MODULE 5

SOFTWARE QUALITY

OBJECTIVES

When you have completed this chapter you will be able to:

- explain the importance of software quality to software users and developers;
- define the qualities of good software;
- design methods of measuring the required qualities of software;
- monitor the quality of the processes in a software project;
- use external quality standards to ensure the quality of software acquired from an outside supplier;
- develop systems using procedures that will increase their quality.

13.1 Introduction

While quality is generally agreed to be 'a good thing', in practice what is meant by the 'quality' of a system can be vague. We need to define precisely what qualities we require of a system. However, we need to go further – we need to judge objectively whether a system meets our quality requirements and this needs measurement. This would be of particular concern to someone like Brigette at Brightmouth College in the process of selecting a package.

For someone – like Amanda at IOE – who is developing software, waiting until the system exists before measuring it would be leaving things rather late. Amanda might want to assess the likely quality of the final system while it was still under development, and also to make sure that the development methods used would produce that quality. This leads to a different emphasis – rather than concentrating on the quality of the final system, a potential customer for software might check that the suppliers were using the best development methods.

This chapter examines these issues.

13.2 The Place of Software Quality in Project Planning

Quality will be of concern at all stages of project planning and execution, but will be of particular interest at the following points in the Step Wise framework (Figure 13.1).

- *Step 1: Identify project scope and objectives* Some objectives could relate to the qualities of the application to be delivered.
- *Step 2: Identify project infrastructure* Within this step, activity 2.2 identifies installation standards and procedures. Some of these will almost certainly be about quality.
- *Step 3: Analyse project characteristics* In activity 3.2 ('Analyse other project characteristics – including quality based ones') the application to be implemented is examined to see if it has any special quality requirements. If, for example, it is safety critical then a range of activities could be added, such as *n*-version development where a number of teams develop versions of the same software which are then run in parallel with the outputs being cross-checked for discrepancies.

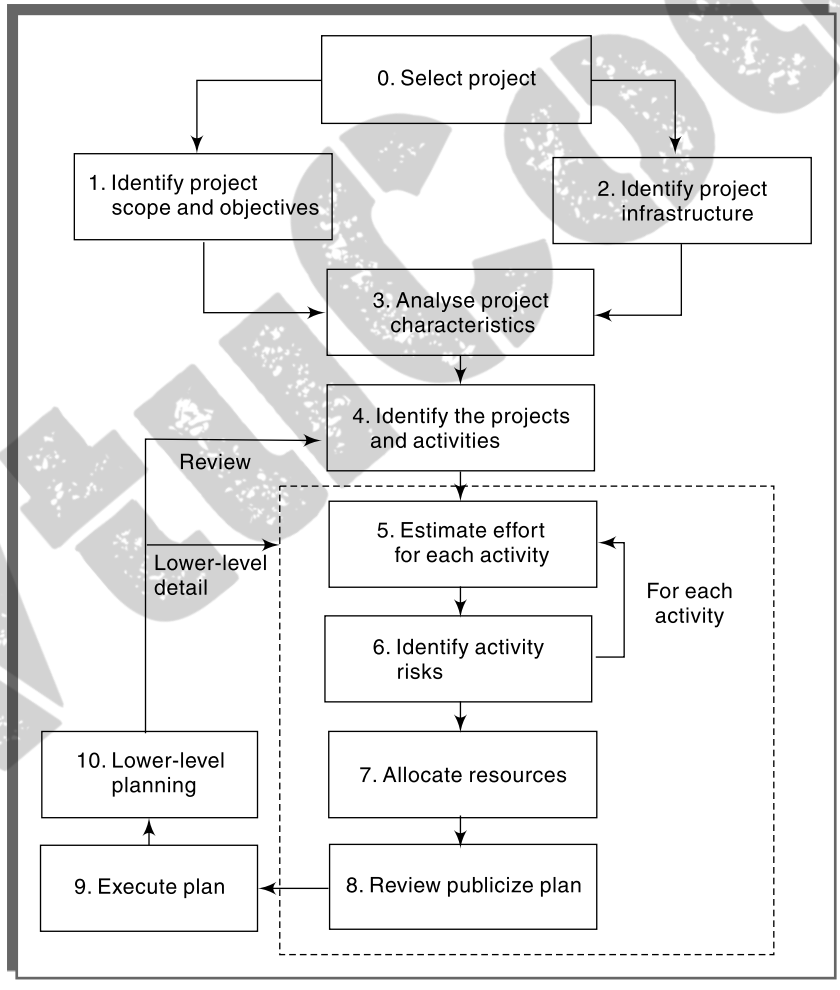


FIGURE 13.1 The place of software quality in Step Wise

- *Step 4: Identify the products and activities of the project* It is at this point that the entry, exit and process requirements are identified for each activity. This is described later in this chapter.
- *Step 8: Review and publicize plan* At this stage the overall quality aspects of the project plan are reviewed.

13.3 The Importance of Software Quality

We would expect quality to be a concern of all producers of goods and services. However, the special characteristics of software create special demands.

- *Increasing criticality of software* The final customer or user is naturally anxious about the general quality of software, especially its reliability. This is increasingly so as organizations rely more on their computer systems and software is used in more safety-critical applications, for example to control aircraft.
- *The intangibility of software* can make it difficult to know that a project task was completed satisfactorily. Task outcomes can be made tangible by demanding that the developer produce 'deliverables' that can be examined for quality.
- *Accumulating errors during software development* As computer system development comprises steps where the output from one step is the input to the next, the errors in the later deliverables will be added to those in the earlier steps, leading to an accumulating detrimental effect. In general, the later in a project that an error is found the more expensive it will be to fix. In addition, because the number of errors in the system is unknown, the debugging phases of a project are particularly difficult to control.

For these reasons quality management is an essential part of effective overall project management.

13.4 Defining Software Quality

In Chapter 1 we noted that a system has functional, quality and resource requirements. Functional requirements define what the system is to do, the resource requirements specify allowable costs and the quality requirements state how well this system is to operate.

EXERCISE 13.1

At Brightmouth College, Brigette has to select the best off-the-shelf payroll package for the college. How should she go about this in a methodical manner?

One element of the approach could be the identification of criteria against which payroll packages are to be judged. What might these criteria be? How could you check the extent to which packages match these criteria?

Some qualities of a software product reflect the external view of software held by *users*, as in the case of usability. These *external qualities* have to be mapped to *internal factors* of which the *developers* would be aware. It could be argued, for example, that well-structured code is likely to have fewer errors and thus improve reliability.

Defining quality is not enough. If we are to judge whether a system meets our requirements we need to be able to measure its qualities.

A good measure must relate the number of units to the maximum possible. The maximum number of faults in a program, for example, is related to the size of the program, so a measure of *faults per thousand lines of code* is more helpful than *total faults in a program*.

Trying to find measures for a particular quality helps to clarify and communicate what that quality really is. What is being asked is, in effect, 'how do we know when we have been successful?'

The BS ISO/IEC 15939:2007 standard *Systems and software engineering – measurement process* has codified many of the practices discussed in this section.

The measures may be *direct*, where we can measure the quality directly, or *indirect*, where the thing being measured is not the quality itself but an indicator that the quality is present. For example, the number of enquiries by users received by a help desk about how one operates a particular software application might be an indirect measurement of its usability.

When project managers identify quality measurements they effectively set targets for project team members, so care has to be taken that an improvement in the measured quality is always meaningful. For example, the number of errors found in program inspections could be counted, on the grounds that the more thorough the inspection process, the more errors will be discovered. This count could, of course, be improved by allowing more errors to go through to the inspection stage rather than eradicating them earlier – which is not quite the point.

When there is concern about the need for a specific quality characteristic in a software product then a quality specification with the following minimum details should be drafted:

- *definition/description:* definition of the quality characteristic;
- *scale:* the unit of measurement;
- *test:* the practical test of the extent to which the attribute quality exists;
- *minimally acceptable:* the worst value which might be acceptable if other characteristics compensated for it, and below which the product would have to be rejected out of hand;
- *target range:* the range of values within which it is planned the quality measurement value should lie;
- *now:* the value that applies currently.

EXERCISE 13.2

Suggest quality specifications for a word processing package. Give particular attention to the way that practical tests of these attributes could be conducted.

There could be several measurements applicable to a quality characteristic. For example, in the case of reliability, this might be measured in terms of:

- *availability:* the percentage of a particular time interval that a system is usable;
- *mean time between failures:* the total service time divided by the number of failures;
- *failure on demand:* the probability that a system will not be available at the time required or the probability that a transaction will fail;
- *support activity:* the number of fault reports that are generated and processed.

EXERCISE 13.3

The enhanced IOE maintenance jobs system has been installed, and is normally available to users from 8.00 a.m. until 6.00 p.m. from Monday to Friday. Over a four-week period the system was unavailable for one whole day because of problems with a disk drive and was not available on two other days until 10.00 in the morning because of problems with overnight batch processing runs.

What were the availability and the mean time between failures of the service?

Maintainability can be seen from two different perspectives. The user will be concerned with the *elapsed time* between a fault being detected and it being corrected, while the software development managers will be concerned about the *effort* involved.

Associated with reliability is *maintainability*, which is how quickly a fault, once detected, can be corrected. A key component of this is *changeability*, which is the ease with which the software can be modified. However, before an amendment can be made, the fault has to be diagnosed. Maintainability can therefore be seen as changeability plus a new quality, *analysability*, which is the ease with which causes of failure can be identified.

13.5 ISO 9126

Currently, in the UK, the main ISO 9126 standard is known as BS ISO/IEC 9126-1:2001. This is supplemented by some 'technical reports' (TRs), published in 2003, which are provisional standards. At the time of writing, a new standard in this area, ISO 25000, is being developed.

Over the years, various lists of software quality characteristics have been put forward, such as those of James McCall and of Barry Boehm. A difficulty has been the lack of agreed definitions of the qualities of good software. The term 'maintainability' has been used, for example, to refer to the ease with which an error can be located and corrected in a piece of software, and also in a wider sense to include the ease of making any changes. For some, 'robustness' has meant the software's tolerance of incorrect input, while for others it has meant the ability to change program code without introducing errors. The ISO 9126 standard was first introduced in 1991 to tackle the question of the definition of software quality. The original 13-page document was designed as a foundation upon which further, more detailed, standards could be built. The ISO 9126 standards documents are now very lengthy. Partly this is because people with differing motivations might be interested in software quality, namely:

- *acquirers* who are obtaining software from external suppliers;
- *developers* who are building a software product;
- *independent evaluators* who are assessing the quality of a software product, not for themselves but for a community of users – for example, those who might use a particular type of software tool as part of their professional practice.

ISO 9126 has separate documents to cater for these three sets of needs. Despite the size of this set of documentation, it relates only to the definition of software quality attributes. A separate standard, ISO 14598, describes the procedures that should be carried out when assessing the degree to which a software product conforms to the selected ISO 9126 quality characteristics. This might seem unnecessary, but it is argued that ISO 14598 could be used to carry out an assessment using a different set of quality characteristics from those in ISO 9126 if circumstances required it.

The difference between internal and external quality attributes has already been noted. ISO 9126 also introduces another type of quality – *quality in use* – for which the following elements have been identified:

- *effectiveness:* the ability to achieve user goals with accuracy and completeness;
- *productivity:* avoiding the excessive use of resources, such as staff effort, in achieving user goals;
- *safety:* within reasonable levels of risk of harm to people and other entities such as business, software, property and the environment;
- *satisfaction:* smiling users.

'Users' in this context includes not just those who operate the system containing the software, but also those who maintain and enhance the software. The idea of quality in use underlines how the required quality of the software is an attribute not just of the software but also of the context of use. For instance, in the IOE scenario, suppose the maintenance job reporting procedure varies considerably, depending on the type of equipment being serviced, because different inputs are needed to calculate the cost to IOE. Say that 95% of jobs currently involve maintaining photocopiers and 5% concern maintenance of printers. If the software is written for this application, then despite good testing, some errors might still get into the operational system. As these are reported and corrected, the software would become more 'mature' as faults become rarer. If there were a rapid switch so that more printer maintenance jobs were being processed, there could be an increase in reported faults as coding bugs in previously less heavily used parts of the software code for printer maintenance were flushed out by the larger number of printer maintenance transactions. Thus, changes to software use involve changes to quality requirements.

ISO 9126 identifies six major external software quality characteristics:

- *functionality*, which covers the functions that a software product provides to satisfy user needs;
- *reliability*, which relates to the capability of the software to maintain its level of performance;
- *usability*, which relates to the effort needed to use the software;
- *efficiency*, which relates to the physical resources used when the software is executed;
- *maintainability*, which relates to the effort needed to the make changes to the software;
- *portability*, which relates to the ability of the software to be transferred to a different environment.

ISO 9126 suggests sub-characteristics for each of the primary characteristics. They are useful as they clarify what is meant by each of the main characteristics.

Characteristic	Sub-characteristics
Functionality	Suitability
	Accuracy
	Interoperability
	Functionality compliance
	Security

'Functionality compliance' refers to the degree to which the software adheres to application-related standards or legal requirements. Typically these could be auditing requirements. Since the original 1999 draft, a sub-characteristic called 'compliance' has been added to all six ISO external characteristics. In each case, this refers to any specific standards that might apply to the particular quality attribute.

'Interoperability' is a good illustration of the efforts of ISO 9126 to clarify terminology. 'Interoperability' refers to the ability of the software to interact with other systems. The framers of ISO 9126 have chosen this

word rather than 'compatibility' because the latter causes confusion with the characteristic referred to by ISO 9126 as 'replaceability' (see below).

Characteristic	Sub-characteristics
Reliability	Maturity
	Fault tolerance
	Recoverability
	Reliability compliance

'Maturity' refers to the frequency of failure due to faults in a software product, the implication being that the more the software has been used, the more faults will have been uncovered and removed. It is also interesting to note that 'recoverability' has been clearly distinguished from 'security' which describes the control of access to a system.

Characteristic	Sub-characteristics
Usability	Understandability
	Learnability
	Operability
	Attractiveness
	Usability compliance

Note how 'learnability' is distinguished from 'operability'. A software tool could be easy to learn but time-consuming to use because, say, it uses a large number of nested menus. This might be fine for a package used intermittently, but not where the system is used for many hours each day. In this case 'learnability' has been incorporated at the expense of 'operability'.

'Attractiveness' is a recent addition to the sub-characteristics of usability and is especially important where users are not compelled to use a particular software product, as in the case of games and other entertainment products.

Characteristic	Sub-characteristics
Efficiency	Time behaviour
	Resource utilization
	Efficiency compliance
Maintainability	Analysability
	Changeability
	Stability
	Testability
	Maintainability compliance

'Analysability' is the ease with which the cause of a failure can be determined. 'Changeability' is the quality that others call 'flexibility': the latter name is a better one as 'changeability' has a different connotation in plain English – it might imply that the suppliers of the software are always changing it!

'Stability', on the other hand, does not refer to software never changing: it means that there is a low risk of a modification to the software having unexpected effects.

Characteristic	Sub-characteristics
Portability	Adaptability
	Installability
	Coexistence
	Replaceability
	Portability compliance

'Portability compliance' relates to those standards that have a bearing on portability. The use of a standard programming language common to many software/hardware environments would be an example of this. 'Replaceability' refers to the factors that give 'upwards compatibility' between old software components and the new ones. 'Downwards' compatibility is not implied by the definition.

A new version of a word processing package might read the documents produced by previous versions and thus be able to replace them, but previous versions might not be able to read all documents created by the new version.

'Coexistence' refers to the ability of the software to share resources with other software components; unlike 'interoperability', no direct data passing is necessarily involved.

ISO 9126 provides guidelines for the use of the quality characteristics. Variation in the importance of different quality characteristics depending on the type of product is stressed. Once the requirements for the software product have been established, the following steps are suggested:

1. *Judge the importance of each quality characteristic for the application* Thus reliability will be of particular concern with safety-critical systems while efficiency will be important for some real-time systems.
2. *Select the external quality measurements within the ISO 9126 framework relevant to the qualities prioritized above* Thus for reliability mean time between failures would be an important measurement, while for efficiency, and more specifically 'time behaviour', response time would be an obvious measurement.
3. *Map measurements onto ratings that reflect user satisfaction* For response time, for example, the mappings might be as in Table 13.1.
4. *Identify the relevant internal measurements and the intermediate products in which they appear* This would only be important where software was being developed, rather than existing software being evaluated. For new software, the likely quality of the final product would need to be assessed during development. For example, where the external quality in question was time behaviour, at the software design stage an estimated execution time for a transaction could be produced by examining the software code and calculating the time for each instruction in a typical execution of the transaction. In our view the mappings between internal and external quality characteristics and measurements suggested in

the ISO 9126 standard are the least convincing elements in the approach. The part of the standard that provides guidance at this point is a 'technical report' which is less authoritative than a full standard. It concedes that mapping external and internal measurements can be difficult and that validation to check that there is a meaningful correlation between the two in a specific environment needs to be done. This reflects a real problem in the practical world of software development of examining code structure and from that attempting to predict accurately external qualities such as reliability.

TABLE 13.1 Mapping measurements to user satisfaction

Response time (seconds)	Rating
<2	Exceeds expectation
2–5	Within the target range
6–10	Minimally acceptable
>10	Unacceptable

According to ISO 9126, measurements that might act as indicators of the final quality of the software can be taken at different stages of the development life cycle. For products at the early stages these indicators might be qualitative. They could, for example, be based on checklists where compliance with predefined criteria is assessed by expert judgement. As the product nears completion, objective, quantitative, measurements would increasingly be taken.

5. *Overall assessment of product quality* To what extent is it possible to combine ratings for different quality characteristics into a single overall rating for the software? A factor which discourages attempts at combining the assessments of different quality characteristics is that they can, in practice, be measured in very different ways, which makes comparison and combination difficult. Sometimes the presence of one quality could be to the detriment of another. For example, the efficiency characteristics of time behaviour and resource utilization could be enhanced by exploiting the particular characteristics of the operating system and hardware environments within which the software will perform. This, however, would probably be at the expense of portability.

   It was noted above that quality assessment could be carried out for a number of different reasons: to assist software development, acquisition or independent assessment.

   During the development of a software product, the assessment would be driven by the need to focus the minds of the developers on key quality requirements. The aim would be to identify possible weaknesses early on and there would be no need for an overall quality rating.

TABLE 13.2 Mapping response times onto user satisfaction

Response time (seconds)	Quality score
<2	5
2–3	4

(*Contd*)

(*Contd*)

4–5	3
6–7	2
8–9	1
>9	0

The problem here is to map an objective measurement onto an indicator of customer satisfaction which is subjective.

Where potential users are assessing a number of different software products in order to choose the best one, the outcome will be along the lines that product A is more satisfactory than product B or C. Here some idea of relative satisfaction exists and there is a justification in trying to model how this satisfaction might be formed. One approach recognizes some *mandatory* quality rating levels which a product must reach or be rejected, regardless of how good it is otherwise. Other characteristics might be *desirable* but not essential. For these a user satisfaction rating could be allocated in the range, say, 0–5. This could be based on having an objective measurement of some function and then relating different measurement values to different levels of user satisfaction – see Table 13.2.

Along with the rating for satisfaction, a rating in the range 1–5, say, could be assigned to reflect how important each quality characteristic was. The scores for each quality could be given due weight by multiplying it by its importance weighting. These weighted scores can then be summed to obtain an overall score for the product. The scores for various products are then put in the order of preference. For example, two products might be compared as to usability, efficiency and maintainability. The importance of each of these qualities might be rated as 3, 4 and 2, respectively, out of a possible maximum of 5. Quality tests might result in the situation shown in Table 13.3.

TABLE 13.3 Weighted quality scores

Product quality	Importance rating (a)	Product A		Product B	
		Quality score (b)	Weighted score (a × b)	Quality score (c)	Weighted score (a × c)
Usability	3	1	3	3	9
Efficiency	4	2	8	2	8
Maintainability	2	3	6	1	2
Overall			17		19

Finally, a quality assessment can be made on behalf of a user community as a whole. For example, a professional body might assess software tools that support the working practices of its members. Unlike the selection by an individual user/purchaser, this is an attempt to produce an objective assessment of the software independently of a particular user environment. It is clear that the result of such an exercise would vary considerably depending on the weightings given to each software characteristic, and different users could have different requirements. Caution would be needed here.

13.6 Product and Process Metrics

We have already discussed in Section 13.4 that the users assess the quality of a software product based on its external attributes, whereas during development, the developers assess the product's quality based on various internal attributes. We can also say that during development, the developers can ensure the quality of a software product based on a measurement of the relevant internal attributes. The internal attributes may measure either some aspects of the product (called product or of the development process (called process metrics). Let us understand the basic differences between product and process metrics.

- Product metrics help measure the characteristics of a product being developed. A few examples of product metrics and the specific product characteristics that they measure are the following: the LOC and function point metrics are used to measure size, the PM (person-month) metric is used to measure the effort required to develop a product, and the time required to develop the product is measured in months.
- Process metrics help measure how a development process is performing. Examples of process metrics are review effectiveness, average number of defects found per hour of inspection, average defect correction time, productivity, average number of failures detected during testing per LOC, and the number of latent defects per line of code in the developed product.

13.7 Product versus Process Quality Management

The measurements described above relate to *products*. With a product-based approach to planning and control, as advocated by the PRINCE2 project management method, this focus on products is convenient. However, we saw that it is often easier to measure these product qualities in a completed computer application rather than during its development. Trying to use the attributes of intermediate products created at earlier stages to predict the quality of the final application is difficult. An alternative approach is to scrutinize the quality of the *processes* used to develop software product.

Note that Extreme Programming advocates suggest that the extra effort needed to amend software at later stages can be exaggerated and is, in any case, often justified as adding value to the software.

The system development process comprises a number of activities linked so that the output from one activity is the input to the next (Figure 13.2). Errors can enter the process at any stage. They can be caused either by defects in a process, as when software developers make mistakes in the logic of their software, or by information not passing clearly and accurately between development stages.

Errors not removed at early stages become more expensive to correct at later stages. Each development step that passes before the error is found increases the amount of rework needed. An error in the specification found in testing will mean rework at all the stages between specification and testing. Each successive step of development is also more detailed and less able to absorb change.

Errors should therefore be eradicated by careful examination of the deliverables of each step before they are passed on. One way of doing this is by having the following *process requirements* for each step.

- *Entry requirements*, which have to be in place before an activity can start. An example would be that a comprehensive set of test data and expected results be prepared and approved before program testing can commence.
- *Implementation requirements*, which define how the process is to be conducted. In the testing phase, for example, it could be laid down that whenever an error is found and corrected, all test runs must be repeated, even those that have previously been found to run correctly.

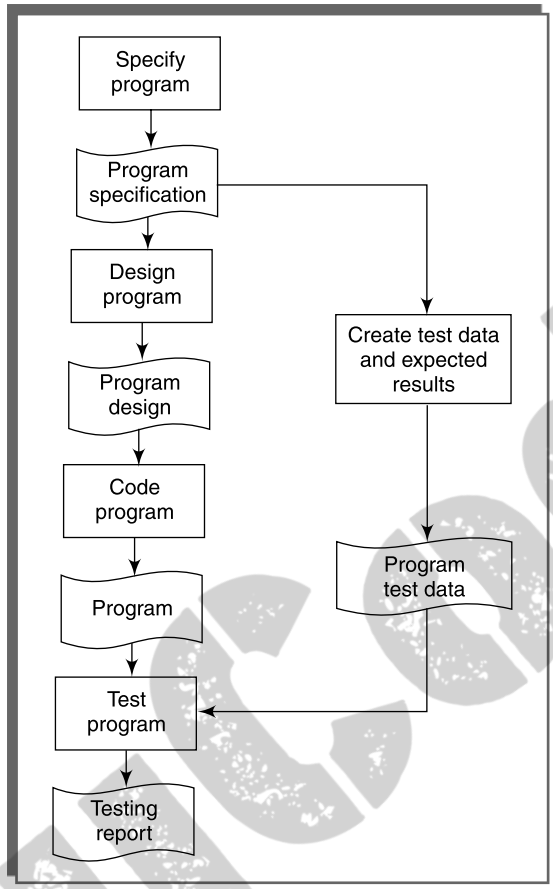


FIGURE 13.2 An example of the sequence of processes and deliverables

- *Exit requirements*, which have to be fulfilled before an activity is deemed to have been completed. For example, for the testing phase to be recognized as being completed, all tests will have to have been run successfully with no outstanding errors.

These requirements may be laid out in installation standards, or a *Software Quality Plan* may be drawn up for the specific project if it is a major one.

EXERCISE 13.4

In what cases might the entry conditions for one activity be different from the exit conditions for another activity that immediately precedes it?

EXERCISE 13.5

What might be the entry and exit requirements for the process *code program* shown in Figure 13.2?

26.1 Observations on Estimation

Planning requires you to make an initial commitment, even though it's likely that this "commitment" will be proven wrong. Whenever estimates are made, you look into the future and accept some degree of uncertainty as a matter of course. To quote Frederick Brooks [Bro95]:

> . . . our techniques of estimating are poorly developed. More seriously, they reflect an unvoiced assumption that is quite untrue, i.e., that all will go well. . . . because we are uncertain of our estimates, software managers often lack the courteous stubbornness to make people wait for a good product.

Although estimating is as much art as it is science, this important action need not be conducted in a haphazard manner. Useful techniques for time and effort estimation do exist. Process and project metrics can provide historical perspective and powerful input for the generation of quantitative estimates. Past experience (of all people involved) can aid immeasurably as estimates are developed and reviewed. Because estimation lays a foundation for all other project planning actions, and project planning provides the road map for successful software engineering, we would be ill advised to embark without it.

Estimation of resources, cost, and schedule for a software engineering effort requires experience, access to good historical information (metrics), and the courage to commit to quantitative predictions when qualitative information is all that exists. Estimation carries inherent risk,[1] and this risk leads to uncertainty.

Project complexity has a strong effect on the uncertainty inherent in planning. Complexity, however, is a relative measure that is affected by familiarity with past effort. The first-time developer of a sophisticated e-commerce application might consider it to be exceedingly complex. However, a Web engineering team developing its tenth e-commerce WebApp would consider such work run-of-the-mill. A number of quantitative software complexity measures have been proposed [Zus97]. Such measures are applied at the design or code level and are therefore difficult to use during

software planning (before a design and code exist). However, other, more subjective assessments of complexity (e.g., function point complexity adjustment factors described in Chapter 23) can be established early in the planning process.

Project size is another important factor that can affect the accuracy and efficacy of estimates. As size increases, the interdependency among various elements of the software grows rapidly.[2] Problem decomposition, an important approach to estimating, becomes more difficult because the refinement of problem elements may still be formidable. To paraphrase Murphy's law: "What can go wrong will go wrong"—and if there are more things that can fail, more things will fail.

The *degree of structural uncertainty* also has an effect on estimation risk. In this context, structure refers to the degree to which requirements have been solidified, the ease with which functions can be compartmentalized, and the hierarchical nature of the information that must be processed.

The availability of historical information has a strong influence on estimation risk. By looking back, you can emulate things that worked and improve areas where problems arose. When comprehensive software metrics (Chapter 25) are available for past projects, estimates can be made with greater assurance, schedules can be established to avoid past difficulties, and overall risk is reduced.

Estimation risk is measured by the degree of uncertainty in the quantitative estimates established for resources, cost, and schedule. If project scope is poorly understood or project requirements are subject to change, uncertainty and estimation risk become dangerously high. As a planner, you and the customer should recognize that variability in software requirements means instability in cost and schedule.

However, you should not become obsessive about estimation. Modern software engineering approaches (e.g., evolutionary process models) take an iterative view of development. In such approaches, it is possible—although not always politically acceptable—to revisit the estimate (as more information is known) and revise it when the customer makes changes to requirements.

26.2 The Project Planning Process

The objective of software project planning is to provide a framework that enables the manager to make reasonable estimates of resources, cost, and schedule. In addition, estimates should attempt to define best-case and worst-case scenarios so that project outcomes can be bounded. Although there is an inherent degree of uncertainty, the software team embarks on a plan that has been established as a consequence of these tasks. Therefore, the plan must be adapted and updated as the project proceeds. In the following sections, each of the actions associated with software project planning is discussed.

TASK SET

Task Set for Project Planning

1. Establish project scope.
2. Determine feasibility.
3. Analyze risks (Chapter 28).
4. Define required resources.
   a. Determine required human resources.
   b. Define reusable software resources.
   c. Identify environmental resources.
5. Estimate cost and effort.
   a. Decompose the problem.
   b. Develop two or more estimates using size, function points, process tasks, or use cases.
   c. Reconcile the estimates.
6. Develop a project schedule (Chapter 27).
   a. Establish a meaningful task set.
   b. Define a task network.
   c. Use scheduling tools to develop a time-line chart.
   d. Define schedule tracking mechanisms.

26.3 SOFTWARE SCOPE AND FEASIBILITY

Software scope describes the functions and features that are to be delivered to end users; the data that are input and output; the "content" that is presented to users as a consequence of using the software; and the performance, constraints, interfaces, and reliability that *bound* the system. Scope is defined using one of two techniques:

1. A narrative description of software scope is developed after communication with all stakeholders.
2. A set of use cases[3] is developed by end users.

Functions described in the statement of scope (or within the use cases) are evaluated and in some cases refined to provide more detail prior to the beginning of estimation. Because both cost and schedule estimates are functionally oriented, some degree of decomposition is often useful. Performance considerations encompass processing and response time requirements. Constraints identify limits placed on the software by external hardware, available memory, or other existing systems.

Once scope has been identified (with the concurrence of the customer), it is reasonable to ask: "Can we build software to meet this scope? Is the project feasible?" All too often, software engineers rush past these questions (or are pushed past them by impatient managers or other stakeholders), only to become mired in a project that is doomed from the onset. Putnam and Myers [Put97a] address this issue when they write:

> [N]ot everything imaginable is feasible, not even in software, evanescent as it may appear to outsiders. On the contrary, software feasibility has four solid dimensions: *Technology*—Is a project technically feasible? Is it within the state of the art? Can defects be reduced to a level matching the application's needs? *Finance*—Is it financially feasible? Can development be completed at a cost the software organization, its client, or the market can

afford? *Time*—Will the project's time-to-market beat the competition? *Resources*—Does the organization have the resources needed to succeed?

Putnam and Myers correctly suggest that scoping is not enough. Once scope is understood, you must work to determine if it can be done within the dimensions just noted. This is a crucial, although often overlooked, part of the estimation process.

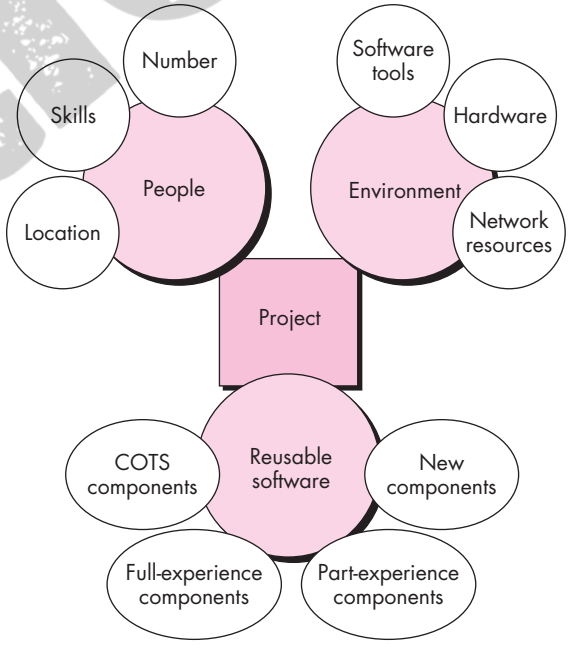
26.4 Resources

The second planning task is estimation of the resources required to accomplish the software development effort. Figure 26.1 depicts the three major categories of software engineering resources—people, reusable software components, and the development environment (hardware and software tools). Each resource is specified with four characteristics: description of the resource, a statement of availability, time when the resource will be required, and duration of time that the resource will be applied. The last two characteristics can be viewed as a *time window*. Availability of the resource for a specified window must be established at the earliest practical time.

26.4.1 Human Resources

The planner begins by evaluating software scope and selecting the skills required to complete development. Both organizational position (e.g., manager, senior software engineer) and specialty (e.g., telecommunications, database, client-server) are

Figure 26.1
Project resources



specified. For relatively small projects (a few person-months), a single individual may perform all software engineering tasks, consulting with specialists as required. For larger projects, the software team may be geographically dispersed across a number of different locations. Hence, the location of each human resource is specified.

The number of people required for a software project can be determined only after an estimate of development effort (e.g., person-months) is made. Techniques for estimating effort are discussed later in this chapter.

26.4.2 Reusable Software Resources

Component-based software engineering (CBSE)[4] emphasizes reusability—that is, the creation and reuse of software building blocks. Such building blocks, often called *components,* must be cataloged for easy reference, standardized for easy application, and validated for easy integration. Bennatan [Ben00] suggests four software resource categories that should be considered as planning proceeds:

Off-the-shelf components. Existing software that can be acquired from a third party or from a past project. COTS (commercial off-the-shelf) components are purchased from a third party, are ready for use on the current project, and have been fully validated.

Full-experience components. Existing specifications, designs, code, or test data developed for past projects that are similar to the software to be built for the current project. Members of the current software team have had full experience in the application area represented by these components. Therefore, modifications required for full-experience components will be relatively low risk.

Partial-experience components. Existing specifications, designs, code, or test data developed for past projects that are related to the software to be built for the current project but will require substantial modification. Members of the current software team have only limited experience in the application area represented by these components. Therefore, modifications required for partial-experience components have a fair degree of risk.

New components. Software components must be built by the software team specifically for the needs of the current project.

Ironically, reusable software components are often neglected during planning, only to become a paramount concern later in the software process. It is better to specify software resource requirements early. In this way technical evaluation of the alternatives can be conducted and timely acquisition can occur.

26.4.3 Environmental Resources

The environment that supports a software project, often called the *software engineering environment* (SEE), incorporates hardware and software. Hardware provides

a platform that supports the tools (software) required to produce the work products that are an outcome of good software engineering practice.[5] Because most software organizations have multiple constituencies that require access to the SEE, you must prescribe the time window required for hardware and software and verify that these resources will be available.

When a computer-based system (incorporating specialized hardware and software) is to be engineered, the software team may require access to hardware elements being developed by other engineering teams. For example, software for a robotic device used within a manufacturing cell may require a specific robot (e.g., a robotic welder) as part of the validation test step; a software project for advanced page layout may need a high-speed digital printing system at some point during development. Each hardware element must be specified as part of planning.

26.5 Software Project Estimation

Software cost and effort estimation will never be an exact science. Too many variables—human, technical, environmental, political—can affect the ultimate cost of software and effort applied to develop it. However, software project estimation can be transformed from a black art to a series of systematic steps that provide estimates with acceptable risk. To achieve reliable cost and effort estimates, a number of options arise:

1. Delay estimation until late in the project (obviously, we can achieve 100 percent accurate estimates after the project is complete!).
2. Base estimates on similar projects that have already been completed.
3. Use relatively simple decomposition techniques to generate project cost and effort estimates.
4. Use one or more empirical models for software cost and effort estimation.

Unfortunately, the first option, however attractive, is not practical. Cost estimates must be provided up-front. However, you should recognize that the longer you wait, the more you know, and the more you know, the less likely you are to make serious errors in your estimates.

The second option can work reasonably well, if the current project is quite similar to past efforts and other project influences (e.g., the customer, business conditions, the software engineering environment, deadlines) are roughly equivalent. Unfortunately, past experience has not always been a good indicator of future results.

The remaining options are viable approaches to software project estimation. Ideally, the techniques noted for each option should be applied in tandem; each used as a cross-check for the other. Decomposition techniques take a divide-and-conquer

approach to software project estimation. By decomposing a project into major functions and related software engineering activities, cost and effort estimation can be performed in a stepwise fashion. Empirical estimation models can be used to complement decomposition techniques and offer a potentially valuable estimation approach in their own right. A model is based on experience (historical data) and takes the form

$$d = f(v_i)$$

where d is one of a number of estimated values (e.g., effort, cost, project duration) and v_i are selected independent parameters (e.g., estimated LOC or FP).

Automated estimation tools implement one or more decomposition techniques or empirical models and provide an attractive option for estimating. In such systems, the characteristics of the development organization (e.g., experience, environment) and the software to be developed are described. Cost and effort estimates are derived from these data.

Each of the viable software cost estimation options is only as good as the historical data used to seed the estimate. If no historical data exist, costing rests on a very shaky foundation. In Chapter 25, we examined the characteristics of some of the software metrics that provide the basis for historical estimation data.

26.6 Decomposition Techniques

Software project estimation is a form of problem solving, and in most cases, the problem to be solved (i.e., developing a cost and effort estimate for a software project) is too complex to be considered in one piece. For this reason, you should decompose the problem, recharacterizing it as a set of smaller (and hopefully, more manageable) problems.

In Chapter 24, the decomposition approach was discussed from two different points of view: decomposition of the problem and decomposition of the process. Estimation uses one or both forms of partitioning. But before an estimate can be made, you must understand the scope of the software to be built and generate an estimate of its "size."

26.6.1 Software Sizing

The accuracy of a software project estimate is predicated on a number of things: (1) the degree to which you have properly estimated the size of the product to be built; (2) the ability to translate the size estimate into human effort, calendar time, and dollars (a function of the availability of reliable software metrics from past projects); (3) the degree to which the project plan reflects the abilities of the software team; and (4) the stability of product requirements and the environment that supports the software engineering effort.

In this section, I consider the *software sizing* problem. Because a project estimate is only as good as the estimate of the size of the work to be accomplished, sizing

represents your first major challenge as a planner. In the context of project planning, size refers to a quantifiable outcome of the software project. If a direct approach is taken, size can be measured in lines of code (LOC). If an indirect approach is chosen, size is represented as function points (FP).

Putnam and Myers [Put92] suggest four different approaches to the sizing problem:

- *"Fuzzy logic" sizing.* This approach uses the approximate reasoning techniques that are the cornerstone of fuzzy logic. To apply this approach, the planner must identify the type of application, establish its magnitude on a qualitative scale, and then refine the magnitude within the original range.
- *Function point sizing.* The planner develops estimates of the information domain characteristics discussed in Chapter 23.
- *Standard component sizing.* Software is composed of a number of different "standard components" that are generic to a particular application area. For example, the standard components for an information system are subsystems, modules, screens, reports, interactive programs, batch programs, files, LOC, and object-level instructions. The project planner estimates the number of occurrences of each standard component and then uses historical project data to estimate the delivered size per standard component.
- *Change sizing.* This approach is used when a project encompasses the use of existing software that must be modified in some way as part of a project. The planner estimates the number and type (e.g., reuse, adding code, changing code, deleting code) of modifications that must be accomplished.

Putnam and Myers suggest that the results of each of these sizing approaches be combined statistically to create a *three-point* or *expected-value* estimate. This is accomplished by developing optimistic (low), most likely, and pessimistic (high) values for size and combining them using Equation (26.1), described in Section 26.6.2.

26.6.2 Problem-Based Estimation

In Chapter 25, lines of code and function points were described as measures from which productivity metrics can be computed. LOC and FP data are used in two ways during software project estimation: (1) as estimation variables to "size" each element of the software and (2) as baseline metrics collected from past projects and used in conjunction with estimation variables to develop cost and effort projections.

LOC and FP estimation are distinct estimation techniques. Yet both have a number of characteristics in common. You begin with a bounded statement of software scope and from this statement attempt to decompose the statement of scope into problem functions that can each be estimated individually. LOC or FP (the estimation variable) is then estimated for each function. Alternatively, you may choose another component for sizing, such as classes or objects, changes, or business processes affected.

Baseline productivity metrics (e.g., LOC/pm or FP/pm[6]) are then applied to the appropriate estimation variable, and cost or effort for the function is derived. Function estimates are combined to produce an overall estimate for the entire project.

It is important to note, however, that there is often substantial scatter in productivity metrics for an organization, making the use of a single-baseline productivity metric suspect. In general, LOC/pm or FP/pm averages should be computed by project domain. That is, projects should be grouped by team size, application area, complexity, and other relevant parameters. Local domain averages should then be computed. When a new project is estimated, it should first be allocated to a domain, and then the appropriate domain average for past productivity should be used in generating the estimate.

The LOC and FP estimation techniques differ in the level of detail required for decomposition and the target of the partitioning. When LOC is used as the estimation variable, decomposition is absolutely essential and is often taken to considerable levels of detail. The greater the degree of partitioning, the more likely reasonably accurate estimates of LOC can be developed.

For FP estimates, decomposition works differently. Rather than focusing on function, each of the information domain characteristics—inputs, outputs, data files, inquiries, and external interfaces—as well as the 14 complexity adjustment values discussed in Chapter 23 are estimated. The resultant estimates can then be used to derive an FP value that can be tied to past data and used to generate an estimate.

Regardless of the estimation variable that is used, you should begin by estimating a range of values for each function or information domain value. Using historical data or (when all else fails) intuition, estimate an optimistic, most likely, and pessimistic size value for each function or count for each information domain value. An implicit indication of the degree of uncertainty is provided when a range of values is specified.

A three-point or expected value can then be computed. The *expected value* for the estimation variable (size) S can be computed as a weighted average of the optimistic (s_{opt}), most likely (s_m), and pessimistic (s_{pess}) estimates. For example,

$$S = \frac{s_{opt} + 4s_m + s_{pess}}{6} \tag{26.1}$$

gives heaviest credence to the "most likely" estimate and follows a beta probability distribution. We assume that there is a very small probability the actual size result will fall outside the optimistic or pessimistic values.

Once the expected value for the estimation variable has been determined, historical LOC or FP productivity data are applied. Are the estimates correct? The only reasonable answer to this question is: "You can't be sure." Any estimation technique, no matter how sophisticated, must be cross-checked with another approach. Even then, common sense and experience must prevail.

26.6.3 An Example of LOC-Based Estimation

As an example of LOC and FP problem-based estimation techniques, I consider a software package to be developed for a computer-aided design application for mechanical components. The software is to execute on an engineering workstation and must interface with various computer graphics peripherals including a mouse, digitizer, high-resolution color display, and laser printer. A preliminary statement of software scope can be developed:

> The mechanical CAD software will accept two- and three-dimensional geometric data from an engineer. The engineer will interact and control the CAD system through a user interface that will exhibit characteristics of good human/machine interface design. All geometric data and other supporting information will be maintained in a CAD database. Design analysis modules will be developed to produce the required output, which will be displayed on a variety of graphics devices. The software will be designed to control and interact with peripheral devices that include a mouse, digitizer, laser printer, and plotter.

This statement of scope is preliminary—it is not bounded. Every sentence would have to be expanded to provide concrete detail and quantitative bounding. For example, before estimation can begin, the planner must determine what "characteristics of good human/machine interface design" means or what the size and sophistication of the "CAD database" are to be.

For our purposes, assume that further refinement has occurred and that the major software functions listed in Figure 26.2 are identified. Following the decomposition technique for LOC, an estimation table (Figure 26.2) is developed. A range of LOC estimates is developed for each function. For example, the range of LOC estimates for the 3D geometric analysis function is optimistic, 4600 LOC; most likely, 6900 LOC; and pessimistic, 8600 LOC. Applying Equation 26.1, the expected value for the 3D geometric analysis function is 6800 LOC. Other estimates are derived in a similar

FIGURE 26.2 Estimation table for the LOC methods

Function	Estimated LOC
User interface and control facilities (UICF)	2,300
Two-dimensional geometric analysis (2DGA)	5,300
Three-dimensional geometric analysis (3DGA)	6,800
Database management (DBM)	3,350
Computer graphics display facilities (CGDF)	4,950
Peripheral control function (PCF)	2,100
Design analysis modules (DAM)	8,400
Estimated lines of code	*33,200*

fashion. By summing vertically in the estimated LOC column, an estimate of 33,200 lines of code is established for the CAD system.

A review of historical data indicates that the organizational average productivity for systems of this type is 620 LOC/pm. Based on a burdened labor rate of $8000 per month, the cost per line of code is approximately $13. Based on the LOC estimate and the historical productivity data, the total estimated project cost is $431,000 and the estimated effort is 54 person-months.[7]

SAFEHOME

Estimating

The scene: Doug Miller's office as project planning begins.

The players: Doug Miller (manager of the *SafeHome* software engineering team) and Vinod Raman, Jamie Lazar, and other members of the product software engineering team.

The conversation:

Doug: We need to develop an effort estimate for the project and then we've got to define a micro schedule for the first increment and a macro schedule for the remaining increments.

Vinod (nodding): Okay, but we haven't defined any increments yet.

Doug: True, but that's why we need to estimate.

Jamie (frowning): You want to know how long it's going to take us?

Doug: Here's what I need. First, we need to functionally decompose the *SafeHome* software … at a high level … then we've got to estimate the number of lines of code that each function will take . . . then . . .

Jamie: Whoa! How are we supposed to do that?

Vinod: I've done it on past projects. You begin with use cases, determine the functionality required to implement each, guesstimate the LOC count for each piece of the function. The best approach is to have everyone do it independently and then compare results.

Doug: Or you can do a functional decomposition for the entire project.

Jamie: But that'll take forever and we've got to get started.

Vinod: No . . . it can be done in a few hours . . . this morning, in fact.

Doug: I agree . . . we can't expect exactitude, just a ballpark idea of what the size of *SafeHome* will be.

Jamie: I think we should just estimate effort . . . that's all.

Doug: We'll do that too. Then use both estimates as a cross-check.

Vinod: Let's go do it . . .

26.6.4 An Example of FP-Based Estimation

Decomposition for FP-based estimation focuses on information domain values rather than software functions. Referring to the table presented in Figure 26.3, you would estimate inputs, outputs, inquiries, files, and external interfaces for the CAD software. An FP value is computed using the technique discussed in Chapter 23. For the purposes of this estimate, the complexity weighting factor is assumed to be average. Figure 26.3 presents the results of this estimate.

FIGURE 26.3
Estimating information domain values

Information domain value	Opt.	Likely	Pess.	Est. count	Weight	FP count
Number of external inputs	20	24	30	24	4	97
Number of external outputs	12	15	22	16	5	78
Number of external inquiries	16	22	28	22	5	88
Number of internal logical files	4	4	5	4	10	42
Number of external interface files	2	2	3	2	7	15
Count total						*320*

Each of the complexity weighting factors is estimated, and the value adjustment factor is computed as described in Chapter 23:

Factor	Value
Backup and recovery	4
Data communications	2
Distributed processing	0
Performance critical	4
Existing operating environment	3
Online data entry	4
Input transaction over multiple screens	5
Master files updated online	3
Information domain values complex	5
Internal processing complex	5
Code designed for reuse	4
Conversion/installation in design	3
Multiple installations	5
Application designed for change	5
Value adjustment factor	**1.17**

Finally, the estimated number of FP is derived:

$$FP_{estimated} = \text{count total} \times [0.65 + 0.01 \times \Sigma(F_i)] = 375$$

The organizational average productivity for systems of this type is 6.5 FP/pm. Based on a burdened labor rate of $8000 per month, the cost per FP is approximately $1230. Based on the FP estimate and the historical productivity data, the total estimated project cost is $461,000 and the estimated effort is 58 person-months.

26.6.5 Process-Based Estimation

The most common technique for estimating a project is to base the estimate on the process that will be used. That is, the process is decomposed into a relatively small set of tasks and the effort required to accomplish each task is estimated.

FIGURE 26.4
Process-based estimation table

Activity →	CC	Planning	Risk analysis	Engineering		Construction release		CE	Totals
Task →				Analysis	Design	Code	Test		
Function									
↓									
UICF				0.50	2.50	0.40	5.00	n/a	8.40
2DGA				0.75	4.00	0.60	2.00	n/a	7.35
3DGA				0.50	4.00	1.00	3.00	n/a	8.50
CGDF				0.50	3.00	1.00	1.50	n/a	6.00
DBM				0.50	3.00	0.75	1.50	n/a	5.75
PCF				0.25	2.00	0.50	1.50	n/a	4.25
DAM				0.50	2.00	0.50	2.00	n/a	5.00
Totals	0.25	0.25	0.25	3.50	20.50	4.50	16.50		46.00
% effort	1%	1%	1%	8%	45%	10%	36%		

CC = customer communication CE = customer evaluation

Like the problem-based techniques, process-based estimation begins with a delineation of software functions obtained from the project scope. A series of framework activities must be performed for each function. Functions and related framework activities[8] may be represented as part of a table similar to the one presented in Figure 26.4.

Once problem functions and process activities are melded, you estimate the effort (e.g., person-months) that will be required to accomplish each software process activity for each software function. These data constitute the central matrix of the table in Figure 26.4. Average labor rates (i.e., cost/unit effort) are then applied to the effort estimated for each process activity. It is very likely the labor rate will vary for each task. Senior staff are heavily involved in early framework activities and are generally more expensive than junior staff involved in construction and release.

Costs and effort for each function and framework activity are computed as the last step. If process-based estimation is performed independently of LOC or FP estimation, we now have two or three estimates for cost and effort that may be compared and reconciled. If both sets of estimates show reasonable agreement, there is good reason to believe that the estimates are reliable. If, on the other hand, the results of these decomposition techniques show little agreement, further investigation and analysis must be conducted.

26.6.6 An Example of Process-Based Estimation

To illustrate the use of process-based estimation, consider the CAD software introduced in Section 26.6.3. The system configuration and all software functions remain unchanged and are indicated by project scope.

Referring to the completed process-based table shown in Figure 26.4, estimates of effort (in person-months) for each software engineering activity are provided for each CAD software function (abbreviated for brevity). The engineering and construction release activities are subdivided into the major software engineering tasks shown. Gross estimates of effort are provided for customer communication, planning, and risk analysis. These are noted in the total row at the bottom of the table. Horizontal and vertical totals provide an indication of estimated effort required for analysis, design, code, and test. It should be noted that 53 percent of all effort is expended on front-end engineering tasks (requirements analysis and design), indicating the relative importance of this work.

Based on an average burdened labor rate of $8000 per month, the total estimated project cost is $368,000 and the estimated effort is 46 person-months. If desired, labor rates could be associated with each framework activity or software engineering task and computed separately.

26.6.7 Estimation with Use Cases

As I have noted throughout Part 2 of this book, use cases provide a software team with insight into software scope and requirements. However, developing an estimation approach with use cases is problematic for the following reasons [Smi99]:

- Use cases are described using many different formats and styles—there is no standard form.
- Use cases represent an external view (the user's view) of the software and can therefore be written at many different levels of abstraction.
- Use cases do not address the complexity of the functions and features that are described.
- Use cases can describe complex behavior (e.g., interactions) that involve many functions and features.

Unlike an LOC or a function point, one person's "use case" may require months of effort while another person's use case may be implemented in a day or two.

Although a number of investigators have considered use cases as an estimation input, no proven estimation method has emerged to date.[9] Smith [Smi99] suggests that use cases can be used for estimation, but only if they are considered within the context of the "structural hierarchy" that they are used to describe.

Smith argues that any level of this structural hierarchy can be described by no more than 10 use cases. Each of these use cases would encompass no more than 30 distinct scenarios. Obviously, use cases that describe a large system are written at a much higher level of abstraction (and represent considerably more development effort) than use cases that are written to describe a single subsystem. Therefore,

before use cases can be used for estimation, the level within the structural hierarchy is established, the average length (in pages) of each use case is determined, the type of software (e.g., real-time, business, engineering/scientific, WebApp, embedded) is defined, and a rough architecture for the system is considered. Once these characteristics are established, empirical data may be used to establish the estimated number of LOC or FP per use case (for each level of the hierarchy). Historical data are then used to compute the effort required to develop the system.

To illustrate how this computation might be made, consider the following relationship:[10]

$$\text{LOC estimate} = N \times \text{LOC}_{\text{avg}} + [(S_a/S_h - 1) + (P_a/P_h - 1)] \times \text{LOC}_{\text{adjust}} \qquad (26.2)$$

where

N = actual number of use cases
LOC_{avg} = historical average LOC per use case for this type of subsystem
$\text{LOC}_{\text{adjust}}$ = represents an adjustment based on n percent of LOC_{avg} where n is defined locally and represents the difference between this project and "average" projects
S_a = actual scenarios per use case
S_h = average scenarios per use case for this type of subsystem
P_a = actual pages per use case
P_h = average pages per use case for this type of subsystem

Expression (26.2) could be used to develop a rough estimate of the number of LOC based on the actual number of use cases adjusted by the number of scenarios and the page length of the use cases. The adjustment represents up to n percent of the historical average LOC per use case.

26.6.8 An Example of Use-Case–Based Estimation

The CAD software introduced in Section 26.6.3 is composed of three subsystem groups: user interface subsystem (includes UICF), engineering subsystem group (includes the 2DGA, 3DGA, and DAM subsystems), and infrastructure subsystem group (includes CGDF and PCF subsystems). Six use cases describe the user interface subsystem. Each use case is described by no more than 10 scenarios and has an average length of six pages. The engineering subsystem group is described by 10 use cases (these are considered to be at a higher level of the structural hierarchy). Each of these use cases has no more than 20 scenarios associated with it and has an average length of eight pages. Finally, the infrastructure subsystem group is described by five use cases with an average of only six scenarios and an average length of five pages.

FIGURE 26.5
Use-case estimation

	use cases	scenarios	pages	scenarios	pages	LOC	LOC estimate
User interface subsystem	6	10	6	12	5	560	3,366
Engineering subsystem group	10	20	8	16	8	3100	31,233
Infrastructure subsystem group	5	6	5	10	6	1650	7,970
Total LOC estimate							42,568

Using the relationship noted in Expression (26.2) with $n = 30$ percent, the table shown in Figure 26.5 is developed. Considering the first row of the table, historical data indicate that UI software requires an average of 800 LOC per use case when the use case has no more than 12 scenarios and is described in less than five pages. These data conform reasonably well for the CAD system. Hence the LOC estimate for the user interface subsystem is computed using expression (26.2). Using the same approach, estimates are made for both the engineering and infrastructure subsystem groups. Figure 26.5 summarizes the estimates and indicates that the overall size of the CAD is estimated at 42,500 LOC.

Using 620 LOC/pm as the average productivity for systems of this type and a burdened labor rate of $8000 per month, the cost per line of code is approximately $13. Based on the use-case estimate and the historical productivity data, the total estimated project cost is $552,000 and the estimated effort is 68 person-months.

26.6.9 Reconciling Estimates

The estimation techniques discussed in the preceding sections result in multiple estimates that must be reconciled to produce a single estimate of effort, project duration, or cost. To illustrate this reconciliation procedure, I again consider the CAD software introduced in Section 26.6.3.

The total estimated effort for the CAD software ranges from a low of 46 person-months (derived using a process-based estimation approach) to a high of 68 person-months (derived with use-case estimation). The average estimate (using all four approaches) is 56 person-months. The variation from the average estimate is approximately 18 percent on the low side and 21 percent on the high side.

What happens when agreement between estimates is poor? The answer to this question requires a reevaluation of information used to make the estimates. Widely divergent estimates can often be traced to one of two causes: (1) the scope of the project is not adequately understood or has been misinterpreted by the planner, or (2) productivity data used for problem-based estimation techniques is inappropriate for the application, obsolete (in that it no longer accurately reflects the software engineering organization), or has been misapplied. You should determine the cause of divergence and then reconcile the estimates.

INFO

Automated Estimation Techniques for Software Projects

Automated estimation tools allow the planner to estimate cost and effort and to perform what-if analyses for important project variables such as delivery date or staffing. Although many automated estimation tools exist (see sidebar later in this chapter), all exhibit the same general characteristics and all perform the following six generic functions [Jon96]:

1. *Sizing of project deliverables.* The "size" of one or more software work products is estimated. Work products include the external representation of software (e.g., screen, reports), the software itself (e.g., KLOC), functionality delivered (e.g., function points), and descriptive information (e.g., documents).
2. *Selecting project activities.* The appropriate process framework is selected, and the software engineering task set is specified.
3. *Predicting staffing levels.* The number of people who will be available to do the work is specified. Because the relationship between people available and work (predicted effort) is highly nonlinear, this is an important input.
4. *Predicting software effort.* Estimation tools use one or more models (Section 26.7) that relate the size of the project deliverables to the effort required to produce them.
5. *Predicting software cost.* Given the results of step 4, costs can be computed by allocating labor rates to the project activities noted in step 2.
6. *Predicting software schedules.* When effort, staffing level, and project activities are known, a draft schedule can be produced by allocating labor across software engineering activities based on recommended models for effort distribution discussed later in this chapter.

When different estimation tools are applied to the same project data, a relatively large variation in estimated results can be encountered. More important, predicted values sometimes are significantly different than actual values. This reinforces the notion that the output of estimation tools should be used as one "data point" from which estimates are derived—not as the only source for an estimate.

26.7 Empirical Estimation Models

An estimation model for computer software uses empirically derived formulas to predict effort as a function of LOC or FP.[11] Values for LOC or FP are estimated using the approach described in Sections 26.6.3 and 26.6.4. But instead of using the tables described in those sections, the resultant values for LOC or FP are plugged into the estimation model.

The empirical data that support most estimation models are derived from a limited sample of projects. For this reason, no estimation model is appropriate for all classes of software and in all development environments. Therefore, you should use the results obtained from such models judiciously.

An estimation model should be calibrated to reflect local conditions. The model should be tested by applying data collected from completed projects, plugging the data into the model, and then comparing actual to predicted results. If agreement is poor, the model must be tuned and retested before it can be used.

26.7.1 The Structure of Estimation Models

A typical estimation model is derived using regression analysis on data collected from past software projects. The overall structure of such models takes the form [Mat94]

$$E = A + B \times (e_v)^C \tag{26.3}$$

where *A, B,* and *C* are empirically derived constants, *E* is effort in person-months, and e_v is the estimation variable (either LOC or FP). In addition to the relationship noted in Equation (26.3), the majority of estimation models have some form of project adjustment component that enables *E* to be adjusted by other project characteristics (e.g., problem complexity, staff experience, development environment). Among the many LOC-oriented estimation models proposed in the literature are

$E = 5.2 \times (\text{KLOC})^{0.91}$	Walston-Felix model
$E = 5.5 + 0.73 \times (\text{KLOC})^{1.16}$	Bailey-Basili model
$E = 3.2 \times (\text{KLOC})^{1.05}$	Boehm simple model
$E = 5.288 \times (\text{KLOC})^{1.047}$	Doty model for KLOC > 9

FP-oriented models have also been proposed. These include

$E = -91.4 + 0.355\ \text{FP}$	Albrecht and Gaffney model
$E = -37 + 0.96\ \text{FP}$	Kemerer model
$E = -12.88 + 0.405\ \text{FP}$	Small project regression model

A quick examination of these models indicates that each will yield a different result for the same values of LOC or FP. The implication is clear. Estimation models must be calibrated for local needs!

26.7.2 The COCOMO II Model

In his classic book on "software engineering economics," Barry Boehm [Boe81] introduced a hierarchy of software estimation models bearing the name COCOMO, for *COnstructive COst MOdel.* The original COCOMO model became one of the most widely used and discussed software cost estimation models in the industry. It has evolved into a more comprehensive estimation model, called COCOMO II [Boe00]. Like its predecessor, COCOMO II is actually a hierarchy of estimation models that address the following areas:

- *Application composition model.* Used during the early stages of software engineering, when prototyping of user interfaces, consideration of software and system interaction, assessment of performance, and evaluation of technology maturity are paramount.
- *Early design stage model.* Used once requirements have been stabilized and basic software architecture has been established.
- *Post-architecture-stage model.* Used during the construction of the software.

Like all estimation models for software, the COCOMO II models require sizing information. Three different sizing options are available as part of the model hierarchy: object points, function points, and lines of source code.

FIGURE 26.6
Complexity weighting for object types.
Source: [Boe96].

Object type	Complexity weight		
	Simple	Medium	Difficult
Screen	1	2	3
Report	2	5	8
3GL component			10

The COCOMO II application composition model uses object points and is illustrated in the following paragraphs. It should be noted that other, more sophisticated estimation models (using FP and KLOC) are also available as part of COCOMO II.

Like function points, the *object point* is an indirect software measure that is computed using counts of the number of (1) screens (at the user interface), (2) reports, and (3) components likely to be required to build the application. Each object instance (e.g., a screen or report) is classified into one of three complexity levels (i.e., simple, medium, or difficult) using criteria suggested by Boehm [Boe96]. In essence, complexity is a function of the number and source of the client and server data tables that are required to generate the screen or report and the number of views or sections presented as part of the screen or report.

Once complexity is determined, the number of screens, reports, and components are weighted according to the table illustrated in Figure 26.6. The object point count is then determined by multiplying the original number of object instances by the weighting factor in the figure and summing to obtain a total object point count. When component-based development or general software reuse is to be applied, the percent of reuse (%reuse) is estimated and the object point count is adjusted:

$$\text{NOP} = (\text{object points}) \times [(100 - \%\text{reuse})/100]$$

where NOP is defined as new object points.

To derive an estimate of effort based on the computed NOP value, a "productivity rate" must be derived. Figure 26.7 presents the productivity rate

$$\text{PROD} = \frac{\text{NOP}}{\text{person-month}}$$

for different levels of developer experience and development environment maturity.

Once the productivity rate has been determined, an estimate of project effort is computed using

$$\text{Estimated effort} = \frac{\text{NOP}}{\text{PROD}}$$

In more advanced COCOMO II models,[12] a variety of scale factors, cost drivers, and adjustment procedures are required. A complete discussion of these is beyond

FIGURE 26.7 **Productivity rate for object points.**
Source: [Boe96].

Developer's experience/capability	Very low	Low	Nominal	High	Very high
Environment maturity/capability	Very low	Low	Nominal	High	Very high
PROD	4	7	13	25	50

the scope of this book. If you have further interest, see [Boe00] or visit the COCOMO II website.

26.7.3 The Software Equation

The *software equation* [Put92] is a dynamic multivariable model that assumes a specific distribution of effort over the life of a software development project. The model has been derived from productivity data collected for over 4000 contemporary software projects. Based on these data, we derive an estimation model of the form

$$E = \frac{\text{LOC} \times B^{0.333}}{P^3} \times \frac{1}{t^4} \tag{26.4}$$

where

E = effort in person-months or person-years
t = project duration in months or years
B = "special skills factor"[13]
P = "productivity parameter" that reflects: overall process maturity and management practices, the extent to which good software engineering practices are used, the level of programming languages used, the state of the software environment, the skills and experience of the software team, and the complexity of the application

Typical values might be $P = 2000$ for development of real-time embedded software, $P = 10{,}000$ for telecommunication and systems software, and $P = 28{,}000$ for business systems applications. The productivity parameter can be derived for local conditions using historical data collected from past development efforts.

You should note that the software equation has two independent parameters: (1) an estimate of size (in LOC) and (2) an indication of project duration in calendar months or years.

To simplify the estimation process and use a more common form for their estimation model, Putnam and Myers [Put92] suggest a set of equations derived from the software equation. Minimum development time is defined as

$$t_{\min} = 8.14 \frac{\text{LOC}}{p^{0.43}} \text{ in months for } t_{\min} > 6 \text{ months} \tag{26.5a}$$

$$E = 180\, Bt^3 \text{ in person-months for } E \geq 20 \text{ person-months} \tag{26.5b}$$

Note that t in Equation (26.5b) is represented in years.

Using Equation (26.5) with $P = 12{,}000$ (the recommended value for scientific software) for the CAD software discussed earlier in this chapter,

$$t_{\min} = 8.14 \times \frac{33{,}200}{12{,}000^{0.43}} = 12.6 \text{ calendar months}$$

$$E = 180 \times 0.28 \times (1.05)^3 = 58 \text{ person-months}$$

The results of the software equation correspond favorably with the estimates developed in Section 26.6. Like the COCOMO model noted in Section 26.7.2, the software equation continues to evolve. Further discussion of an extended version of this estimation approach can be found in [Put97b].