar amount for contract items, and "B," days required to complete the project. Bid days are multiplied by a hypothetical cost per day, set by the owner, and added to the A component to obtain the total bid: A + (B * Cost per day) = Total bid. Also called *Cost plus time* or *biparameter bidding/contracting method*.

**Application for Payment**—See *Payment Request*.

**Arbitration**—A formal process by which parties agree to submit their disputes for determination by a third, impartial party (referred to as the *arbitrator*) rather than to pursue their claims before a judge and jury in a court of law. The parties often agree in advance to binding arbitration of their dispute, either as a clause in the contract or at the occurrence of a dispute. This method of avoiding litigation can save both time and money.

**Arrow Diagramming Method (ADM)**—See *Activity on Arrow (AOA) Network*.

**As-Built Schedule**—A schedule prepared after the project has started and reflects work occurrence as it actually happened in reality rather than what was planned to happen. Activities are plotted by their actual start and actual finish, disregarding any logic.

**As Late As Possible**—A constraint in some computer scheduling programs that forces the maximum delay in starting an activity without delaying succeeding activities. Also called the *Zero Free Float* constraint.

**As-of Date**—See *Data Date*.

**As-Planned Schedule**—The schedule submitted by the contractor—as usually required by the contract—and approved by the owner before the start of the project (and sometimes before the signing of the contract).

**At Completion Cost**—See *At Completion Total Cost*.

**At Completion Duration (ACD)**—The duration of an activity after its completion. For activities not started yet, *At Completion Duration* is same as the *Original Duration*. For in-progress activities, *At Completion Duration* is equal to the summation of *Actual Duration* and *Remaining Duration*. For completed activities, *At Completion Duration* is equal to *Actual Duration*.

**At Completion Total Cost**—Total costs (direct and indirect) incurred in an activity, a group of activities, or the entire project throughout the completion of the overall assigned work.

**Backward Pass**—The process of navigating through a network from end to start and calculating the late dates for each activity. Backward pass starts with the imposed finish date of the project, if given. If not, it starts with the finish date calculated by the *Forward Pass*. Dates calculated by the *Backward Pass*, along with those calculated by the *Forward Pass*, help identify the critical path and calculate float for all activities.

**Backward Resource Leveling**—Leveling resources, starting from the project's finish and then working backward through all project activities, fulfilling their

resource requirements and maintaining the total resource usage within the set limits. With such restrictions, the project may have a longer duration than originally planned, and the project start may have to occur before the scheduled date.

**Bar chart**—A graphical representation of project activities shown in a time-scaled bar line, with no links shown between activities. Originally developed by Henry L. Gantt in 1917. Also called a *Gantt chart.*

**Baseline**—The original approved plan for a project, including approved changes. It usually includes *Baseline Budget* and *Baseline Schedule*. It is used as a benchmark for comparison with actual performance (see *Project Control*).

**Baseline Budget**—The project's original approved budget, including any approved changes.

**Baseline Schedule**—A schedule prepared by the contractor before the start of the project—and usually approved by the owner—typically used for performance comparison.

**Beginning-of-Day Convention**—When any date mentioned for an activity means the start of the day. Usually used only by computer software for start dates.

**Beneficial Occupancy**—The use of premises (or a portion of it) for its intended purpose, even though the project work may not be complete. This term is almost the same as *Substantial Completion*. See also *Certificate of Substantial Completion.*

**Beta Distribution**—A continuous probability, with a probability distribution function defined on the interval [0, 1]. It is used in PERT with three time estimates for the completion of an activity: the optimistic duration, the most likely duration, and the pessimistic duration. Using these three durations, the beta distribution allows the calculation of the means and variances of activity completion times. The beta distribution also has an advantage over the normal distribution in that it can be skewed right (toward the pessimistic duration) or left (toward the optimistic duration), or it can be symmetrical.

**Bill of Quantity (BOQ)**—In the United States, this term may mean a list of all materials and their corresponding quantities that are required in a project. In the United Kingdom, this term is equivalent to *Schedule of Values.*

**BIM**—See *Building Information Modeling.*

**Biparameter Contracting Method**—See *A + B Contracting Method.*

**Budget at Completion (BAC)**—The sum of the total budgets throughout the completion of work on an activity, a group of activities, or the entire project.

**Budgeted Cost for Work Performed (BCWP)**—The sum of the approved cost estimates (including any overhead allocation) for activities (or portions of activities) completed during a given period (usually project-to-date). See also *Earned Value (EV).*

**Budgeted Cost for Work Scheduled (BCWS)**—The sum of the approved cost estimates (including any overhead allocation) for activities (or portions of activities) scheduled to be performed during a given period (usually project-to-date).

**Building Information Modeling (BIM)**—A process involving the generation and management of digital representations of physical and functional characteristics of places. Building Information Models (BIMs) are files (often but not always in proprietary formats and containing proprietary data) that can be exchanged or networked to support decision making about a place. Current BIM software is used by individuals, businesses, and government agencies to plan, design, construct, operate, and maintain diverse physical infrastructures, from water, wastewater, electricity, gas, refuse, and communication utilities to roads, bridges, and ports, from houses, apartments, schools, and shops to offices, factories, warehouses, and prisons. (*Wikipedia* online). Another brief definition: a data-rich, object-oriented, intelligent and parametric digital representation of a facility/building components.

**Calculated Finish Date**—The completion date of the project as calculated in the *Forward Pass* of the *Critical Path Method*.

**Calendar**—Calendars show the days on which work on activities may be performed.

**Calendar Unit**—The smallest unit of time used for activity duration and scheduling the entire project.

**Central Limit Theorem (CLT)**—The central limit theorem demonstrates that in large enough samples, the distribution of a sample mean approximates a normal curve, regardless of the shape of the distribution of the population from which the samples were drawn. The larger the value of the sample size is, the better the approximation to the normal distribution.

**Certificate of Completion**—A written document forwarded to the general contractor by the architect, engineer, or owner stating that construction is complete according to the contract agreement (approved plans, specifications, change orders, etc.).

**Certificate of Occupancy**—A written document issued by a local governmental agency stating that the building or facility is in a condition to be occupied (i.e., in compliance with public health and building codes).

**Certificate of Substantial Completion**—A written document forwarded to the general contractor by the architect, engineer, or owner indicating that the project is substantially complete. This document initiates the time period for the final payment to the contractor.

**Change of the Critical Path**—A partial or complete change in the *Critical Path* in a CPM schedule that was caused by a change in the duration of an activity(ies) and/or a change in the logic of the schedule. Practically speaking, the *Critical Path* changes if a near-critical path has increased to exceed the original *Critical Path* or if the original *Critical Path* has decreased to become shorter than another path in the schedule.

**Change Order (CO)**—A formal written document, signed by the owner, directing the contractor to make changes from the original contract. A change order can be used for adding, deleting, or substituting work items. A change order usually—but not always—has an impact on the project's cost and schedule. Also called *Variation Order (VO)*.

**Claim**—A request from one contracting party (usually the contractor) to another party (usually the owner) for additional compensation, a time extension, or both. See *Delay Claims.*

**Combination Relationship**—Two activities related (or connected) by two logical relationships, usually start-to-start and finish-to-finish.

**Comparison Schedule**—The original (usually *As-Planned*) schedule is revised to incorporate any claimed delays. Typically for a delay claim, the contractor submits two schedules: one without the causative factors (factors allegedly causing the schedule delays) and one with the causative factors (called the "impacted" schedule). By comparing the two schedules, the contractor hopes to prove that the delay was caused by the alleged factors.

**Compensable Delays**—Project delays, caused by the actions or inactions of another party (usually the owner), that entitle the contractor to a time extension, monetary compensation, or both.

**Concurrent Delay**—A combination of two or more independent causes of delay during the same general time period.

**Constraint**—An externally imposed restriction affecting when an activity can start and/or finish. Constraints may conflict with logical relationships. Individual scheduling programs provide the user with a variety of constraint types, some of which can override logic and some of which are subject to logic.

**Constructability**—"The optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (Construction Industry Institute, 1986a, p. 2). Or "the practice of peer reviewing the plans and specifications prior to issuing for bid with the intent of correcting errors, omissions, inconsistencies or discrepancies" (RSMeans, 2010).

**Constructive Acceleration**—Schedule acceleration by the contractor that occurs when a delay takes place beyond a contractor's control and yet the owner expects the project to be completed by the original contract completion date. The contractor usually files a claim for this acceleration after the completion of the contract.

**Contiguous Activity**—An activity that cannot be split or paused. Once work starts on a contiguous activity, it has to continue until its completion.

**Contingency**—See *Contingency Fees* or *Schedule Contingency.*

**Contingency Fees**—Amounts included in the construction budget to cover the cost of unforeseen events that will most likely occur during the life of the project. Such fees are estimated or calculated directly proportional to the risk taken with the project.

**Contract**—A legally binding agreement that obligates one party (the architect, engineer, constructor, etc.) to offer products and/or services under certain terms (budget, schedule, specifications), and obligates the other party (owner) to pay for these products/service.

**Contract Closeout**—The completion and settlement of the contract, including resolution of any open items. From a financial management standpoint, closeout

involves settling all financial and accounting matters between the contractor and the owner.

**Contractor-Created Float**—Schedule float that was created as a result of the contractor's work being completed in a shorter than planned period of time. This float may be created by shorter actual durations for performed activities, a change in the logic, different calendars (6- or 7-day rather than 5-day week), or a combination of these factors. This float is not a part of the total float calculated in the original baseline schedule.

**Cost Accounting**—"The systematic recording and analysis of the costs of materials, labor, and overhead incident to production" (Merriam-Webster, 2014)

**Cost at Completion**—See *Actual Cost at Completion*.

**Cost Breakdown**—See *Schedule of Values*.

**Cost-Loaded Schedule**—A CPM schedule in which each activity has a cost figure assigned to it. In some software packages, the user may assign resources (labor, equipment, materials) to each activity, and then the software calculates the cost using the cost of these resources given in the resource dictionary.

**Cost Performance Index (CPI)**—The ratio of *Earned Value* of an activity to its *Actual Cost*. CPI = BCWP/ACWP or CPI = EV/AC.

**Cost Ratio**—A method of measuring percent complete for an activity (or a project) by distributing (linearly or by using other curves) the cost over the duration of the activity (or project). Percent complete = Actual Cost/Total Cost. This method works well for activities with fixed budgets and fixed durations, such as a salary staff member.

**Cost/Schedule Control System Criteria (C/SCSC)**—A formal planning and control reporting system developed by the Department of Defense in the 1960s for its contractors to use. It is used for reporting a project schedule and financial information. This system was later simplified and modified to what is currently known as *Earned Value Management*.

**Cost This Period**—See *Actual Cost This Period*.

**Cost to Complete**—See *Estimate to Complete (ETC)*.

**Cost to Date**—See *Actual Cost (AC)*.

**Cost Variance (CV)**—The difference between the *Earned Value* of an activity and its *Actual Cost*. CV = BCWP − ACWP or EV − AC.

**CPM**—See *Critical Path Method*.

**Crash Cost (CC)**—Total cost of a construction project (direct and indirect), including the impact of crashing (maximum compression of) the schedule.

**Crash Duration (CD)**—The least possible duration for a construction project schedule. It is usually achieved by maximum *Schedule Compression*.

**Critical Activity**—An activity on the critical path. Any delay in the timely completion of a critical activity will result in a delay in the entire project

**Critical Path**—The longest continuous path in a network from start to finish. It represents the summation of the durations of activities and lags along that path, taking into consideration calendars, constraints, resources, and other impacting factors.

**Critical Path Method (CPM)**—A scheduling technique using networks for graphic display of the work plan. The method is used to determine the length of a project and to identify the activities that are critical to the completion of the project.

**Cumulative Distribution Function**—A function used to compute probabilities for a continuous random variable having values up to a certain value *x:* $F(x) = Pr\ (X \leq x)$.

**Current Finish Date**—The current (updated) estimate of the point in time when the project (or a specific activity) will be completed.

**Damages**—A measure of monetary compensation that a court or arbitrator awards to a plaintiff for loss or injury suffered by the plaintiff's person, property, or other legally recognizable rights.

**Dangling Activity**—An activity tied from only one end (start or finish). A dangling activity has only a predecessor(s) or successor(s), not both.

**Data Date**—The date as of which all progress on a project is reported.

**Degressing**—Degressing an in-progress schedule is reversing all progress reflected on the schedule to go back to the starting point. This practice is used when there is no baseline schedule but there is a need to create one after construction has started.

**Delay**—An event or condition that results in work activity starting, or project completion, later than originally planned, or an interruption or a hindrance to planned progress.

**Delay Claim**—A claim for extension of time, monetary compensation, or both for a delay caused by actions of another party. Delay claims are classified into excusable, compensable, and nonexcusable.

**Dependency**—See *Logic Relationship*.

**Design-Bid-Build**—Design-bid-build (also called *traditional*) contracting/project delivery method. The owner contracts with a design firm/consultant to complete the design of the contracted facility, and then selects the constructor through a competitive bidding process. The awarded bidder will become the contractor who will build the facility.

**Design-Build (DB) Contracting Method**—Design-build is a contracting/project delivery method whereby the owner contracts with a single entity (DB contractor) to do both the design and the construction of the contracted facility. The DB contractor may be a general contractor, with the design services being subcontracted, a design firm with the construction services being subcontracted, or both design and construction being done in-house. Such a contract may involve a variety of stipulations, mostly to deal with the amount and method of payment.

**Design Development (DD)**—The second phase of a designer's basic services (the first phase being schematic design), which includes developing all engineering and architectural drawings, specifications, and the cost estimate. This phase may occur in stages, each of which is defined by a certain percent completion. For example, DD30 means the design development is at 30% complete. This indicates that about 30% of the information in the design has been determined.

Potential contractors have to assume the remaining 70% information. Further stages follow with the percentage increasing, for example, DD60, DD90, indicating more design information has been determined. The final design is the third and final phase of the design process. It follows design development.

**Direct Cost**—Cost that is directly associated with a specific activity or work item. It typically includes labor, materials, equipment, and subcontracts.

**Dispute Review Board (DRB)**—A panel of three experienced, respected, and impartial reviewers, organized before construction begins, which meets at the job site periodically. The DRB is usually formed by the owner, who selects a member to be approved by the contractor, the contractor selecting a member to be approved by the owner, with the two chosen members selecting the DRB chair, to be approved by both parties. The board becomes familiar with the project and its development by meeting regularly. It helps prevent and resolve disputes between the contracting parties.

**Dissolve an Activity**—A function in Primavera software that deletes an activity but assigns its predecessors to its successors so that there won't be an interruption in the logic of the schedule.

**Double-Restricted Float (in Precedence Networks)**—The amount of time we have to delay the rest of work in an activity after it has started on its critical start, then finish on its critical finish date without delaying the entire project.

**Driving Relationship**—A relationship from a predecessor activity that controls the start or finish of a successor activity. For any activity with predecessors, there must be at least one driving relationship.

**Driving Resource**—A resource that determines the duration of an activity to which it is assigned. The activity duration is calculated based on the resource availability and resource quantity needed to complete the activity.

**Dummy Activity**—A fictitious activity with zero duration and no budget or resources assigned, used in *Activity on Arrow Networks* to maintain correct logic or distinguish activities' identities.

**Duration**—See *Activity Duration*.

**Dynamic Minimum Lag (DML)**—A new type of logical relationship in *Critical Path Method* (CPM) scheduling. A DML relationship is dynamic; it moves along the activity in parallel to work progress to make sure the minimum lag is maintained at all times, not just at the start of finish.

**Early Dates (for an activity)**—The *Early Start* date and *Early Finish* date of an activity.

**Early Finish (for an activity) (EF)**—The earliest date on which an activity can finish within project constraints.

**Early Start (for an activity) (ES)**—The earliest date on which an activity can start within project constraints.

**Earned Value (EV)**—See *Budgeted Cost for Work Performed (BCWP)*.

**Earned Value Analysis (EVA)**—Analysis of a project's progress to discover how the actual money was budgeted and spent as compared to the value of the work achieved.

**Earned Value Management (EVM)**—A method of integrating scope, schedule, and budget to measure a project's performance. It compares the amount of work that was planned with what was actually earned and with what was actually spent to determine if the cost and schedule performance are as planned.

**Effort-Driven Activity**—See *Resource-Driven Activity.*

**End-of-Day Convention**—A convention adopted by most scheduling books assuming that when a day (date) is mentioned, it implies the end of that day. An end of a day is equivalent to the beginning of the next day. For this reason, network calculations start on day 0 (i.e., end of day 0), which practically means the beginning of day 1. Using this convention, the duration of an activity is equal to the difference between its finish date and its start date.

**Estimate at Completion (EAC)**—The expected total cost of an activity or project when the defined scope of work is completed. *EAC* = *Actual Cost* (*AC*) + *Estimate to Complete* (*ETC*).

**Estimate-Generated Schedule**—A list of project activities along with their durations, generated by the cost estimating software. The list does not form a CPM schedule because it lacks logic links (relationships) and other schedule attributes. It may help form the foundation of a schedule.

**Estimate to Complete (ETC)**—The projected cost to complete the activity or project from its present state.

**Event**—A point in time marking a start or end of an activity. Contrary to an activity, an event does not consume time or resources, and while statusing (updating) a project, an event can be statused as "not started" or "complete" but not "in progress." In computer software, events with significance can be created as "milestones," and they are either "start milestones," such as "notice to proceed," or "finish milestones," such as "substantial completion."

**Exculpatory Clauses**—Disclaimer verbiage that is designed to shift risk.

**Excusable Delay**—A delay that entitles the contractor to additional time for completing the contract work. Excusable delays usually stem from reasons beyond the contractor's control.

**Exemplary Damages**—See *Punitive Damages.*

**Expected Duration**— The expected duration of an activity is the duration an activity is expected to take (in PERT calculations), taking into account the different possible values (optimistic, most likely, and pessimistic durations) and their weights. It is the mean (mathematical average) duration and is calculated using the following equation:

$$T_e = \frac{T_o + 4T_m + T_p}{6}$$

which is a form of the general equation:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i$$

**Fast-Track Projects**—Starting the construction process on a project while design is still underway (i.e., overlapping the design and construction of a project). The PMI (2013) defines *fast-tracking* as a "schedule compression technique in which activities or phases normally done in sequence are performed in parallel for at least a portion of their duration."

**Finish Milestone**—An event marking the completion of an activity(s) with special significance such as *Substantial Completion* of construction.

**Finish-Restricted Float (in Precedence Networks)**—The amount of time we can delay the start of work on an activity, or the rest of it if it has started, and then finish on its critical finish date without delaying the entire project.

**Finish-to-Finish (FF) Relationship**—A logic restraint that does not allow for the completion of one activity (the successor) until another activity (the predecessor) is completed.

**Finish-to-Start (FS) Relationship**—A logic restraint that does not allow for the start of one activity (the successor) until another activity (the predecessor) is completed.

**Float**—The maximum amount of time an activity can be delayed without violating certain conditions, depending on the type of float. See the specific type of float for its exact definition. Float is sometimes called *slack* or *leeway*.

**Force Majeure**—An event or effect that cannot be reasonably anticipated or controlled, which usually entitles the contractor to relief from a contractual obligation, usually an extension in the time to complete the project.

**Forecasted Cost Variance (FCV)**—The expected *Cost Variance (CV)* of an activity or a project after its completion, assuming the continuation of productivity and job conditions without change.

**Forecasted Schedule Variance (FSV)**—The expected *Schedule Variance (SV)* of an activity or a project after its completion, assuming the continuation of productivity and job conditions without change.

**Forward Resource Leveling**—Leveling resources, starting from a project's start and going through all project activities, fulfilling their resource requirements and maintaining the total resource usage within the set limits. With such restrictions, some activities have to be delayed until resources are available, and the project duration may be longer than planned, causing the finish date to occur later than originally scheduled.

**Forward Pass**—The process of navigating through a network from start to finish and calculating the early dates for each activity and the project's completion date.

**Free Float FF**—The maximum amount of time an activity can be delayed from its *Early Start* date without delaying the early start of the succeeding activities.

**Frequency of Updating**—The time interval between two regular schedule updates.

**Front-End Loading the Cost**—Overestimating early work activities and underestimating later work activities while maintaining the same overall contract total. It is a practice done by some contractors to get early money. Owners dislike and often dispute this practice.

**Gantt Chart**—See *Bar Chart*.

**General Overhead**—See *Indirect Cost*.

**Graphical Evaluation and Review Technique (GERT)**—A network analysis technique that allows for conditional and probabilistic treatment of logical relationships (i.e., some activities may not be performed).

**Hub**—An activity or milestone in logic networks, with numerous predecessors and/or successors.

**I-J Method**—See *Activity on Arrow (AOA) Network*.

**Impact Schedule**—A schedule similar to the original (usually *As-Planned*) schedule but incorporating the causative factors (factors allegedly causing the schedule delays). By comparing the two schedules (original and impact), the contractor hopes to prove that the delay was caused by the alleged factors.

**Imposed Finish Date**—The project's completion date, as specified in the contract or stipulated by the owner.

**Independent Float (Ind. F)**—The maximum amount of time an activity can be delayed without delaying the early start of the succeeding activity(ies) and without being affected by the allowable delay of the preceding activities.

**Indirect Cost**—An expense that cannot be directly associated with a specific activity or work item, such as overhead, profit, or insurance. If the expense can be attributed to a specific project, then it is part of job overhead; otherwise, it is part of general overhead.

**Interfering Float (Int. F)**—The maximum amount of time an activity can be delayed from its e*arly start* without delaying the entire project but causing delay to the e*arly start* of the succeeding activity(ies). It represents the part of the total float that remains after deducting free float. Mathematically speaking, Int.F = TF − FF.

**Interruptible Activity**—An activity that can be performed in two or more separate segments. It is an activity that can be interrupted or paused.

**Inventory Buffer**—A theory in materials management that calls for all materials to be purchased, delivered, and stored on-site prior to installation.

**Job Overhead**—See *Indirect Cost*.

**Just in Time**—A theory in materials management that calls for delivering materials at the time of installation only. Thus, materials are not stored on-site.

**Lag**—A minimum waiting period between the finish (or start) of an activity and the start (or finish) of its successor.

**Lane Rental Bidding/Contracting Method**—The lane rental contracting method is an innovative contracting technique by which a contractor is charged a fee for occupying lanes or shoulders to do the work. Under this system, the owner (usually the public agency) assigns an hourly or daily charge for closing a lane or shoulder and charges the contractor for the closure. The objective of the method is to motivate contractors to minimize closures on high-volume roadways and/or during high-volume time periods. This method is similar to the *A + B Bidding/Contracting Method*.

**Late Dates (for an activity)**—The *Late Start* date and *Late Finish* date of that activity.

**Late Finish (for an activity) (LF)**—The latest date on which an activity can finish without extending the project duration.

**Late Start (for an activity) (LS)**—The latest date on which an activity can start without extending the project duration.

**Lead**—A negative *Lag*.

**Lean Construction**—Lean construction is a holistic facility design and delivery philosophy with an overarching aim of maximizing value to all stakeholders through systematic, synergistic, and continuous improvements in the contractual arrangements, the product design, the construction process design and methods selection, the supply chain, and the workflow reliability of site operations (Dr. T. Abdelhamid, https://www.msu.edu/user/tariq/Learn_Lean.html). Here is another definition (Koskela et al., 2002): lean construction is a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value.

**Least-Cost Duration (LCD)**—The duration of an activity associated with the *Least Cost Schedule*.

**Least-Cost Schedule**—A CPM schedule accelerated to reach the point where the total cost of the project (direct and indirect) is minimum. If the duration of the schedule increases or decreases, the total cost will increase.

**Lien Waiver**—A document from a contractor, subcontractor, vendor, equipment lessor, or other party to the construction project (the claimant) stating he or she has received payment and waives any future lien rights to the property (of the owner).

**Linear Scheduling Method (LSM)**—A scheduling method that consists of a simple diagram showing the location and time at which a certain crew will be working on a given operation. It is most suited for construction projects with few linear activities (usually with large quantities) that have to be done in the same order or sequence but can, and do, overlap (e.g., heavy construction projects, such as roads, earthwork, or utility piping).

**Line of Balance (LOB) Method**—See *Linear Scheduling Method (LSM)*.

**Liquidated Damages**—A stipulation in a contract of a monetary amount that must be paid by the contractor if the contractor fails to satisfactorily complete the project by the contract finish date. Liquidated damages are usually assessed per day of delay and they may increase after a certain number of days (e.g., $1,000 per day for the first week, $1,500 per day for the second week, and so on).

**Litigation**—The process of carrying on a legal contest by judicial process. The parties submit their disputes to the jurisdiction and procedures of federal or state courts for resolution.

**Logic Loop**—A circular logical relationship between two activities in a network; that is, each one is a predecessor and a successor to the other one. A loop is an error that must be corrected or else CPM calculations (whether manually or by computer) will halt.

**Logic Network**—A diagram showing project activities and their logical relationships (interdependencies)

**Logical Relationship**—The interdependency of activities in a network: one activity (the *Predecessor*) has to finish (or start) before another (the *Successor*) can start (or finish), with or without a *Lag*. There are four types of logic relationships: *finish-to-start, start-to-start, finish-to-finish, and start-to-finish*.

**Look-Ahead Schedule**—A segment of the overall schedule that includes only activities that have work planned during a certain period of time, such as during the next month or the next two weeks. Project managers may use *Look-Ahead Schedules* to focus on the immediate future activities.

**Loop**—See *Logic Loop*.

**Man-Hour Ratio**—A method of measuring percent complete of an activity (or a project) by distributing (linearly or by using other curves) the budgeted man-hours over the duration of the activity (or project). Percent complete = Actual man-hours/Total man-hours. This method is similar to *Cost Ratio* method except that it uses man-hours instead of money.

**Master Schedule**—A CPM schedule that includes more than one *Subschedule*. Typically, a general contractor requires his subcontractors to submit their schedules and then incorporates them as *Subschedules* in the *Master Schedule*, which shows all work items in the project. Relationships in a *Master Schedule* may be internal, that is, within the same *Subschedule*, or external, that is, between activities from two different *Subschedules*.

**Materials Management**—The planning and controlling of all necessary efforts to ensure that the correct quality and quantity of materials and equipment are appropriately specified in a timely manner, are obtained at a reasonable cost, and are available when needed.

**Mechanics Lien**—A charge or claim upon the property of another individual as security for a debt that is created in order to obtain priority of payment of the price or value of work that is performed and materials that are provided in the erection or repair of a building or other structure (*The Free Dictionary*, online).

**Mediation**—A method of trying to resolve a dispute by the use of an impartial intermediary to suggest ways to settle the dispute, rather than imposing a decision upon the parties.

**Milestone**—An event marking the start or completion of an activity with special significance. A milestone can be a *Start Milestone* or a *Finish Milestone*.

**Monte Carlo Simulation**—The technique used in project management applications to estimate the likely range of outcomes from a complex random process by simulating the process a large number of times.

**Most Likely Duration**—The duration believed to have more likelihood of occurring than any other duration.

**Negative Float**—A situation that occurs when an activity is performed even on its early dates and fails to meet the project's imposed finish date or other constraint.

**Negotiation**—When two or more parties with competing interests discuss an issue with the aim of reaching an agreement. It is the first step toward resolving a claim.

**Network**—A graphical representation of the activities (and events) composing the project, in a logical and chronological depiction. Network diagrams are basically of two types: *arrow networks* and *node networks.* Arrow networks are also called *arrow diagramming method (ADM), activity on arrow (AOA)*, or the *I-J method*. Node networks are also called *activity on node* (AON) or Node Diagramming Method. Precedence diagrams or *precedence diagramming method (PDM)* are an advanced form of node networks.

**Noncompensable Delay**—A project delay beyond the control, and not the fault of, the owner, caused byunusual weather conditions, natural disasters (earthquakes, floods, hurricanes, etc.), wars or national crises, and labor strikes. Such delays usually do not entitle the contractor to monetary compensation but most likely entitles the contractor to a time extension.

**Nondriving Relationship**—A relationship between a predecessor and a successor that does not affect the current activity dates. If a nondriving relationship is omitted, the CPM calculations—including all activity start and finish dates—should not change. However, a nondriving relationship may become driving if network conditions change, such as activities' durations or logic, or if activities are added or deleted.

**Nonexcusable Delay**—A delay that does not entitle the contractor to either a time extension or monetary compensation.

**Nonworkdays**—Days on which no work is/was performed, such as holidays, rain days, shutdowns, and the like. Nonworkdays are of two types: known, such as holidays and scheduled shutdowns, and unknown, such as weather days and unscheduled shutdowns.

**Normal Cost**—The cost of a project that is performed within the *Normal Duration.*

**Normal Distribution**—A probability distribution forming a symmetrical bell-shaped curve.

**Normal Duration**—The amount of time it takes to finish the project under ordinary circumstances without any deliberate acceleration or deceleration.

**Optimistic Duration**—Optimistic duration is the amount of time an activity is expected to take if everything goes smoothly and efficiently within the realistic—even though this may not be likely—realm of expectations.

**Original Duration**—The number of time units (days, weeks, months, etc.) estimated to complete an activity that has not started yet.

**Overhead**—See *Indirect Cost.*

**Overlapping Activities**—Two activities are said to overlap when the successor starts while its predecessor is in progress. Mathematically speaking, the duration of the combination of the two activities is less than the summation of the two activities' durations.

**Payment Request (Pay Request, Payment Requisition)**—A formal written request for payment by a contractor or subcontractor for work completed on a contract and—if allowed for in the contract—materials purchased and stored on the job site or in a warehouse during a specified period of time. Subcontractors

submit their payment requests to the general contractor, who combines them with his or her own in one total payment request to the owner. Typically, this process is done on a monthly basis.

**Percent Complete**—See *Activity Percent Complete* or *Project Percent Complete*.

**Pessimistic Duration**—The duration under almost the worst case scenario within the realistic—even though it may not be likely—realm of expectations.

**Planned Value (PV)**—See *Budgeted Cost for Work Scheduled (BCWS)*.

**Portfolio**—A group of projects, not necessarily related or dependent, usually under one project manager or department. The PMI defines it as a collection of projects or programs, and other work that are grouped together to facilitate effective management of that work to meet strategic business objectives.

**Precedence Diagramming Method (PDM)**—A node network (see *Activity on Node Network)* that allows for the use of four types of relationships: finish-to-start (FS), start-to-start (SS), finish-to-finish (FF), and start-to-finish (SF).

**Precedence Network**—See *Precedence Diagramming Method*.

**Predecessor Activity**—An activity that has to finish (or start) in order for the succeeding activity or activities to start (or finish). It also has been defined as an activity that has some measurable portion of its duration logically restraining a subsequent activity or activities.[1]

**Probability Density Function (PDF)**—A function used to compute probabilities for a continuous random variable at a certain value. The area under the curve of a probability density function over an interval represents probability (chance of occurrence): $f(x) = \Pr(X = x)$.

**Probability Distribution**—A function or mathematical model that describes all of the values that the random variable can take and the probability (chance of occurrence) associated with each. Also called a *probability function*.

**Probability Universe**—The set of values of all possible outcomes for a random variable.

**Procurement**—The process of acquiring materials, equipment, and/or services from external sources for use in a project. It is a process that usually starts long before the start of the construction process and ends with project completion or project closeout.

**Professional Engineer (PE)**—An engineer licensed by an authority (usually the government of the state) after fulfilling certain requirements (minimum experience and passing an exam).

**Pro Forma**—A projection or estimate of the cost/benefit ratio or rate of return on an investment. Project owners and investors usually use a pro forma to help them make a decision about whether or not to carry out the project. Typically, a pro forma includes all expected costs (initial, recurring, and occasional) and expected revenues throughout the life cycle of the project, and then calculates the rate of return.

[1] Theoretically, this portion can be zero, but practically it has to be greater than zero.

**Program**—A program is a group of related projects and/or services intended to meet a common objective and usually managed by one entity. A program can also indicate a large and complex project that is divided into several projects for more effective management. The PMI defines a program as a group of related projects managed in a coordinated way to obtain benefits and control that is not available by managing them individually. Programs may include elements of related work outside the scope of the discrete projects in the program.

**Program Evaluation and Review Technique (PERT)**—An event-oriented network analysis technique that is used to estimate a project's duration when there is a high degree of uncertainty with individual activity duration estimates. PERT applies the critical path method to a weighted average duration estimate. PERT is considered a probabilistic, or stochastic, method. The name "PERT Diagram" is incorrectly used in the construction industry sometimes to denote a *Logic Network*.

**Progress Override**—An option used in Primavera scheduling software to ignore a logic relationship between two activities after actual work has violated this logic. For example, if activity A is a predecessor (with FS relationship) to activity B but activity B has started before activity A is completed, this option allows the remainder of B to proceed without regard to the completion of A. See also *Retained Logic*.

**Progress Payments**—Periodic (usually monthly) payments made by the owner to the general contractor (and by the general contractor to the subcontractors) upon the approval of the *Payment Request*. Owners usually retain a portion of the *Progress Payment* (5–10%, typically) until the successful completion of the project.

**Progressive Elaboration**—The continuous evolution of the project design documents along with its impact on the project's cost estimate and schedule. Unlike *Scope Creep*, progressive elaboration is not considered a negative practice since it represents the changing in project's attributes (cost, schedule) as the project scope becomes clarified as a result of the development of the design documents.

**Project**—A temporary endeavor undertaken to create a unique product, service, or result (PMI, 2008).

**Project Breakdown Structure (PBS)**—A task-oriented family tree of activities that organizes, defines, and displays the work to be accomplished. See *Work Breakdown Structure*.

**Project Charter**—Project charter is a statement of the scope, objectives, and participants in a project. It provides a preliminary delineation of roles and responsibilities, outlines the project objectives, identifies the main stakeholders, and defines the authority of the project manager. It serves as a reference of authority for the future of the project (*Wikipedia* online).

**Project Closeout**—The full completion of a project signed off on by all responsible parties, and the finalization of all paperwork and payments.

**Project Control**—The continuous process of monitoring work progress, comparing it to *Baseline Schedule* and *Baseline Budget* (what was supposed to happen or what was planned), finding any variances (deviations from baselines), where and how much; analyzing the variances to find out the causes and then taking corrective actions whenever and wherever necessary to bring the project back on schedule and within budget.

**Project Cost Breakdown**—See *Schedule of Values.*

**Project Management**—The application of knowledge, skills, tools, and techniques to project activities to meet the project requirements. It is accomplished through the application and integration of the project management processes of initiation, planning, execution, monitoring and controlling, and closing (PMI, 2013).

**Project Management Office (PMO)**—The department or group that defines and maintains the standards of process, generally related to project management, within the organization.

**Project Management Plan**—A formal, approved document used to guide both project execution and project control. The primary uses of the project plan are to document planning assumptions and decisions, facilitate communication among stakeholders, and document approved scope, cost, and schedule baselines. A project plan may be summary or detailed.

**Project Management Team**—The individuals involved in the management of a project. This involvement can be in different capacities, at different levels, or at different times. The team is usually led by the *Project Manager (PM)*.

**Project Manager (PM)**—The individual responsible for managing a project and its completion within its scope, budget, and schedule.

**Project Monitoring**—A term sometimes used to mean project control. Technically, it includes the first three functions of *Project Control* (monitoring, comparing, finding).

**Project Percent Complete**—A completion percentage of the work in a project based on a chosen method of measuring work progress.

**Project Plan**—See *Project Management Plan.*

**Project Planning**—The process of choosing the one method and order of work to be adopted for a project from all the various ways and sequences in which it could be done. Project planning serves as a foundation for several related functions, such as cost estimating, scheduling, project control, quality control, safety management, and so on.

**Project Risk**—"An uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objective such as scope, schedule, cost, and quality. A risk may have one or more causes and, if it occurs, one or more impacts" (PMI, 2013).

**Project Scheduling**—The determination of the timing and sequence of operations in the project and their assembly to give the overall completion time. Scheduling focuses on one part of the planning effort.

**Project Tracking**—See *Project Control.*

**Punch List**—A list made near to the completion of a project, showing the items of work remaining in order to complete the project scope.

**Punitive Damages**—Damages awarded by a judge to a plaintiff in excess of those required to compensate the plaintiff for losses incurred. Used to punish the defendant for wrongful conduct and to show the plight of the defendant as an example to potential wrongdoers.

**Qualitative Analysis**—The determination of the likelihood of a risk occurring on a project, as well as the assessment of the severity of that risk should it occur, and prioritizing the resultant list of risks.

**Quantitative Analysis**—The assigning of a probability to the qualitative description of a risk, ranking risks, and calculating the potential impact from both individual risks and the cumulative effect of all identified risks.

**Rain Days**—See *Nonworkdays.*

**Recovery Schedule**—A schedule prepared during the course of construction, after the project has fallen behind (either has failed to meet an interim target or has shown serious signs of failure to meet its expected completion date), with adjustments made by the contractor to expedite the remainder of the project in order to ensure a timely finish.

**Redundancy**—A duplication in depicting logical relationships. For example, if A and B are predecessors to C but A is a predecessor to B, then the relationship between A and C is redundant. Redundancies often happen when inserting activities after the logic network has been built. Unlike *Logic Loop*s, a redundancy is not an error and it will not halt CPM calculations.

**Relationship**—See *Logic Relationship.*

**Remaining Duration**—The number of time units (days, weeks, months, etc.) estimated to complete an in-progress activity.

**Request for Change (RFC)**—A request initiated by the owner, or the party representing the owner, authorizing the contractor for a change in the scope of the contract. The request is usually—but not always—preceded by an agreement on the impact of the change on the cost and schedule of the project.

**Request for Information (RFI)**—Solicitation issued to prospective bidders, which is used to obtain information relative to how a prospective contractor proposes to perform certain work, its qualifications, and terms and conditions. Not used to obtain price information.

**Request for Payment**—See *Payment Request.*

**Request for Proposal (RFP)**—A formal invitation by the owner or its representative to potential bidders, containing a scope of work that seeks a formal response (proposal) describing both the methodology and the compensation that will form the basis of a contract.

**Request for Quotation (RFQ)**—A formal invitation to submit a price for goods and/or services as specified.

**Resource**—Any measurable effort or substance that is required or consumed by work activities in a project. In context of construction projects, resources are labor, materials, and equipment.

**Resource Allocation**—The assignment of the required resources to each activity, in the required amount and timing.

**Resource Constraint**—A type of constraint (or restriction) that subjects the start and continuity of an activity to the availability of required resources. See *Resource Allocation*, *Resource-Driven Activity*, *Resource-Driven Schedule*, and *Resource Leveling*.

**Resource-Driven Activity**—An activity for which duration is calculated based on availability of required resources. Typically, several activities compete for limited resources, and the scheduler has to set the priority rules among them.

**Resource-Driven Schedule**—A CPM schedule with some or all activities is *resource driven*. Logic relationships still apply in addition to resource constraints.

**Resource Histogram**—A display of the number of units required (for future work) or consumed (for past work) of a specific resource during a specified period of time. The user can view the usage per unit of time or the cumulative usage. The user can compare the resource usage to the resource limit (availability). The histogram may plot the resource usage in terms of number of units or cost.

**Resource Leveling**—Minimizing the fluctuations in day-to-day resource usage throughout the project. It is usually done by shifting noncritical activities within their available float. It attempts to make the daily use of a certain resource as uniform as possible.

**Resource Loading**—See *Resource Allocation*.

**Resource Usage Profile**—See *Resource Histogram*.

**Restraint**—See *Constraint*.

**Retainage**—A portion of the eligible *Progress Payment* that is held by the owner until the contractor fulfills his or her contractual obligations. The contract usually specifies the amount and conditions of the retainage. In large projects, it is customary to either reduce the retainage percentage or stop retaining any money by the owner after the project reaches a certain completion stage, such as 50% complete. Also called *Retention*.

**Retained Logic**—Maintaining a logical relationship between predecessor and successor activities even though the successor activity has violated this logic and has started before the predecessor activity has finished. In other words, the rest of work in the successor activity will still have to wait until the rest of work in the predecessor activity has been completed.

**Retention**—See *Retainage*.

**Risk**—See *Project Risk*.

**Risk Allocation**—A determination of how to respond to risks, which can include shifting risks, avoiding risks, preventing or eliminating risks, and incorporating risks into the schedule.

**Project Risk Management**—A process designed to examine uncertainties occurring during project delivery and to implement actions dealing with those uncertainties in order to achieve project objectives. Project risk management includes the processes of conducting risk management planning, identification,

analysis, response planning, and controlling risk on a project (PMI,'s PMBOK, 5th Edition 2013).

**Risk Register**—A checklist of potential risks developed during the risk identification phase of risk management.

**Roll-up Schedule**—See *Summary Schedule*.

**S Curve**—A cumulative curve plotting work progress against time. Work progress may be expressed in terms of units of work, budget, man-hours, percent complete, or something else. The curve loosely resembles the letter *S* because work typically starts on a light scale and then intensifies toward the middle of the project, and finally lightens up again toward the end of the project. The curve is sometimes called *lazy-S curve*.

**Schedule**—A display of project activities and events, along with their timing, plotted chronologically on a calendar. A schedule may or may not be based on the *critical path method (CPM)*.

**Schedule Acceleration**—See *Schedule Compression*.

**Schedule Compression**—Shortening the project's schedule without reducing the project's scope to meet certain time and/or cost objectives. Schedule compression usually—but not always—increases the project's cost and often has physical limitations as to how much the schedule can be shortened.

**Schedule Contingency**—An amount of time added to the base-estimated duration to allow for unknown impacts to the project schedule or to achieve a certain level of confidence in the estimated duration.

**Schedule Crashing**—See *Schedule Compression*.

**Schedule of Values**—A listing of elements, systems, items, or other subdivisions of the work, establishing a value for each, the total of which equals the contract sum. The schedule of values is used for establishing the cash flow of a project and serves as the basis for payments requests (*RSMeans*, 2010). Also called *project cost breakdown* or simply *cost breakdown*.

**Schedule Performance Index (SPI)**—The ratio of work performed to work scheduled. SPI = BCWP/BCWS or SPI = EV/PV.

**Schedule Updating**—Reflecting actual performance information in the schedule, in time of occurrence and amount (or percentage) of performed work, as well as implementing any changes to the future work on the schedule.

**Schedule Variance (SV)**—The difference between work performed and work scheduled. SV = BCWP − BCWS or SV = EV − PV.

**Scheduler**—A project scheduling professional in charge of preparing and updating a CPM schedule for a construction project. The scheduler is also responsible for producing reports required by management pertaining to the schedule.

**Scheduling**—See *Project Scheduling*.

**Scope Creep**—The continuous and gradual expansion of the scope of a project (size, area, design, materials, etc.) after the contract has been signed, as a result of multiple and successive owner-issued change orders. Scope creep usually results from the owner's lack of vision, lack of appreciating the impact of changes on

the cost and schedule, unrealistic expectations, decentralized decision making, and/or other factors. It usually results in negative consequences to the owner, including the reduction of the value obtained in the project.

**Sequestering the Float**—Eliminating or reducing the float of an activity or activities by inflating durations, inserting unnecessary logic relationships, inserting unnecessary lags, or a combination of these procedures. This is a technique practiced by some contractors in order to maintain inconspicuous ownership of the float. Most owners dislike this practice and disallow it by inserting a "no sequestering the float" clause in the contract.

**Settlement**—An agreement by which the parties consent to settle a dispute between them.

**Shop Drawings**—Shop Drawings are drawings, diagrams, schedules, and other data specially that are prepared for work by the contractor or a subcontractor, sub-subcontractor, manufacturer, supplier, or distributor to illustrate some portion of the work. The purpose is to demonstrate the way in which the contractor proposes to conform to the information given and the design concept expressed in the contract documents (AIA).

**Single-Restricted Float**—Activity float that is restricted from its start or finish, not both. See *Start-Restricted Float* and *Finish-Restricted Float*.

**Slack**—See *Float*.

**Soft Logic**—See *Resource Constraint*.

**Standard Normal Distribution**—A normal distribution with the parameters mean, $\mu = 0$ and standard deviation, $\sigma = 1$. The random variable for this distribution is denoted by $Z$. The $z$-tables (values of the random variable $Z$ and the corresponding probabilities) are widely used for normal distributions.

**Start Milestone**—An event marking the start of an activity with special significance, such as notice to proceed (NTP).

**Start-Restricted Float (in Precedence Networks)**—The amount of time we can delay the rest of the work in an activity after it has started on its critical start date, without delaying the entire project.

**Start-to-Finish (SF) Relationship**—A logic restraint that does not allow for the start of one activity (the successor) until another activity (the predecessor) is completed.

**Start-to-Start (SS) Relationship**—A logic restraint that does not allow for the start of one activity (the successor) until another activity (the predecessor) has started.

**Status date**—See *Data Date*.

**Store Period Performance**—A function in Primavera software that adds the latest "Cost this Period" to the "Cost to Date," and then makes "Cost this Period" zero. This is a practice the scheduler has to do every time there is a schedule update, along with a *Payment Request*.

**Stretchable Activity**—An activity with a flexible duration that increases or decreases to accommodate the amount of available resources or other restrictions. The activity duration of a *stretchable activity* is determined by the CPM calculations based on the user's resource and/or other restrictions.

**Submittal**—A sample, manufacturer's data, shop drawing, or other such item submitted to the owner or the design professional by the contractor for approval or other action, usually a requirement of the contract documents.

**Subschedule**—Generally, a subschedule is portion of a larger schedule based on certain criteria, such as responsibility, area, phase, period of time, and so on. It is a common practice to refer to the schedule reflecting the work of one subcontractor or other single participant in the project as a subschedule. A subschedule may have starting date, completion date, and/or duration that is usually different from the *Master Schedule*.

**Substantial Completion**—The point in time when the project is ready for use by the owner for the purpose intended and is so certified. See *Certificate of Substantial Completion*.

**Successor Activity**—An activity that cannot start (or finish) until another activity (predecessor) has finished (or started).

**Summary Schedule**—A schedule (usually *Bar Chart*) in which activities are summarized (combined) by a certain criterion, such as responsibility, phase, or area. If Work Breakdown Structure (WBS) is used, it is possible to summarize (roll up) the schedule at any level higher than the individual activity. Summary schedules are usually used to inform upper management about the overall project situation without providing too much detail.

**Sunk Cost**—A cost already incurred that cannot be avoided even if the project is terminated. It cannot be recovered, regardless of future events.

**Target Schedule**—See *Baseline Schedule*.

**Task**—See *Activity*.

**Time Contingency**—See *Schedule Contingency*.

**Time Plus Cost Contracting Method**—See *A + B Contracting Method*.

**Time Ratio**—A method of measuring percent complete for an activity (or a project) by dividing the actual duration by the total duration. This method works well for activities with uniform work over its duration. The method also has a variety of ways of making calculations, mainly using actual or planned durations.

**Time-Scaled Logic Diagrams (or Bar Charts with Relationships)**—A bar chart with logic relationships (all or driving) depicted.

**Total Float (TF)**—The maximum amount of time an activity can be delayed from its early start without delaying the entire project and without violating a schedule constraint.

**Turn-Key Project**—A project in which a builder/developer contracts to construct a completed facility that includes all items necessary for use and occupancy. All that is required of the buyer to begin using the facility is to turn a key in the new door's lock and enter (Source: http://www.teachmefinance.com/). The term *turn-key* does not indicate a specific contracting or delivery method, but in most cases, it implies a design-build (DB) contract.

**Units Completed**—A method of measuring percent complete for an activity that is made up of small, similar, and repetitive units of work. Percent complete = Units completed/Total units. This method can be applied to the entire project if

the project can be divided into similar types of work, such as road construction or earthmoving projects.

**Unrestricted Float (in Precedence Networks)**—The amount of time we can delay all or part of an activity from its early start without delaying the entire project.

**Updated Impact Schedule**—A method developed by the U.S. Army Corps of Engineers for helping resolve delay claims. The concept is to create an *As-Built Schedule* or an updated schedule from the start of the project only to the point just before the delay occurred. The "original," or baseline, schedule is updated with progress information and then compared to the impacted completion date on another schedule on which a delay is included.

**Updated Schedule**—A revised schedule reflecting project information at a given data date regarding completed activities, in-progress activities, and changes in the logic, cost, and resources required and allocated at any activity level. (Popescu and Charoenngam, 1995, p. 566).

**Value Engineering (VE)**—A science that studies the relative value of various materials and construction techniques. Value engineering considers the initial cost of construction, coupled with the estimated cost of maintenance, energy use, life expectancy, and replacement cost.

**Variation Order**—See *Change Order*.

**Work Breakdown Structure (WBS)**—A task-oriented, detailed breakdown of activities that organizes, defines, and graphically displays all of the work to be accomplished in order to achieve the final objectives of a project. The WBS breaks down the project into progressively more detailed levels. Each descending level represents an increasingly detailed definition of a project component. In CPM scheduling, the components at the lowest WBS level are used as activities to build the project schedule.

**Workdays**—Days on which work was or is to be performed.

**Work Package**—A well-defined scope of work that terminates in a deliverable product or completion of a service.

**Zero Free Float**—See *as Late as Possible*.

**Zero Total Float**—A constraint in some computer scheduling programs that assigns a total float value of zero, causing the Early Dates to equal the Late Dates of the activity.

**Z-function**—See *Standard Normal Distribution*.

# References


Ahuja, H. N., S. P. Dozzi, and S. M. Abourizk. 1994. *Project Management*. 2nd ed. Hoboken, NJ: Wiley.

The American Institute of Architects. 2007. *General Conditions of the Contract for Construction*. Washington, DC: The American Institute of Architects.

———.*Document A201™ A2011-2007*. Washington, DC: The American Institute of Architects.l

Anbari, F. T. December 2009. "Earned Value Project Management Method and Extensions." *Project Management Journal* 34: 12–23 http://www.marcoullis.com/PROJECTS/ANBARI/pdf/selected/Anbari_Research_EVM_Anbari_PMJ.pdf

Antill, J. M., and R. W. Woodhead. 1990. *Critical Path Methods in Construction Practice*. 4th ed. Hoboken, NJ: Wiley.

Associated General Contractors (AGC) of America. 2005. *The Contractor's Guide to BIM*, 1st ed. AGC Research Foundation, Las Vegas, NV.

Association for the Advancement of Cost Engineering (AACE) International. 2006. Recommended Practice No. 52R-06, "Time impact analysis—as applied in construction." The AACE International, WV.

August, R. 2003. *International Law Dictionary and Directory*. Pullman, WA: Ray August.

The Autodesk Company. 2011. *Autodesk Navisworks Manage User Guide*. The Autodesk Company.

Bingham Tony. February 14, 2003. "Adjudication Is King." *Building* 52.

*Blinderman Construction Co. v. United States*, 17 Cl. Ct. 860 (1989).

Bramble, B. B., and M. T. Callahan. 2014. *Construction Delay Claims*. 5th ed., § 1.01, B, D. New York: Aspen.

The Business Roundtable. 1980. *Scheduled Overtime Effect on Construction Projects*. Report C-2. New York: The Business Roundtable.

Callahan, M. T., D. G. Quackenbush, and J. E. Rowings. 1992. *Construction Project Scheduling*. New York: McGraw-Hill.

Cho, A. 1997. "Packing More Road into Parkway." *Engineering News-Record (ENR)*, May 12, 30–32.

Construction Industry Institute. 2014. Best Practices (online). https://www.construction-institute.org/scriptcontent/bp.cfm?section=aboutcii

Construction Industry Institute. July 1986a. *Constructability: A Primer*. Publication no. 3–1. Austin, TX: Construction Industry Institute.

——. November 1986b. *Costs and Benefits of Materials Management Systems*. Publication no. 7–1. Austin, TX: Construction Industry Institute.

——. 1987a. *Guidelines for Implementing a Constructability Program*. Publication no. 3–2. Austin, TX: Construction Industry Institute.

——. 1987b. *Project Control for Construction*. Publication no. 6–5. Austin, TX: Construction Industry Institute.

——. November 1988a. *Concepts and Methods of Schedule Compression*. Publication no. 6–7. Austin, TX: Construction Industry Institute.

——. November 1988b. *Project Materials Management Primer*. Publication no. 7–2. Austin, TX: Construction Industry Institute.

——. May 1993. *Constructability: Implementation Guide*. Publication no. 34–1. Austin, TX: Construction Industry Institute.

Construction Management Association of America. (CMAA). 2003. *Capstone: The History of Construction Management Practice and Procedures*. McLean, VA: Construction Management Association of America.

The Construction Specifications Institute (CSI), MasterFormat® 2014, http://www.csinet.org/numbersandtitles. Accessed 2014.

Dell'Acqua, G., R. Lamberti, and P. Discetti. 2005. "Computer-based linear scheduling application for highway construction planning." Proceedings of the Third International SIIV Congress on People, Land, Environment and Transport Infrastructures, September 22–24, 2005, Bari, Italy, Società Italiana Infrastrutture Viarie, Ancona, Italy, 14 p,

Fair, M. L. 1994. A Comparative Study of Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), and Graphic Evaluation and Review Technique (GERT). Master's thesis, Indiana University of Pennsylvania.

*Fortec Constructors v. United States*, 8 Cl. Ct. 490 (1985).

Gould, F. E., and N. E. Joyce. 2003. *Construction Project Management*. 2nd ed. Upper Saddle River, NJ: Prentice Hall.

Harmelink, D. J., and R. A. Yamín. 2000. "Development and application of linear scheduling techniques to highway construction projects." Final Report, FHWA/IN/JTRP-2000/21, Joint Transportation Research Program, Project No. C-36–67YY, File No. 9–10–50, SPR-2330, in Cooperation with the Indiana Department of Transportation and the U.S. Department of Transportation Federal Highway Administration, Purdue University, West Lafayette, IN: 89 p.

Harris, R. B. 1978. *Precedence and Arrow Networking Techniques for Construction*. Hoboken, NJ: Wiley.

Hendrickson, C., and T. Au. 1989. *Project Management for Construction*. Upper Saddle River, NJ: Prentice Hall.

Holweg, M.. 2007.

Houghton Mifflin. 2000. *The American Heritage Dictionary of the English Language*. 4th ed. Boston: Houghton Mifflin.

Huang, R. Y., and D. W. Halpin. 1995. "POLO: Planning and optimization for linear operations." Proceedings of the 1995 2nd Congress on Computing in Civil Engineering, Atlanta, GA, June 5–8, 1995, 1: 1126–1133.

Huang, R. Y., and D. W. Halpin. 2000. "Graphically-based LP Modeling for Linear Construction Scheduling." *Engineering, Construction and Architectural Management* 7 (1): 41–51.

Hulett, David. 2009. *Practical Schedule Risk Analysis*. Gower Publishing Limited.

The Institution of Professional Engineers New Zealand (IPENZ) Engineers New Zealand. April 2008. "Practice Note 13: Constructability." http://www.ipenz.org.nz/ipenz/forms/pdfs/PN13_Constructability.pdf

Kankainen, J., and O. Seppänen. 2003. "A line-of-balance based schedule planning and control system." Proceedings of the Eleventh Annual Conference of the International Group for Lean Construction, ed. Martínez, J. C., Formoso, C. T., July 22–24, 2003, Virginia Polytechnic Institute and State University, Blacksburg, VA: 12 p.

Kenley, Russell, and O. Seppänen. 2006. "Location-based management system for construction: Principles and underlying logic." Proceedings of the 2006 Joint CIB W55-W65-W86 Symposium on Construction of the 21st Century: Global and Local Challenges, eds. Pietroforte, R., deAngelis, E., Polverino, F., Rome, Italy, October 18–20, 2006, Conseil International du Bâtiment, Rotterdam, The Netherlands, 19 p.

Knowles. 2002. "Adjudication." Professional Education Seminar.

Koskela, L., G. Howell, G. Ballard, and I. Tommelein. 2002. "The Foundations of Lean Construction." In *Design and Construction: Building in Value*. R. Best and G. deValence, eds. Oxford, UK: Butterworth-Heinemann, Elsevier.

Larew, R. E. 1998. "Are Any Construction Overtime 'Studies' Reliable?" *Cost Engineering* 40 (9).

Liker, J.K. (2004). The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer, New York: McGraw-Hill, Inc.

Lucko, G. 2008. "Productivity Scheduling Method Compared to Linear and Repetitive Project Scheduling Methods." *Journal of Construction Engineering and Management* 134 (9): 711–720

——. 2009. "Productivity Scheduling Method: Linear Schedule Analysis with Singularity Functions." *Journal of Construction Engineering and Management* 135 (4): 246–253.

Meredith, J. R., and S. J. Mantel, Jr., 2008. *Project Management*. 7th ed. Hoboken, NJ: Wiley.

Merriam-Webster. 2003. *Merriam-Webster's Collegiate Dictionary*. 11th ed. Springfield, MA: Merriam-Webster.

——. 2009. Merriam-Webster Dictionary Online. Retrieved April 21, 2004, from http://www.m-w.com.

Nageeb, M. R., and B. T. Johnson. 2009. "Line of balance scheduling: Software enabled use in the U.S. Construction Industry. International Proceedings of the 45th Annual Conference of the Associated Schools of Construction, eds. Sulbaran, T., Sterling, C., Gainesville, FL, April 1–4, 2009, Associated Schools of Construction, Fort Collins, CO: 8 p.

National Building Information Modeling Standard (NBIMS). 2007, December. United States National Building Information Modeling Standard, Version 1-Part 1: Overview, Principles and Methodologies.

Neil, J. M. 1982. *Construction Cost Estimating for Project Control*. Upper Saddle River, NJ: Prentice Hall.

Oberlender, G. D. 2000. *Project Management for Engineering and Construction*. 2nd ed. New York: McGraw-Hill.

O'Brien, J. J., and F. L. Plotnick. 2009. *CPM in Construction Management*. 7th ed. New York: McGraw-Hill.

Oglesby, C., H. Parker, and G. Howell. 1989. *Productivity Improvement in Construction*. New York: McGraw-Hill.

Pasiphol, S., and C. M. Popescu. 1994. "Qualitative criteria combination for total float distribution." In 1994 AACE transactions, DCL.03.1–DCL.03.6. Morgantown, WV: American Association of Cost Engineers International.

Peña-Mora, F., C. E. Sosa, and D. S. McCone. 2003. *Introduction to Construction Dispute Resolution*. Upper Saddle River, NJ: Prentice Hall.

Pickavance, Keith. 2005. *Delay and Disruption in Construction Contracts*. 4th ed. London: LLP, Sweet & Maxwell.

Pinedo, Michael. 2002. *Scheduling, Theory, Algorithms, and Systems*. 2nd ed. Upper Saddle River, NJ: Prentice Hall.

Ponce de Leon, G. 1986. "Float ownership: Specs treatment." *Cost Engineering*, 28 (10): 12–15.

Popescu, C. M., and C. Charoenngam. 1995. *Project Planning, Scheduling, and Control in Construction: An Encyclopedia of Terms and Applications*. Hoboken, NJ: Wiley.

Prentice Hall. 2000. *Construction Project Log Book*. Upper Saddle River, NJ: Prentice Hall.

——. Project Management Body of Knowledge. 2013. 5th edition. Newtown Square, PA: Project Management Institute.

Rosenbaum, D. B. 1994. "Contractor Finishes Early." *Engineering News-Record (ENR)*, July 18, 9.

——. 1995. "Fast Quake Recovery Redeemed State Transportation Department." *Engineering News-Record (ENR)*, January 16, 33.

Rosta, P. 1994a. "Contractor Drops Bridges." *Engineering News-Record (ENR)*, March 21, 13.

——. 1994b. "Fast Work Earns Big Bonus." *Engineering News-Record (ENR)*, April 18, 12.

RSMeans. 2010a. *Means Illustrated Construction Dictionary*. 4th ed. Kingston, MA: RSMeans.

——. 2010b. *RSMeans Building Construction Cost Data*. Note R012909–85. Kingston, MA: R. S. Means.

SAVE International. What is Value Engineering? http://www.value-eng.org/value_engineering.php. Accessed 2014.

Senouci, A., and Mubarak, S. 2012. "Profit Optimization for Construction Projects under Extreme Hot Weather Conditions," 2012 International Total Cost Management Conference, November 14–15, 2012, Dubai, UAE.

——. 2012. "Genetic Algorithm-based Multi-Objective Model for Scheduling of Linear Construction Projects Under Extreme Weather Conditions," The First Australasia and South-East Asia Structural Engineering and Construction Conference, November 28 to December 2, 2012, Perth, Australia.

——. 2013. "Multi-Objective Optimization Model for Scheduling of Construction Projects under Extreme Weather Conditions." *Journal of Civil Engineering and Management*, accepted for publication.

——. 2103. "Time-Profit Trade-Off of Construction Projects in Extreme Hot Weather Regions," Construction CPM Conference, January 28 to February 1, 2013, New Orleans, Louisiana, USA.

Sweet, J., and M. M. Schneier. 2008. *Legal Aspects of Architecture, Engineering and the Construction Process*. 8th ed. Eagan, MN: Thomson West.

Tulacz, G. J. 1994. "Penhall: Not Just a Wrecking Crew." *Engineering News-Record (ENR)*, July 11, 28.

U.S. Department of Defense (DoD). Earned Value Management (EVM) Division (online) http://www.acq.osd.mil/evm/

Warburton, R.D.H., and V. Kanabar. 2008. The Practical Calculation of Schedule Variance in Terms of Schedule. Paper presented at the PMI Global Congress 2008—North America, Denver, Colorado, October 2008.

Wickwire, J. M., T. J. Driscoll, S. B. Hurlbut, and M. J. Groff. 2009. *Construction Scheduling: Preparation, Liability, and Claims*, Hoboken, NJ: Wiley.

——. 2002. *Construction Scheduling: Preparation, Liability, and Claims*. 2nd ed. Hoboken, NJ: Wiley.

*Wilner v. United States*, 16 Cl. Ct. 260 (1992).

Winter, Ron. 2011. *DCMA 14-Point Schedule Assessment* http://www.ronwinterconsulting.com/DCMA_14-Point_Assessment.pdf

Woolf, Murray B. 2007. *Faster Construction Projects with CPM Scheduling*. New York: McGraw Hill.

Yamín, R. A. 2002. Cumulative Effect of Productivity Rates in Linear Schedules. Thesis submitted to the faculty of Purdue University in partial fulfillment of the requirements for the degree of doctor of philosophy, Purdue University, West Lafayette, Indiana.

# Bibliography

## PLANNING, SCHEDULING, AND PROJECT CONTROL


Antill, J. M., and R. W. Woodhead. 1990. *Critical Path Methods in Construction Practice*. 4th ed. Hoboken, NJ: Wiley.

Associated General Contractors of America. 2004. *Construction Planning and Scheduling*. 2nd ed. Alexandria, VA: Associated General Contractors of America.

Baldwin, B., and D. Bordoli. 2014. *Handbook for Construction Planning and Scheduling*. 1st ed. Chichester, UK: Wiley.

Burke, R. 2013. *Project Management: Planning and Control Techniques*. 5th ed. Hoboken, NJ: Wiley.

Callahan, M. T., D. G. Quackenbush, and J. E. Rowings. 1992. *Construction Project Scheduling*. New York, NY: McGraw-Hill.

Cho, A. 1997. "Packing more road into parkway." *Engineering News-Record (ENR)*, May 12, pp. 30–32.

Del Pico, Wayne J. 2013. *Project Control Integrating Cost and Schedule in Construction*. Hoboken, NJ: Wiley.

Dreger, J. B. 1992. *Project Management: Effective Scheduling*. New York, NY: Van Nostrand Reinhold.

Feigenbaum, L. 2002. *Construction Scheduling with Primavera Project Planner*. 2nd ed. Upper Saddle River, NJ: Prentice Hall.

Harris, P. E. 1999 (revised 2006). *Planning Using Primavera Project Planner P3 Version 3.0*. Melbourne, Australia: Eastwood Harris.

——. 2013. *Project Planning and Control Using Oracle Primavera P6 Versions 8.1, 8.2 & 8.3 Professional Client & Optional Client:: For All Industries Including Versions 4 to 7*. Melbourne, Australia: Eastwood Harris.

Harris, R. B. 1978. *Precedence and Arrow Networking Techniques for Construction*. Hoboken, NJ: Wiley.

Heldman, Kim. 2013. *PMP Project Management Professional Exam Study Guide*. 7th ed. Indianapolis, IN: Wiley.

Hinze, J. W. 2011. *Construction Planning and Scheduling*. 4th ed. Upper Saddle River, NJ: Prentice Hall.

Horsley, F. W. 2004. *Means Scheduling Manual*. 3rd ed. Kingston, MA: RSMeans.

Hutchings, J. F. 2004. *Project Scheduling Handbook*. New York, NY: Marcel Dekker.

Kelley, R. M. 1988. *Planning Techniques (Basic and Advanced)*. Kettering, OH: Kelley Communication Development.

Lewis, J. P. 2010. *Project Planning, Scheduling, and Control*. 5th ed. New York, NY: McGraw-Hill.

Marchman, D. A. 2002. *Construction Scheduling with Primavera Project Planner*. 2nd ed. Clifton Park, NY: Delmar.

Moder, J. J., C. R. Phillips, and E. W. Davis. 1995. *Project Management with CPM, PERT and Precedence Diagramming*. 3rd ed. Middleton, WI: Blitz.

Mulcahy, Rita. 2013. *PMP Exam Prep: Rita's Course in a Book for Passing the PMP Exam*. 8th ed. Minnetonka, MN: RMC Publications.

Newitt, J. S., 2009. *Construction Scheduling: Principles and Practices*. 2nd ed. Upper Saddle River, NJ: Prentice Hall.

O'Brien, J. J., and F. L. Plotnick. 2009. *CPM in Construction Management*. 7th ed. New York, NY: McGraw-Hill.

Pasiphol, S., and C. M. Popescu. 1994. Qualitative Criteria Combination for Total Float Distribution. In *1994 AACE Transactions*, DCL.03.1-DCL.03.6. Morgantown, WV: American Association of Cost Engineers International.

Patrick, C. 2004. *Construction Project Planning and Scheduling*. Upper Saddle River, NJ: Prentice Hall.

Pierce, D. R., Jr., 2012. *Project Scheduling and Management for Construction*. 4th ed. Hoboken, NJ: Wiley.

Pinedo, Michael. 2014. *Scheduling, Theory, Algorithms, and Systems*. 4th ed. New York, NY: Springer.

Ponce de Leon, G. 1986. "Float ownership: Specs treatment." *Cost Engineering*, 28 (10): 12–15.

Popescu, C. M., and C. Charoenngam. 1995. *Project Planning, Scheduling, and Control in Construction: An Encyclopedia of Terms and Applications*. Hoboken, NJ: Wiley.

Rosenbaum, D. B. 1994. "Contractor finishes early." *Engineering News-Record (ENR)*, July 18, p. 9.

Rosenbaum, D. B. 1995. "Fast quake recovery redeemed state transportation department." *Engineering News-Record (ENR)*, January 16, p. 33.

Rosta, P. 1994. "Contractor drops bridges." *Engineering News-Record (ENR)*, March 21, p. 13.

——. 1994. "Fast work earns big bonus." *Engineering News-Record (ENR)*, April 18, p. 12.

Samad, S. A., ed. 1999. *Planning and scheduling*. Professional Practice Guide (PPG) #4. Morgantown, WV: American Association of Cost Engineers International.

Stevens, J. D. 1990. *Techniques for Construction Network Scheduling*. New York, NY: McGraw-Hill.
Tulacz, G. J. 1994. "Penhall: Not just a wrecking crew." *Engineering News-Record (ENR)*, July 11, p. 28.
Weber, S. L. 2004. *Scheduling Construction Projects: Principles and Practices*. 1st ed. Upper Saddle River, NJ: Prentice Hall.
Wiest, J. D., and F. K. Levy. 1977. *A Management Guide to PERT/CPM*. 2nd ed. Upper Saddle River, NJ: Prentice Hall.
Willis, E. M. 1986. *Scheduling Construction Projects*. Hoboken, NJ: Wiley.
Woolf, Murray B. 2007. *Faster Construction Projects with CPM Scheduling*. New York, NY: McGraw Hill.
——. 2012. *CPM Mechanics: The Critical Path Method of Modeling Project Execution Strategy*. Rochester, MI: ICS-Publications.

## PROJECT AND CONSTRUCTION MANAGEMENT

Ahuja, H. N., S. P. Dozzi, and S. M. Abourizk. 1994. *Project Management*. 2nd ed. Hoboken, NJ: Wiley.
Angus, R. B., N. A. Gundersen, and T. P. Cullinane. 2003. *Planning, Performing, and Controlling Projects*. 3rd ed. Upper Saddle River, NJ: Prentice Hall.
Barrie, D. S., and B. C. Paulson. 1992. *Professional Construction Management*. 3rd ed. New York, NY: McGraw-Hill.
Bennett, F. L. 2003. *The Management of Construction: A Project Life Cycle Approach*. Boston: Butterworth-Heinemann.
The Business Roundtable. 1989. *Scheduled Overtime Effect on Construction Projects*. Report C-2. New York: The Business Roundtable.
Certo, S. C. 2013. *Modern Management*. 13th ed. Upper Saddle River, NJ: Prentice Hall.
Collier, K. 1994. *Managing Construction: The Contractual Viewpoint*. Albany, NY: Delmar.
Construction Industry Institute. 1986, July. *Constructability: A Primer*. Publication no. 3-1. Austin, TX: Construction Industry Institute.
——. 1986, November. *Costs and Benefits of Materials Management Systems*. Publication no. 7-1. Austin, TX: Construction Industry Institute.
——. 1987. *Guidelines for Implementing a Constructability Program*. Publication no. 3-2. Austin, TX: Construction Industry Institute.
——. 1988, November. *Concepts and Methods of Schedule Compression*. Publication no. 6-7. Austin, TX: Construction Industry Institute.
——. 1988, November. *Project Materials Management Primer*. Publication no. 7-2. Austin, TX: Construction Industry Institute.
——. 1993, May. *Constructability: Implementation Guide*. Publication no. 34-1. Austin, TX: Construction Industry Institute.
Fisk, E. R. 2013. *Construction Project Administration*. 10th ed. Upper Saddle River, NJ: Prentice Hall.

Flannes, S. W., and Levin, G. 2005. *Essential People Skills for Project Managers*. Vienna, VA: Management Concepts.

Gould, F. E., and N. E. Joyce. 2008. *Construction Project Management*. 3rd ed. Upper Saddle River, NJ: Prentice Hall.

Graham, R. J. 1989. *Project Management as if People Mattered*. Bala Cynwyd, PA: Primavera Press.

Halpin W. H., and B. A. Senior. 2011. *Construction Management*. 4th ed. Hoboken, NJ: Wiley.

Hegazy, T. 2002. *Computer-Based Construction Project Management*. Upper Saddle River, NJ: Prentice Hall.

Hendrickson, C., and T. Au. 1989. *Project Management for Construction*. Upper Saddle River, NJ: Prentice Hall.

Jackson, B. J. 2010. *Construction Management Jumpstart*. 2nd ed. Indianapolis, IN: Wiley.

Kerzner, H. 2009. *Project Management: A Systems Approach to Planning, Scheduling and Controlling*. 10th ed. Hoboken, NJ: Wiley.

Levin, G. 2010. *Interpersonal Skills for Portfolio, Program, and Project Managers*. 1st ed. Tysons Corner, VA: Management Concepts Press.

Levy, S. M. 2011. *Project Management in Construction*. 6th ed. New York, NY: McGraw-Hill.

Levy, S. M., and A. M. Civitello. 2014. *Construction Operations Manual of Policies and Procedures*. 5th ed. New York, NY: McGraw Hill.

Meredith, J. R., and S. J. Mantel, Jr., 2008. *Project Management*. 7th ed. Hoboken, NJ: Wiley.

Naylor, H. 1995. *Construction Project Management: Planning and Scheduling*. Albany, NY: Delmar.

Neil, J. M. 1982. *Construction Cost Estimating for Project Control*. Upper Saddle River, NJ: Prentice Hall.

Nunnally, S. W. 2010. *Construction Methods and Management*. 8th ed. Upper Saddle River, NJ: Prentice Hall.

Oberlender, G. D. 2014. *Project Management for Engineering and Construction*. 3rd ed. New York, NY: McGraw-Hill.

Pilcher, R. 1992. *Principles of Construction Management*. 3rd ed. New York, NY: McGraw-Hill.

Pinto, J. K., and O. P. Kharbanda. 1995. *Successful Project Managers*. New York, NY: Van Nostrand Reinhold.

Project Management Institute. 2013. *A Guide to the Project Management Body of Knowledge: PMBOK Guide*. 5th ed. Newtown Square, PA: Project Management Institute.

Radosavljevic, M., and J. Bennett. 2012. *Construction Management Strategies: A Theory of Construction Management*. 1st ed. Hoboken, NJ: Wiley.

Ritz, G. J., and S. M. Levy. 2013. *Total Construction Project Management*. 2nd ed. New York, NY: McGraw-Hill.

Rosenau, M. D., Jr. 2005. *Successful Project Management*. 4th ed. Hoboken, NJ: Wiley.

Sears, S. K., G. A. Sears, and R. H. Clough. 2008. *Construction Project Management: A Practical Guide to Field Construction Management*. 5th ed. Hoboken, NJ: Wiley.

Weinstein, J. T. Jaques. 2010. *Achieving Project Management Success in the Federal Government*. 1st ed. Tysons Corner, VA: Management Concepts Press.

## CONSTRUCTION SCHEDULING LAW

*Blinderman Construction Co. v. United States*, 17 Cl. Ct. 860 (1989).

Bockrath, Joseph T., and Fredric L. Plotnick. 2010. *Contracts and the Legal Environment for Engineers and Architects*. 7th ed. New York, NY: McGraw-Hill.

Bramble, B. B., and M. T. Callahan. 2010. *Construction Delay Claims*. 4th ed. New York, NY: Aspen.

*Fortec Constructors v. United States*, 8 Cl. Ct. 490 (1985).

Heuer, C. R. 1989. *Means Legal Reference for Design and Construction*. Kingston, MA: RSMeans.

Peña-Mora, F., C. E. Sosa, and D. S. McCone. 2003. *Introduction to Construction Dispute Resolution*. Upper Saddle River, NJ: Prentice Hall.

Pickavance, Keith. 2010. *Delay and Disruption in Construction Contracts*. 4th ed. London: Sweet & Maxwell.

Stokes, M. 1980. *Labor Law in Contractors' Language*. New York, NY: McGraw-Hill.

Sweet, J. J. 1993. *Avoiding or Minimizing Construction Litigation*. Hoboken, NJ: Wiley.

Sweet, J., and Schneier, M. M. 2012. *Legal Aspects of Architecture, Engineering and the Construction Process*. 8th ed. Stamford, CT: Cengage Learning.

Theodore J. Trauner Jr.,, William A. Manginelli, J. Scott Lowe, Mark F. Nagata, and Brian J. Furniss, et al. (2009). *Construction Delays: Understanding Them Clearly, Analyzing Them Correctly*. 2nd ed. Burlington, MA: Elsevier.

Wickwire, J. M., T. J. Driscoll, and S. B. Hurlbut. 2009. *Construction Scheduling: Preparation, Liability, and Claims*. 3rd ed. New York, NY Aspen.

Wilner v. United States, 16 Cl. Ct. 260 (1992).

## OTHER

The American Institute of Architects. 2007. *General Conditions of the Contract for Construction*. Document A201™, Washington, DC: The American Institute of Architects.

The Associated General Contractors of America. 2005. *The Contractor's Guide to BIM*. 1st ed. Arlington, VA: AGC Research Foundation.

August, R. 2003. *International Law Dictionary and Directory*. Pullman, WA: Ray August.

Autodesk, Inc.. April. *Autodesk Navisworks Manage 2012 User Guide*.

Barba-Arkhon International. 1996. *Schedule Delay and Loss of Productivity Analysis*. 11th Annual Construction Superconference, Mount Laurel, NJ: Barba-Arkhon International.

Bent, J. A. 2007. *Applied Cost and Schedule Control*. 2nd ed. New York, NY: Marcel Dekker.

The Business Roundtable. 1989. *Scheduled Overtime Effect on Construction Projects*. Report C-2. New York: The Business Roundtable.

Construction Industry Institute. 1986, November. *Costs and Benefits of Materials Management Systems*. Publication no. 7-1. Austin, TX: Construction Industry Institute.

——. 1986. *Project Control for Engineering*. Publication no. 6-1. Austin, TX: Construction Industry Institute.

——. 1986. *Scope, Definition, and Control*. Publication no. 6-2. Austin, TX: Construction Industry Institute.

——. 1987. *Project Control for Construction*. Publication no. 6-5. Austin, TX: Construction Industry Institute.

——. 1988, November. *Concepts and Methods of Schedule Compression*. Publication no. 6-7. Austin, TX: Construction Industry Institute.

——. 1988, November. *Project Materials Management: Primer*. Publication no. 7-2. Austin, TX: Construction Industry Institute.

——. 1988. *Work Packaging for Project Control*. Publication no. 6-6. Austin, TX: Construction Industry Institute.

——. 1990. *The Impact of Changes on Construction Cost and Schedule*. Publication no. 6-10. Austin, TX: Construction Industry Institute.

——. 1991. *Organizing for Project Success*. Special publication no. 12-2. Austin, TX: Construction Industry Institute.

——. 1993, May. *Constructability: Implementation Guide*. Publication no. 34-1. Austin, TX: Construction Industry Institute.

——. 2011. *The CSI Construction Specifications Practice Guide*. 1st ed. Hoboken, NJ: Wiley.

Cretu, O., R. Stewart, and T. Berends. 2011. *Risk Management for Design and Construction*. Hoboken, NJ: Wiley.

Dell'Isola, A. 1997. *Value Engineering: Practical Applications*. Kingston, MA: RSMeans.

Fair, M. L. 1994. *A Comparative Study of Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), and Graphic Evaluation and Review Technique (GERT)*. Master's thesis, Indiana University of Pennsylvania.

Fleming, Q. W., and J. M. Koppelman. 2010. *Earned Value Project Management*. 4th ed. Newtown Square, PA: Project Management Institute.

Haltenhoff, C. E. 1999. *The CM Contracting System: Fundamentals and Practices*. Upper Saddle River, NJ: Prentice Hall.

Holweg, M. 2007. "The genealogy of lean production." *Journal of Operations Management*, 25, 420–437.

Houghton Mifflin. 2000. *The American Heritage Dictionary of the English Language*. 4th ed. Boston: Houghton Mifflin.

Hulett, David. 2009. *Practical Schedule Risk Analysis*. Farnham, Surrey, UK: Gower Publishing Limited.

——. 2011. *Integrated Cost-Schedule Risk Analysis*. Ashgate Publishing.

Koskela, L., et al. 2002. "The foundations of lean construction," in *Design and Construction: Building in Value*, R. Best and G. D. Valence, eds. Oxford: Butterworth-Heinemann, 211–226.

Larew, R. 1995. "Are any construction overtime 'studies' reliable?" *Cost Engineering*, 40 (9).

Liker, J. K. 2004. *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. New York, NY: McGraw-Hill.

Locher, W. D., and A. Civitello, Jr. 2008. *Contractor's Guide to Change Orders*. 2nd ed. Anaheim, CA: BNi Building News.

Merriam-Webster. 2008. *Merriam-Webster's Collegiate Dictionary*. 11th ed. Springfield, MA: Merriam-Webster.

Morrisey, G. L., T. L. Sechrest, and W. B. Warman. 1997. *Loud and Clear: How to Prepare and Deliver Effective Business and Technical Presentations*. 4th ed. New York, NY: Perseus Books.

National Institute of Building Sciences. 2007, December. *United States National Building Information Modeling Standard, Version 1- Part 1: Overview, Principles and Methodologies.*

Neil, J. M. 1982. *Construction Cost Estimating for Project Control*. Upper Saddle River, NJ: Prentice Hall.

Oglesby, C., H. Parker, and G. Howell. 1989. *Productivity Improvement in Construction*. New York, NY: McGraw-Hill.

Peurifoy, R. L., et al. 2010. *Construction Planning, Equipment, and Methods*. 7th ed. New York, NY: McGraw-Hill.

Prentice Hall. 2000. *Construction Project Log Book*. Upper Saddle River, NJ: Prentice Hall.

RSMeans. 2010. *Means Illustrated Construction Dictionary*. 4th ed. Kingston, MA: RSMeans.

——. 2014. R. S. Means *Building Construction Cost Data*. Kingston, MA: RSMeans.

Regan, S. T. 2013. *AACE International Decision and Risk Management Professional (DRMP) Certification Study Guide*.: CreateSpace Independent Publishing Platform.

Thomas, P. I. 2000. *The Contractor's Field Guide*. Upper Saddle River, NJ: Prentice Hall.

Thompson, P., and J. Perry, eds. 1992. *Engineering Construction Risks: A Guide to Project Risk Analysis and Risk Management*. London: Telford.

Warburton, R. D. H., and V. Kanabar. 2008. "The Practical Calculation of Schedule Variance in Terms of Schedule." Paper presented in the PMI Global Congress 2008—North America, Denver, Colorado, October 2008.

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