4

ENGINEERING DESIGN METHODS AND TOOLS

Throughout the system engineering process described in Chapter 2, there is a series of design activities performed with the objective of ultimately providing a system that will fulfill a designated consumer need. The successful completion of these activities, amplified to some extent through the specific requirements covered in Chapter 3, is dependent on the proper application of selected design methods and practices. This, in turn, is strongly influenced by the technology and tools available to and used by the responsible design engineer(s).

For years, the basic design process involved a series of activities, accomplished on an individual-by-individual basis using step-by-step manual procedures. Ideas were generated, conceptually oriented layout or arrangement drawings were prepared and approved, system components were evaluated and selected from design standards documentation, detailed drawings and parts lists were developed and reviewed, mock-ups and models were constructed, and so on. In essence, the design process involved a long series of activities, usually requiring a great deal of time and often not very well coordinated.

With the advent of computer technology, the design process has changed significantly. Through the introduction of computer graphics in the late 1950s and early 1960s, user-input devices in the late 1960s and early 1970s (keyboards, light pens, joysticks), and the current development of sophisticated design workstations, system/product design now includes the application of many innovations. Computer technology is available to facilitate the generation of graphics material, the accomplishment of various types of analyses, and the fulfillment of data management activities. More recently, the development of information technology (IT), electronic data interchange (EDI), and electronic commerce (EC) techniques/methods has enabled the design process to be much more extensive, more efficient, and accomplished in less time and with reduced cost. It is not uncommon today to establish a central design database (using various computer-aided design (CAD)/computer-aided manufacturing (CAM) techniques) and to have individual designers from various parts of the world providing their respective inputs from remote locations and in a timely manner. In essence, the design process has changed significantly through the past several decades.

It is within this context (i.e., the current design environment) that the subject of system engineering must be addressed. The purpose of this chapter is to briefly highlight some of these relatively recent concepts in design and to discuss system engineering objectives as they relate to current design methods.

4.1 CONVENTIONAL DESIGN PRACTICES

For most projects dealing with small- and large-scale systems, the major steps in system development include conceptual design, preliminary design, and detail design, as illustrated in the flow process presented in Figure 1.12. This flow process should, of course, be tailored to the specific requirement. Although the basic steps are applicable in the development of all systems, the level of effort and the duration of the project will vary from one situation to the next.

Inherent within the fundamental steps identified in Figure 1.12 are many different activities, all related to the prime objective of designing a system to meet a consumer need. For relatively large projects, such as the commercial aircraft system and the ground mass-transit system referenced in Section 3.3, there may be a requirement for technical expertise representing many different disciplines; for example, electrical engineers, mechanical engineers, structural engineers, materials engineers, aerospace engineers, civil engineers, and reliability engineers. In support of the responsible design engineers in the various fields, there is a need for draftspersons, technical illustrators, component part specialists, laboratory technicians, computer programmers, test technicians, purchasing and contracts specialists, legal experts, and so on. There are many different and varied levels of specialization required for most projects, and each assigned specialty contributes to the design.

To review the steps in design further, Figure 4.1 is presented as an amplification of Figure 3.1. As design progresses, actual definition is accomplished through documentation in the form of plans and specifications (already discussed), procedures, drawings, materials and parts lists, reports and analyses, computerized databases, and so on. The design configuration may be the best possible in the eyes of the designer; however, the results are practically useless unless properly documented so that others can first understand what is being conveyed and then be able to translate the output into a producible entity.

In addressing the aspect of documentation, emphasized in Figure 4.1 to define the various levels of system development, the results of design have generally been conveyed through a combination of the following:

1. *Design drawings:* Assembly drawings, specification control drawings, construction drawings, installation drawings, logic diagrams, piping diagrams,

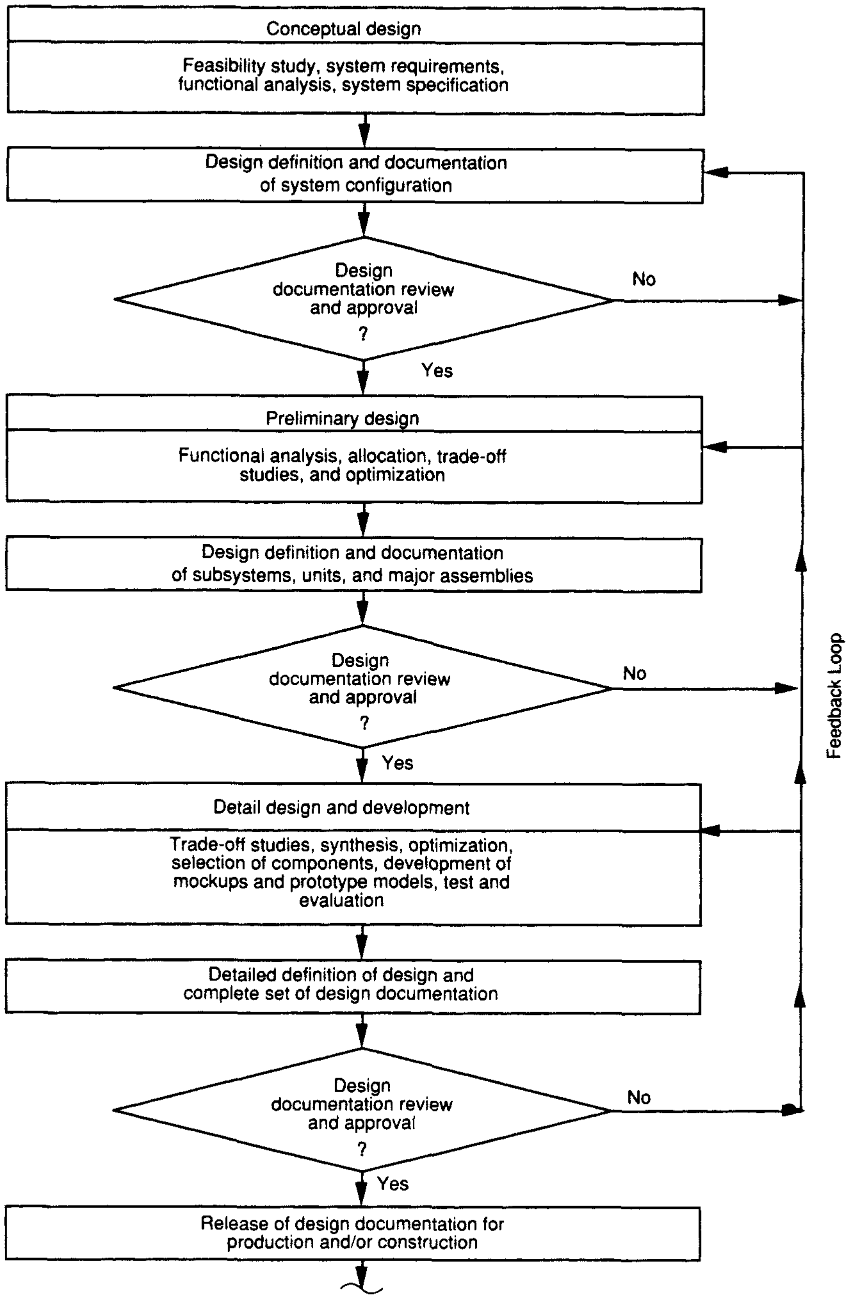

Figure 4.1 Basic design sequence.

schematic diagrams, interconnection diagrams, wiring and cable harness diagrams

2. *Materials and parts lists:* Parts lists, materials lists, long-lead-item lists, bulk-item lists, provisioning lists
3. *Analysis reports:* Trade-off study reports supporting design decisions, finite-element analysis reports, reliability and maintainability analyses and predictions, safety reports, logistic support analysis records, configuration identification reports, computer software documentation.

Based on the steps in design definition (shown in Figure 4.1), ideas are generated and converted to drawings, drawings are reviewed by various interested disciplines and/or organizations, recommended changes are initiated and incorporated as appropriate, and approved drawings (designated by drawing "sign-off") are released for production. For the most part, the steps in this informal day-to-day process have been completed in series and often require a great deal of time. For instance, an electrical engineer may start the process with a proposed layout of components on a circuit board, a mechanical engineer may then provide the necessary structural and cooling requirements, a reliability engineer may follow with a prediction and evaluation of the selected components, and so on. These responsible individuals may be located in different buildings, and the documentation processing and communications often become quite lengthy. Further, this procedure takes on an additional degree of complexity as the number of drawings and drawing change notices increases.

In essence, this day-to-day design activity, particularly for large-scale systems, may include the generation and processing of hundreds of drawings and drawing change notices (DCNs). Many different design disciplines may be represented, with engineering personnel located throughout the producer's organization and, in some instances, at various remote supplier facilities. The communications, both in terms of verbal discussions pertaining to design approaches and the handling of design documentation, are marginal, and the elapsed times are often extensive. In some cases, it may require a month, or more, to route a single drawing through the review steps for approval.

These somewhat conventional practices of the past have created some major challenges. In numerous instances, procedures have been bypassed, changes have been implemented without the proper approvals and necessary coordination, and appropriate configuration controls have not been practiced. In essence, the basic objectives of system engineering have not been followed.

4.2 ANALYTICAL METHODS

Inherent within the overall spectrum of system engineering is an ongoing analytical process in which the design engineer is engaged in some form of synthesis, analysis, evaluation, and design optimization activities (refer to Section 2.9, Chapter 2). When known solutions fail to hold sufficient promise for future application, more promising opportunities are sought. This leads to the identification of various possible future courses of action and the ultimate selection of a preferred approach. In other words, the design engineer(s) is often faced with many different decisions in progressing from the early identification of a conceptual approach to the development of a well-defined product output. The accomplishment of various types and levels of trade-off analyses is necessary in reaching the ultimate objective, and some familiarization with decision theory and available analytical techniques is required in reaching this goal.[1]

Although it is not intended herein to provide comprehensive coverage of the techniques (or models) utilized in system analysis, the following list presents a few areas in which some familiarization is highly recommended:

1. *Probability theory and analysis.* An inherent knowledge of statistics and probability theory is required as a prerequisite for understanding the concepts and principles of reliability and maintainability and for the application of selected program management methods. Recommended probability distribution models should include the uniform, binomial, Poisson, exponential, normal, lognormal, and Weibull distributions.

2. *Economic analysis.* A basic knowledge of economic concepts and principles, interest and interest formulas, and ability in determining economic equivalence for various design alternatives and in conducting break-even evaluations are required in the performance of life-cycle cost (LCC) and related analysis activities.

3. *Optimization methods.* A basic familiarity with classical optimization theory, constrained and unconstrained optimization, and linear and dynamic programming is required in determining optimum system equipment life, recommended components replacement policies (frequencies), equipment packing schemes, preferred transportation routes, and so on.

4. *Queuing theory and analysis.* A basic understanding of queuing theory (e.g., the arrival mechanism, the waiting line, the service mechanism, and their associated distributions), single-channel queuing models, multiple-channel queuing models, and the application of Monte Carlo analysis is required in the design of facilities and those functions involving the processing of various items through some "channel" activity. Establishing the appropriate number of repair channels in the design of a maintenance facility is a good example.

5. *Control concepts and techniques.* A basic familiarity with statistical process control (SPC) techniques, the application of various types of control charts (e.g., *x-bar, R, p,* and *c* charts), determining optimum policy control approaches, quality control methods, and the application of control networks for project/program scheduling is essential for the implementation of total quality management (TQM) and selected program management requirements.

[1]An understanding of some of the basic tools/methods utilized in operations research (or operations management) is essential for the successful implementation of system engineering objectives in this area. Three good references are (1) B. S. Blanchard and W. J. Fabrycky, *Systems Engineering and Analysis,* 3rd ed. (Upper Saddle River, NJ: Prentice-Hall, 1998), Part III; (2) F. S. Hillier, and G. J. Lieberman, *Introduction to Operations Research,* 6th ed. (New York: McGraw-Hill, 1995); and (3) H. A. Taha, *Operations Research: An Introduction,* 6th ed. (Upper Saddle River, NJ: Prentice-Hall, 1996).

Although a detailed knowledge of these and related *operations research* techniques is not expected, some familiarity with these models, and when and how they can be applied, is essential.

4.3 THE ROLE OF ELECTRONIC COMMERCE (EC), INFORMATION TECHNOLOGY (IT), AND THE INTERNET[2]

The recent advent of EC, IT, and the Internet (and their respective interfaces and interrelationships) has certainly revolutionized and enhanced our day-to-day operations and methods for doing business. The term *electronic commerce* (EC) has grown to include all aspects of business and market processes enabled by the Internet and the various World Wide Web technologies; the term *information technology* (IT) refers to the infrastructure that fosters the integration of all of the various mechanisms for transmitting information and data; and the Internet is basically a network of networks and a connecting vehicle for all who have access to a computer and may be interested. More specifically, the introduction and utilization of these technologies has produced the following benefits:

1. *Communications processes.* Through the utilization of e-mail, Internet chat rooms, and specially designed web sites, two or more individuals can communicate worldwide, simultaneously, and on an almost unlimited basis.
2. *Data processing.* Through the application of such technologies as *electronic data interchange* (EDI), various elements of data can be rapidly transmitted and made accessible worldwide, and specifically to those who may have a need.
3. *Data storage and retrieval.* Data warehouses, including multisubject repositories containing highly detailed historical data, can be established for the purposes of storage and to provide rapid access to specific information, wherever or to whomever, in the event of a need.

In the design area, the utilization of these technologies, in conjunction with the application of computer-aided design methods (e.g., CAD/CAM/CIM/CAS/CALS), has resulted in greater productivity, in less time, and with a reduction in resources consumed and ultimate cost. The establishment and utilization of large networks involving the customer, contractors, and suppliers has simplified and enhanced communications and has (in many instances) resulted in greater customer satisfaction in the end. The rapid and wide distribution of design data has enabled quick review and feedback, simplifying the design process and giving everyone concerned access to the same data package. In essence, the application of these technologies has facilitated the overall design process and enabled the various responsible designers to

[2]Although there are numerous references for EC, IT, and the Internet, the following reference can be quite useful: P. Loshin, J. Vacca, and P. Murphy, *Electronic Commerce,* 3rd ed. (Hingham, MA: Charles River Media, 2001).

work closely in a more "team-oriented" environment than they have experienced in the past.

In the business process area (i.e., those processes that support the successful accomplishment of all of the engineering and design-related activities described throughout this text), the application of EC, IT, and Internet technologies has resulted in a number of enhancements:

1. *Business-to-business electronic commerce.* The exchange of business information and the automation of various processes.
2. *Enterprise resource planning (ERP).* The integration and automation of various manufacturing and related processes (refer to Section 3.4.7).
3. *Purchasing and marketing-related activities.* The initiation of purchase orders, the tracking of items in transit, and the status of various inventories.

Not only has the introduction of these technologies significantly influenced our day-to-day activities in system/product design and in the implementation of our business practices, but through the development and utilization of the Internet (and specialized web sites such as WebCT and Blackboard) it has been possible to offer a wide variety of education and training programs worldwide. During the past few years, a large number of academic institutions have been offering a wide mix of educational programs leading to a degree (both undergraduate and graduate), courses leading to some form of certification, and/or courses for vocational training purposes. The growth in distributed distance education has been phenomenal. The opportunities for personal development are great.

It is essential for those involved in the implementation of system engineering requirements to be familiar with and take advantage of the latest technologies and how they can be effectively applied toward meeting the objectives described throughout this text. The key to acquiring real value from these information-related technologies is to motivate people to use them on a frequent and consistent basis, as these technologies work only when the proper incentives and training are provided early in a given program.

4.4 CURRENT DESIGN TECHNOLOGIES AND TOOLS

With the advancements in computer technology through the past three decades, many new tools and techniques have been developed and adapted. Not only have the capabilities of mainframe computers increased significantly, but the availability of personal computers (PCs) has literally changed our ways of doing business, particular in regard to engineering design. In addition, the development of software packages and associated computer models has increased exponentially, and the results have provided the design engineer (and the manager) with a wide variety of tools intended to enhance productivity. Such tools include word processors, graphics packages, spreadsheets, database management packages, and analysis routines.

Given the appropriate computerized design aids, the engineer is able to accomplish a performance analysis employing simulation methods (dynamic versus static, stochastic versus deterministic, continuous versus discrete) in a relatively short time frame. Mathematical programming methods (linear programming, quadratic programming, dynamic programming) can be used in solving resource allocation and assignment problems. Statistical tools are available for plotting distributions and for determining related characteristics (e.g., mean, standard deviation, range, maximum value). Project management aids are used to plot scheduling networks (e.g., the Program Evaluation and Review Technique/PERT and the Critical Path Method/CPM) and cost projections. Database management models are employed extensively for data acquisition and storage, information processing, and report generation. Finally, there are a wide variety of specialized engineering tools that can be effectively utilized by the designer to help solve specific problems (e.g., the design of a digital filter, the layout of components on a circuit board, and the accomplishment of a reliability analysis for System XYZ).

Relative to application in the design and development process, the availability of these tools offers a number of distinct advantages:

1. The combination of personal computers (PCs), included as part of individual design workstations located throughout an entire project design area, with the connections to a central workstation and a mainframe computer (or equivalent), has created an excellent data communications network. Not only is it possible to transmit many different categories of data, in varying formats, to all applicable workstations on a concurrent basis, but this can be accomplished rapidly and efficiently. Design data packages can be developed by individual designers, transmitted to many others simultaneously, and reviewed with recommended changes submitted to the designer in a very short period of time. This capability minimizes the requirement for completing tasks in series, as described in Section 4.1, and allows for a reduction in overall system development time. Figure 4.2 illustrates this concept.[3]

2. The versatility and variety of software packages/models provide the designer with many new tools, not readily available in the past. For instance, in systems design, the use of simulation methods early in the conceptual phase enables the designer to do a better job in determining operational requirements and accomplishing a performance analysis. Three-dimensional computer models may be developed in order to evaluate a variety of possible system configurations, to study the interrelationships among system components, to investigate space allocations, to study the performance of human task sequences, and so on. The use of mathematical/statistical models allows the designer to investigate many more alternatives (as compared with what has been possible in the past), involving numerous calculations and the processing of large amounts of data in a short period of time. In essence, the design engineer of today has many more tools available, and the capabilities of these tools allow for a more in-depth analysis and investigation of design alternatives. This capability, ap-

[3] One of the objectives through concurrent engineering is to reduce the length of the system acquisition process by appropriately applying new technologies in design and development.

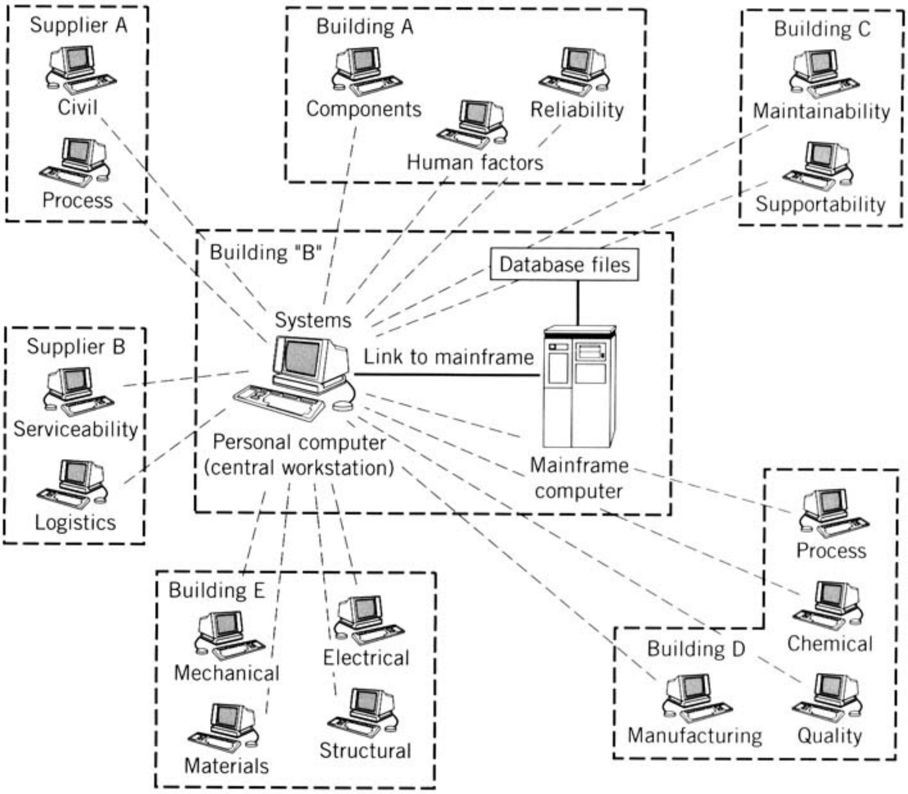

Figure 4.2 Example project design communications network.

plied early in the system life cycle, helps to reduce the risks associated with design decision making by eliminating nonfeasible options in the beginning.

3. The data handling capabilities, provided through computer technology, allow for the acquisition, processing, storage, and retrieval of greater varieties and larger amounts of data than in the past. Data storage and retrieval methods are simplier, and data processing times are much less. Not only is it easy to capture certain design information on drawings, but the generation and distribution of parts/materials lists can be handled expeditiously. Further, reports and technical publications can be produced automatically by employing a combination of graphics and word processing methods.

In regard to the system engineering objectives defined in Chapter 1, the advent of computer technology (along with the many tools that are currently available) can have a very beneficial impact. Specifically:

1. A more in-depth and complete analysis of system requirements can be accomplished during an early stage in design when the life-cycle impacts are the greatest. This, in turn, tends to foster more emphasis on a top-down, life-cycle approach in system development.

2. An improved communications process can evolve as a result of (a) being able to disseminate data rapidly and effectively, (b) being able to transmit information to multiple individuals and/or organizations concurrently, and (c) being able to incorporate design changes expeditiously. These improvements in communications help to provide the necessary integration of the many different disciplinary areas involved in the design process.

On the other hand, adapting to the new computerized technology is not without some concerns and challenges. First, the development and implementation of a standardized approach for converting design information into a digital format are required. All designers, supporting personnel, producer and consumer organizations, and suppliers must utilize the same language and data format, follow identical practices, and so on.[4]

Second, the methods for linking personal computers (PCs) throughout a company via a local-area network (LAN), between companies via a wide-area network (WAN), and/or the linking of PCs to mainframe computers, are critical to the communications process. Figure 4.2, illustrating a "star topology," shows one approach, with the objective of allowing for the transmission of design information to multiple workstations concurrently. Another approach, often utilized, is a circular configuration (i.e., "ring topology"), in which data must pass through various workstations in sequence prior to arriving at the centralized computer. This configuration generally does not allow for the transmission to all interested designers simultaneously, and the process assumes a series of actions progressing from one remote workstation to another.

In any event, the design of the protocols and the various networks (e.g., LANs, WANs) must be such as to promote the rapid and effective communication of system/product design information. Further, the hardware and software packages to be utilized must be fully compatible. The various workstations must be able to "talk to each other," and the appropriate levels of communications within a network, and between networks, must be possible. In other words, methods and procedures must be established to allow for the rapid and efficient transmission of design data between the various suppliers and the producer (i.e., the contractor), and between the producer and the consumer (i.e., the customer).[5]

In considering the system engineering objectives highlighted in Chapter 1, these must be viewed in the context of the overall design environment. The objectives relate to the application of a total, top-down, integrated, life-cycle approach in the de-

[4]The Department of Defense recognized this requirement and attempted to provide some standardization through the application of MIL-D-28000, Military Specification, "Digital Representation for Communication of Product Data: IGES Application Subsets" (Washington, DC: Department of Defense). This standard includes the definition of a series of application-specific subsets of the initial graphics exchange specification (IGES), the popular name for American National Standard ANSI Y14.26M, "Digital Representation for Communication of Product Definition Data."

[5]The development of the initial graphics exchange specification (IGES) was initiated to allow for the transfer of design data between networks, CAD/CAM systems, and so on. The capability is being supplemented by the product data exchange specification (PDES), which will encompass the complete set of data elements that defines a system/product for all applications over its expected life cycle.

velopment of a system that will meet the needs of the consumer, both effectively and efficiently. The successful fulfillment of these objectives is, of course, dependent on the activities accomplished throughout the system development process. This, in turn, is highly influenced by the design capability and environment that exist within the producer/supplier organization. If the appropriate tools are available and properly utilized, the realization of system engineering objectives may be relatively easy. On the other hand, if the environment is not conducive to the accomplishment of *good* design, then additional efforts will be required to ensure that the desired system engineering objectives are met.

Thus, not only will vary the requirements for system engineering as a function of the nature and complexities of the system being developed, but they must also include consideration of the capability designated to support the design process. The degree to which computerized technology is being utilized may have a significant impact on the system engineering process.

4.4.1 The Use of Simulation in System Engineering[6]

Simulation is the process of designing and utilizing an operational model of a system to conduct experiments for the purpose of either understanding the behavior of the system or evaluating alternative strategies and/or system design configurations. The objective is to construct a simplified representation of a system or a process in order to facilitate the analysis, synthesis, and/or evaluation of the system/process. The use of simulation is particularly appropriate in the early stages of system development prior to the point when the various physical elements of the system are available for evaluation; that is, during the "analytical" stage specified in Figure 2.32.

Simulation methods can be applied in the development of three-dimensional computer-aided design (CAD) models to show the overall system configuration and its components, their location, accesses, interrelationships, and so on. A design engineer can visually see the system configuration, as an entity, during the early stages of preliminary design. This will, of course, enable the designer to evaluate different alternatives, identify potential problems, and accomplish an early synthesis of the design. Examples of applications include the simulation of an airplane and the layout of its components, an aircraft cockpit with crew, an automobile with driver, a submarine with installed components, a manufacturing facility with capital equipment installed, and so on. Simulation methods can also be used to illustrate process flow rates (e.g., the flow of materials through a factory along with stoppages), different transportation routings, reliability failure patterns, maintenance and support policy alternatives, and so on.

As conveyed in earlier chapters, one of the objectives of system engineering is to gain as much visibility as possible in the early stages of system development. The in-

[6]Two good references are (1) *Systems Engineering Fundamentals* (Fort Belvoir, VA: Defense Acquisition University (DAU) Press, December 2000), Chapter 13; and (2) S. V. Hoover and R. F. Perry, *Simulation: A Problem Solving Approach* (Reading, MA: Addison-Wesley, 1990). The subject of "simulation" is also covered in a number of texts dealing with operations research methods (refer to Appendix A).

tent is to investigate all feasible approaches to design, identify and eliminate potential problems, select a preferred design configuration, and reduce (if not eliminate) the possibility of risk. The use of simulation techniques allows the designer to investigate many different potential design solutions prior to the procurement of equipment, the development of software, and the acquisition of other physical elements of the system. This, in turn, can lead to significant reductions in cost.

4.4.2 The Use of Rapid Prototyping[7]

In the area of software development in particular, designers are oriented toward the building of "one-of-a-kind" software packages. The issues in software development differ from those in other areas of engineering in that mass production is not the normal objective. Instead, the goal is to develop software that accurately portrays the features that are desired by the user; that is, the interfaces with the customer. For instance, in the design of a complex workstation display, the user may not at first comprehend the implications of the proposed command routines and data format on the screen. When the system is ultimately delivered, problems occur, and the "user interface" is not acceptable for one reason or another. Changes are then recommended, implemented, and the costs of modification and rework are usually high.

The alternative is to develop a protoype early in the system design process, design the applicable software, involve the user in the operation of the prototype, identify areas that need improvement, incorporate the necessary changes, involve the user once again, and so on. This iterative and evolutionary process of software development, accomplished throughout the preliminary and detail design phases, is referred to as *rapid prototyping.* Rapid prototyping is a practice that is often implemented and is inherent within the system engineering process, particularly in the development of large software-intensive systems.

4.4.3 The Use of Mock-ups

Although much information may be acquired through the use of simulation methods in early design, it may be desirable to construct a three-dimensional scale model or physical *mock-up* of the system, or an element thereof, during the preliminary or detail design phase to provide a realistic replica of a proposed equipment/facility configuration. These models or mock-ups can be produced to any desired scale and to varying degrees of detail, depending on the level of emphasis required. Mock-ups may be constructed of heavy cardboard, wood, metal, or a combination of materials. Mock-ups can be developed relatively inexpensively and in a short period of time. The utilization of mock-ups can provide many benefits, their applications include the following:

[7]Two pertinent references are B. W. Boehm, *Software Engineering Economics* (Upper Saddle River, NJ: Prentice-Hall, 1981); and B. Thome (ed.), *Systems Engineering: Principles and Practice of Computer-Based Systems Engineering* (New York: John Wiley & Sons, Inc., 1992).

1. They provide the design engineer with an opportunity to experiment with different facility layouts, packaging schemes, panel displays, and so on, prior to the preparation of formal design data.
2. They provide the reliability/maintainability/human-factors engineer with an opportunity to accomplish a more effective review of a proposed design configuration for the incorporation of supportability characteristics. Problem areas readily become evident.
3. They provide the maintainability/human-factors engineer with a tool for use in the accomplishment of predictions and detailed task analyses. It is often possible to simulate operator and maintenance tasks to acquire task sequence and time data.
4. They provide the design engineer with an excellent tool for conveying the final design approach during a formal design review.
5. They serve as an excellent marketing tool.
6. They can be employed to facilitate the training of system operator and maintenance personnel.
7. They are utilized by production and industrial engineering personnel in developing fabrication and assembly procedures and in the design of factory tooling and associated test fixtures.
8. At a later stage in the system life cycle, they may serve as a tool for the verification of a modification kit design prior to the preparation of formal data and the development of kit hardware.

In general, mock-ups are extremely beneficial. They have been used effectively in facility design, aircraft design, and the design of smaller systems/equipment.

4.5 COMPUTER-AIDED DESIGN (CAD)[8]

Computer-aided design (CAD), defined in a broad sense, refers to the application of computerized technology to the design process. With the availability of computer tools that can be appropriately utilized in the performance of certain design functions, the designer can accomplish more, at a faster pace, and earlier in the life cycle. These tools, including supporting software, incorporate graphics capabilities (vector and raster graphics, line and bar charts, x–y plotting, scatter diagrams, three-dimensional displays), analytical capabilities (mathematical and statistical programs for analysis and evaluation), and data management capabilities (data storage and retrieval, data processing, drafting, and reporting). These capabilities are usually combined in integrated packages for application to solve a specific design problem. A few examples of design applications follow:

[8]Other terms often used to define this area of activity are *computed-aided engineering* (CAE) and *computer-aided systems engineering* (CASE).

1. The utilization of graphics, combined with word processing and database management capabilities, enables the designer to:

(a) Lay out components on electrical/electronic circuit boards, design routing paths for logic circuitry, incorporate diagnostic provisions on microelectronic chips, and so on. CAD capabilities are being used extensively in the design of large scale integration (LSI) and very large scale integration (VLSI) electronic modules and standard packages.

(b) Lay out individual components for sizing, positioning, and space allocation purposes through the use of three-dimensional displays.

(c) Develop solids models enabling assemblies, surfaces, intersections, interferences, and so on, to be clearly delineated via the automatic generation of isometric and exploded views of detailed dimensional and assembly drawings. Component surface areas, volumes, weights, moments of inertia, centers of gravity, and other parameters can be determined automatically. CAD capabilities are being used extensively in the development of solids models for large systems; e.g., airplanes, surface ships, submarines, ground vehicles, facilities, bridges, dams, and highways. Many of these models allow the designer to view the system as an entity while providing a top-down hierarchical breakout of system components at different levels. Both two- and three-dimensional displays can be presented, using color graphics as an enhancement.

(d) Develop three-dimensional models of facilities, operator consoles, maintenance work spaces, and the like, for the purpose of evaluating the interface relationships between humans and other elements of the system. CAD tools are being utilized to simulate both operator and maintenance task sequences.

2. The utilization of analytical methods, combined with word processing, spreadsheet, and database management capabilities, enables the designer to:

(a) Accomplish system requirements and performance analyses in support of design trade-off studies; e.g., finite-element analysis, structural analysis, stress-strength analysis, thermal analysis, weight/loads analysis, materials analysis.

(b) Perform reliability analyses in support of design; e.g., allocations, predictions, failure mode, effect, and criticality analysis (FMECA), fault-tree analysis (FTA), sneak circuit analysis, critical useful life analysis, environmental stress analysis.

(c) Perform maintainability analyses in support of design; e.g., allocations, predictions, FMECA, diagnostic and test requirements analysis, maintenance task analysis (MTA).

(d) Perform human-factors analyses; e.g., functional analysis, operator task analysis, operational sequence diagrams (OSDs), training requirements analysis.

(e) Perform safety analyses; e.g., hazard analysis, fault-tree analysis.

(f) Perform supportability analyses; e.g., maintenance requirements analysis, level-of-repair analysis, spares requirements analysis, transportation requirements analysis, test equipment requirements analysis, facilities requirements analysis.

(g) Perform value/cost analyses; e.g., value engineering analysis, life-cycle cost analysis.

3. The utilization of database management, combined with graphics, spreadsheet, and word processor capabilities, enables the designer to:

(a) Develop functional flow diagrams, information/data flow diagrams, dependency diagrams, reliability block diagrams, action diagrams, decision trees and tables.

(b) Develop and maintain a database that includes historical design data, parts lists, materials lists, supplier information, technical reports. The purpose is to be able to store standard data on common items and to be able to retrieve (or recall) such information quickly and reliably for future applications.

(c) Develop a management information system (MIS) that enables the accomplishment of project review and control functions; e.g., data communications, personnel loading projections, cost projections, technical performance measures (TPMs) "tracking," PERT/CPM reporting, project reporting requirements.

Through a review of these areas of application, one can see that the utilization of computer technology is widespread and growing at a rapid rate. On the other hand, although there are many uses of computer-aided design technology, they are not very well integrated.

From the overall life cycle illustrated in Figure 4.3, CAD tools are being applied throughout the design and development process, the results of which feed directly into the computer-aided manufacturing (CAM) and computer-aided support (CAS) capabilities. The application of CAD tools has been evolving since the 1960s and 1970s, primarily following a "bottom-up" approach.[9]

Unlike the integrated network concept illustrated in Figure 4.2, individual design workstations have been developed on a somewhat independent basis. A workstation constitutes a grouping or arrangement of equipment (e.g., graphics terminal, computer, keyboard), combined and laid out in such a manner as to help the designer in completing selected tasks. The capabilities of a design workstation will vary depending on (1) the specific design functions to be performed, (2) the nature and complexity of the system being developed (and its components), (3) the education and vision of the responsible designer, in terms of his or her interest and willingness to adapt relative to the utilization of new computer technologies, (4) the degree of management support relative to modernizing the design capability, and/or (5) the availability of the necessary budgetary resources to acquire and support the capital equipment items that are incorporated as part of the design workstation. In many instances, adapting to computerized technologies in design requires a "cultural" change, or reorientation, pertaining to the methods used in task accomplishment. Further, whereas experience has indicated that the use of CAD methods is very cost-effective in the long term, the initial acquisition cost of the required capital assets may be perceived as being too high. In any event, these apparent obstacles must be overcome if progress is to be made in this area.

[9]Through the years, different terms have been used to describe computer-aided applications applied to logistics and logistic support, including *computer-aided support* (CAS), *computer-aided logistics* (CAL), and *computer-aided logistic support* (CALS). Although the terms may vary with usage, the principles and concepts remain the same.

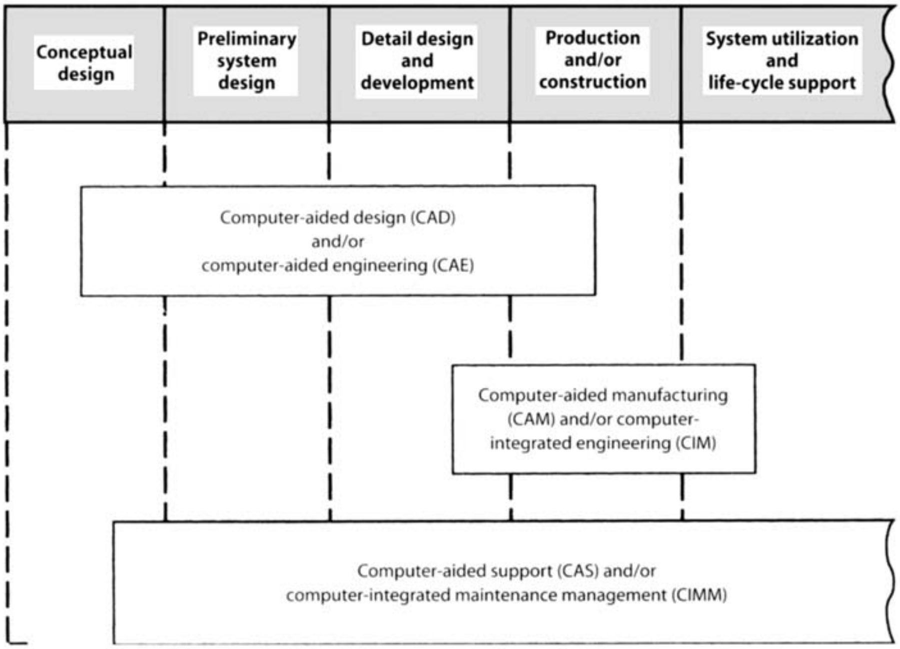

Figure 4.3 Application of CAD/CAM/CAS.

The capabilities of design workstations have evolved from a configuration in which the user was able to design a specific component part, or perform a detailed analysis of some rather isolated function of the system, to a comprehensive configuration integrating many of the diverse technologies discussed earlier. Initially, a graphics terminal was used to design a part, analyze stresses, study and evaluate a mechanical action, and so on. Now, a design workstation can be utilized to effectively accomplish many of the functions noted earlier; for example, the layout of components on circuit boards, the development of three-dimensional solid models, and the utilization of sophisticated analytical methods. Relative to the future, much more can be accomplished in terms of design integration and the incorporation of new capabilities, and the potential for additional growth is great.

The total integrated flow concept illustrated in Figure 4.4 reflects a long-range goal. At the beginning, a comprehensive design workstation can be developed and constructed, along with the appropriate software, to reflect the capabilities inferred from the integrated approach presented in Figure 4.2. In addition to the requirements for electrical design, mechanical design, and structural design, reliability, maintainability, and human factors, supportability and comparable requirements must be integrated into the design process. In other words, all of the design requirements specified in Figure 3.5 (Chapter 3, Section 3.2) must be appropriately integrated, the design communications network illustrated in Figure 4.2 must be available and uti-

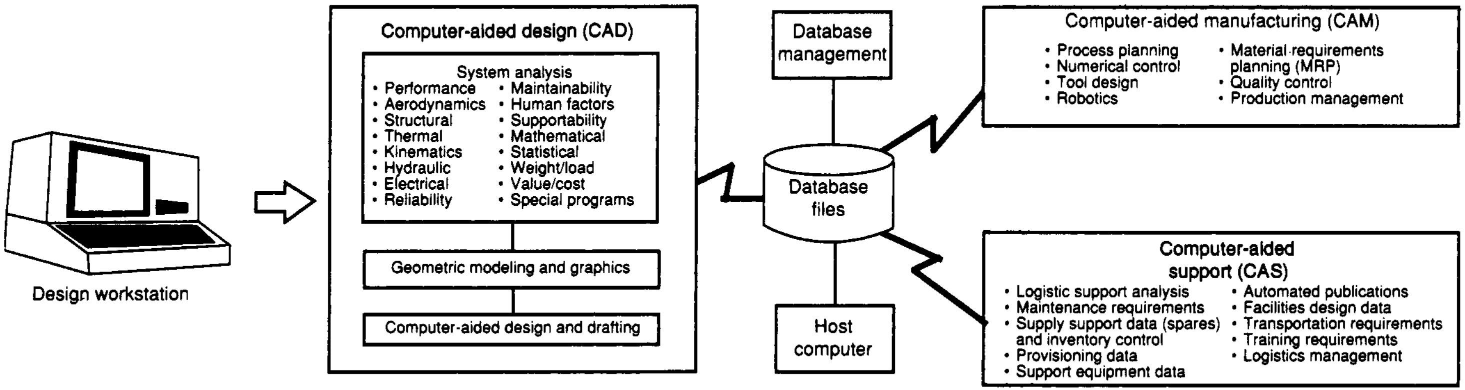

Figure 4.4 Major CAD/CAM/CALS interfaces.

lized, and each of the design workstations assigned to a given project must have the capability to deal with these overall requirements.

In addition to providing a capability that will promote a completely integrated design approach, a provision must be incorporated to allow for the smooth transition of information from the design process to the manufacturing process and to the system support structure. Perhaps, in the not too distant future, the design engineer (with the assistance of a team of discipline-oriented experts) will be able to provide the appropriate design input at the workstation that will, in turn, automatically flow into both the CAM and CAS processes, through the application of effective data communications methods. This provision, of course, will require complete compatibility (language, data format, etc.) among CAD, CAM, and CAS, at both the producer (contractor) and the supplier levels.

Relative to the current status of CAD tools and their applications, many industrial firms have developed and installed CAD capabilities, integrated design workstations, supporting software, and the like. These capabilities vary significantly from one installation to the next. However, in most instances (and particularly for large-scale systems), the use of graphics technology, analytical methods, and database management capabilities has been effectively employed in accomplishing some of the more traditional design activities; for example, electrical circuit design, mechanical packaging design, and structural design. On the other hand, very little has been accomplished relative to the integration of reliability, maintainability, human factors, and supportability into this process; that is, the design disciplines discussed throughout Chapter 3.

Although computer technology has been successfully applied in the development of reliability models, maintainability models, logistic support models, and so on, these tools have been utilized on a "stand-alone" basis. In general, the design activities associated with these disciplines have been accomplished independently, not properly integrated into the basic engineering design process, and the tools that have been developed in these areas have not been integrated with each other or into the more traditional design workstations.[10]

In response to the need to become more effective, from the standpoint of contributing to the design process in a timely manner, there has been a great deal of effort expended during the past few years in developing reliability, maintainability, and supportability models. If one were to survey the literature in this area, more than 350 models of varying types could be identified, and this number is growing at a rapid rate. A brief description of a few of these models, which are being utilized in support of different design applications today, follows, to provide some insight as to the type of tools that are available:

1. *Computer-Aided System Engineering* (CORE). CORE supports both static and dynamic analysis of system requirements, functional behavior, and system architecture, with automatic generation of customizable reports via a simple scripting lan-

[10]The term *islands of automation* is often used in referring to analytical tools that are not integrated and are employed on an independent basis. There are many areas where this condition exists today.

guage. The model enables the user to develop a system description in a well-defined, structured manner, provides a full database framework and flexible schema to support requirements traceability, and can be easily implemented using a PC with a Microsoft Windows capability (VITECH Corp., 2070 Chain Bridge Road, Suite 320, Vienna, VA 22182).

2. *Cost Analysis Strategy Assessment* (CASA). CASA is utilized to develop life-cycle cost (LCC) estimates for a wide variety of systems and equipment. It incorporates various analysis tools into one functioning unit and allows the analyst to generate data files, perform life-cycle costing, sensitivity analysis, risk analysis, cost summaries, and the evaluation of alternatives. (Defense Acquisition University, DSS Directorate (DRI-S), Fort Belvoir, VA 22060.)

3. *Equipment Designer's Cost Analysis System* (EDCAS). EDCAS is a design tool that can be used in the accomplishment of a level-of-repair analysis (LORA). It includes a capability for the evaluation of repair versus discard-at-failure decisions, and it can handle up to 3500 unique items concurrently (i.e., 1500 line replaceable units, 2000 shop replaceable units). Repair-level analysis can be accomplished at two indenture levels of the system, and the results can be used in determining optimum spare/repair part requirements and in the accomplishment of life-cycle cost analysis (LCCA). EDCAS is available through a simplified personal computer-oriented University Edition (UE) and a full-scale laboratory model edition and is compatible with the requirements of MIL-STD-1390B, "Level of Repair," Department of Defense, Washington, DC. (Systems Exchange, Monterey, CA.)

4. *Optimum Repair Level Analysis* (ORLA) *Model.* A level-of-repair analysis (LORA) model used to examine the economic feasibility of maintenance and support alternatives. Up to four alternatives can be evaluated, with life-cycle cost broken down into 13 distinct logistics areas. (U.S. Army-MICOM, Code AMSMI-LC-TA-L, Redstone Arsenal, AL 35898.)

5. *Optimum Supply and Maintenance Model* (OSAMM). OSAMM is a level-of-repair analysis (LORA) model used to determine the optimum economic maintenance policy for each item that fails, to identify items in terms of repair versus discard, to identify economic screening criteria, and to evaluate support equipment/repairmen options. Four levels of support and four indenture levels of equipment can be evaluated. (U.S. ARMY-CECOM, Fort Monmouth, NJ 07703.)

6. *OPUS Model.* OPUS is a versatile model used primarily for spare/repair parts and inventory optimization. It considers different operational scenarios and system utilization profiles in determining demand patterns for spares, and it aids in the evaluation of various design packaging schemes. Alternative support policies and structures may be evaluated on a cost-effectiveness basis. (Systecon AB, Linnëgatan 5, Box 5205, S-10245, Stockholm, Sweden.)

7. *PC Availability.* This model utilizes Markov analysis to study the influence of failure rates, repair rates, and logistic support on system availability. The objective is to provide assistance in the development of optimum system configuration design and repair policies. (Management Sciences, Inc., 6022 Constitution Avenue, N.E., Albuquerque, NM 87110.)

8. *Relex PRISM.* This constitutes a reliability software suite, which includes capabilities for the development of reliability block diagrams, reliability predictions, maintainability predictions, failure mode and effects analysis (FMEA)/FMECA, FTA/event trees, Weibull analysis, and life-cycle cost analysis. (Relex Software Corporation, 540 Pellis Road, Greensburg, PA 15601.)

9. *Tiger Computer Program.* This is a family of computer programs that can be used to evaluate, by Monte Carlo simulation, equipment or a large-scale complex system in order to establish various reliability, readiness, and availability measures. Key features include the ranking of equipment by degree of unreliability and unavailability, evaluating a mission with multiphase types, and performing sensitivity analyses on a complex system by downgrading or upgrading the characteristics of each piece of equipment. (Reliability Engineering, Naval Sea Systems Command, Department of the Navy, Washington, DC 20362.)

10. *VMETRIC.* This is a spares model that can be used to optimize system availability by determining the appropriate individual availabilities for system components and the stockage requirements for three indenture levels of equipment (e.g., line replaceable units, shop replaceable units, and subassemblies) at all echelons of maintenance. Outputs include optimum stock levels at each echelon of maintenance, Economic Order Quantity (EOQ) quantities, and optimal reorder intervals. (Systems Exchange, Monterey, CA.)

These models are only a representative few in the total spectrum of tools available throughout the industrial and government sectors today. However, as indicated earlier, they have been developed on an independent basis and are being utilized outside the mainstream design effort. The primary objectives in the future are to:

1. Evaluate and integrate these and other tools, as applicable, so that they can be utilized interactively, as conveyed in the illustration in Figure 2.27. The goal is to develop a set of tools that (a) can be effectively utilized in response to a variety of needs, (b) can address the system as an entity, while being utilized to evaluate different components of the system, and (c) can "talk to each other" in terms of data communications.

2. Incorporate these and other tools, as appropriate, into the workstations for all responsible designers. The design engineer, using the ideal workstation shown in Figure 4.4, should have available not only the necessary tools for the accomplishment of a structural analysis, but also the tools needed for the accomplishment of a reliability analysis as well. The same individual may not accomplish both tasks; however, he or she needs to view the results of both (and their impacts on each other) concurrently in order to make intelligent design decisions.

In regard to system engineering, as it applies to CAD applications, the challenges for the future are directly in line with these objectives. The appropriate tools must be available and well integrated into the typical design workstation, in such a manner as to promote the proper consideration of all disciplines in the system design process.

4.6 COMPUTER-AIDED MANUFACTURING (CAM)

Computer-aided manufacturing (CAM) refers to the application of computerized technology to the manufacturing or production process. This application, reflected in the context of the system life cycle presented in Figure 4.3, primarily includes the use of automated methods as they pertain to the following activities:

1. *Process planning:* Throughout the production process, there may be a series of steps required to fabricate a component, to assemble a group of items, or both. Process planning addresses the entire flow of activities, evolving from the definition of a given design configuration to the finished product delivered to the consumer, and CAM applications include those activities that can be automated. Whereas the activities associated with process planning have been known and practiced for a long time, the use of computer technology in accomplishing these activities is a relatively recent innovation.[11]

2. *Numerical control* (NC): Within the production process, there may be many instances in which machine tools are required for milling, drilling, cutting, routing, welding, bending, or a combination of these operations. The application of computerized technology for the control of machine tools, with prerecorded coded information, to make a part has been practiced for many years. However, these activities have often been accomplished in isolation from other activities in the production process. NC instructions have been prepared by programmers taking information from engineering drawings, programs have been tested, revised, retested, and so on. As this can be quite expensive, the goal in the future is to be able to generate NC input instructions directly from the design database, developed through the CAD applications discussed in Section 4.5.

3. *Robotics:* At various stages in the production process, there may be applications in which robots can be effectively employed for the purpose of materials handling (i.e., the carrying of parts from one location to the next) or for the positioning of tools and workpieces in preparation for NC applications. In some instances, robots are actually being used to operate drills, welders, and other tools. Computer technology is, of course, employed in the programming of robots for these and related production operations.

4. *Production management:* Throughout the production process, there is an ongoing management activity in which computer applications can be effectively utilized in support of production forecasting, scheduling, cost reporting, Material Requirements Planning (MRP) activities, the generation of management reports, and so on. There is a requirement to develop a management information system (MIS) that enables the review and control of production functions.

[11]In evaluating the entire production process, some activities may be found to be similar in nature, for which standard procedures can be utilized. This is particularly true in the manufacture of components where, by appropriate grouping, a common and standardized process can be applied using CAM methods. This approach is often defined as "group technology."

The application of CAM methods to the production process will be different for a "flow shop" as compared with a "job shop" operation, or for the production of multiple quantities versus the construction of a "one-of-a-kind." Independent of the function, the entire process must be addressed as a system, possible CAM applications (i.e., combinations of NC, robotics, and data processing methods) must be identified, and a well-integrated and flexible manufacturing capability must be developed. The objective is to design a production capability with the proper mix of people and degrees of automation.

In the initial design, and subsequent monitoring and control, of a production capability, the principles covered under concurrent engineering and quality engineering must prevail. The manufacturing tolerances, allowable through the application of NC tools and robotics, must be consistent with the initial requirements for system design. Care must be exercised to ensure that unexpected variances, causing possible product degradation through the production process, do not occur. This is of particular concern relative to meeting the objectives of system engineering.

4.7 COMPUTER-AIDED SUPPORT (CAS)[12]

Computer-aided support (CAS) refers to the application of computerized technology to the entire spectrum of logistics and system support activities described in Section 3.4.8. For years, the consideration of logistics and maintenance support requirements has been relegated to an activity downstream in the system life cycle. Further, in the initial definition of system support requirements, the process that has been implemented includes the generation of an extensive amount of data and documentation, much of which is distributed through a network involving many different locations. As systems are produced and delivered for operational use, the overall logistics and support activity often assumes an additional degree of complexity, involving a great deal of data/documentation, the processing and distribution of many different components, and the requirements for a significant amount of data communications. The support requirements, particularly for large-scale systems, have not always been responsive to the system need, and the results have been costly.

In addressing logistics in the context of the system life cycle, there are design-related activities, analysis activities, technical publications activities, provisioning and procurement activities, fabrication and assembly activities, inventory and warehousing activities, transportation and distribution activities, maintenance and product support activities, and management activities across the spectrum. In Figure 4.3, the applications are broad, and there is a certain degree of overlap with CAD and CAM requirements.

[12]In the 1980s, the Department of Defense promoted the concept of computer-aided logistic support (CALS), with the objective of improving quality, timeliness, and responsiveness in the acquisition of future system support requirements. A good reference is MIL-HDBK-59, Military Handbook, *Computer-Aided Acquisition and Logistics Support Guide* (Washington, DC: DOD). These objectives, along with the further enhancement of computer-aid and electronic commerce (EC) methods, are still applicable and are used in the collection and processing of *logistics management information* (LMI) for the acquisition of new systems today.

To provide an indication as to the variety of computer technology applications in the logistics field, the following examples are noted:[13]

1. *Logistics engineering:* The utilization of reliability, maintainability, and supportability models in the accomplishment of design trade-offs is a major requirement throughout system development (e.g., level-of-repair analysis, spares requirements, maintenance loading, transportation analysis, life-cycle cost models). This activity should be integrated into the CAD effort described in Section 4.5, and the use of graphics technology, analytical methods, and database management capabilities is required.

2. *Supportability analysis (SA):* Through the evaluation of a given design configuration, SA data are developed with the objective of identifying the specific requirements for system support; for example, spare parts, test and support equipment, personnel quantities and skill levels. These data must be generated, processed, stored, retrieved, and fed back in a timely manner if the design for supportability is to be realized. Data processing and database management capabilities are required.

3. *Logistics management information (LMI):* This category covers the requirements for spares and repair parts provisioning data, support equipment provisioning data, design drawings and change notices, technical procedures, training manuals, and various reports. The development of technical manuals (i.e., system operating procedures and maintenance instructions) through automated processes is included. Computerized technology applications require the use of spreadsheets, word processing, graphics, and database management capabilities.

4. *Distribution, transportation, and warehousing:* The ongoing maintenance and support of the system throughout its planned life cycle requires the distribution, transportation, handling, and warehousing activities pertaining to spares and repair parts. In addition to the data processing and database management requirements associated with inventory control and MRP activities, the application of automated materials handling equipment and robotics can be effectively employed in the performance of warehousing functions. The automatic "ordering" and "picking" of components from the warehouse shelves, in response to a defined need, provides an excellent example of the use of computerized technology in the logistics area. Further, the opportunities for the future incorporation of "expert systems," or "artificial intelligence," are apparent in considering the "if-then" type of decisions that are necessary throughout materials handling process.

5. *Maintenance and support:* The customer service activities, in support of the system in the field throughout its planned life cycle, include the accomplishment of scheduled and unscheduled maintenance actions. This, in turn, leads to the consumption of maintenance personnel resources, the utilization of test equipment, the requirements for spare parts, the need for formal maintenance procedures, and so on. Although computerized methods have been utilized in the generation of spares/repair

[13]The organization of files of digital data into completed documents and reports is addressed in the defense industry by MIL-STD-1840A, Military Standard, *Automated Interchange of Technical Information, DoD* (Washington, DC: DOD).

parts provisioning data and technical publications, there are additional applications relative to test equipment. In a few instances, handheld testers, with supporting software, have been used for maintenance diagnostics purposes. This area, supported with some selected applications of artificial intelligence, is a prime candidate for future growth.

As is the case relative to CAD, the CAS objective is being implemented at the detail level (i.e., a bottom-up approach). Initially, there was a great deal of effort expended in the development of requirements and interface specifications. In addition, there are many activities under way that are directed toward the development of technical manuals and procedures using automated processes. The development and processing of supportability analysis data is one area in which much has been accomplished. Although these efforts currently represent "islands of automation," the overall objective is to integrate the CAS requirements with CAD/CAM, as illustrated in Figure 4.4.

4.8 SUMMARY

The successful implementation of the system engineering process is highly influenced by technology and the tools available to the designer. The advent of computer technology and the proper use of graphic methods and displays, analytical models, spreadsheets and word processing, database management capabilities, and so on, have enabled the designer to accomplish much more, in a shorter time frame, earlier in the system life cycle, and with less overall risk. As such, the design process has undergone the first phase in the transition from a long series of manually performed tasks to a more efficient integrated and automated process.

Relative to the future, the challenge is to complete the next phase. This involves the integration of the many analytical methods/tools, currently being utilized on an individual stand-alone basis, into the overall design process. The objective is to (1) develop a workstation concept providing the appropriate communications between all responsible design engineering functions (illustrated in Figure 4.2) and (2) develop a capability allowing the smooth and automated flow of information from the CAD capability to CAM and CAS (illustrated in Figure 4.4). Not only must these capabilities be able to "talk to each other" within the context of a given project, but the design information produced must be compatible and transferable between other projects having similar objectives. Thus, care must be exercised relative to the selection of an appropriate language, data format, and data structure. Nevertheless, a great deal of progress and future growth in this area can be anticipated.

QUESTIONS AND PROBLEMS

1. Describe, in your own words, what is meant by IT, EDI, EC, and the Internet. How are they related (if at all)?

2. Why is it important (in the context of system engineering) to become familiar with some of the analytical methods identified in Section 4.2? Provide some specific examples.

3. Describe, in your own words, what is included in each of the following: CAD, CAM, and CAS.

4. Identify and describe some of the "technologies" that are being applied in the design process. Provide some examples of typical applications.

5. Describe some of the benefits associated with the application of computerized methods in the design process. How do these methods relate to the objectives of system engineering?

6. Identify some of the problems associated with the application of computerized methods in the design process. What cautions must be observed?

7. Relating to the design disciplines identified in Chapter 3, Section 3.4, a listing of typical program tasks is provided. In each of the following disciplines, identify those tasks that can be accomplished using computerized methods. Include some specific examples.

   (a) Reliability engineering tasks
   (b) Maintainability engineering tasks
   (c) Human-factors engineering tasks
   (d) Logistics and supportability tasks
   (e) Quality engineering tasks
   (f) Value/cost engineering tasks

8. Describe what is meant by "artificial intelligence." How can it be applied?

9. How does the application of computer technology impact "concurrent engineering"?

10. Select a system of your choice (describing the tasks in design), and develop a flowchart showing the application of CAD as it is being implemented.

11. How does CAM relate to system engineering? Describe some possible impacts.

12. How does CAS relate to system engineering? Describe some possible impacts.

13. Draw a flowchart showing the interface relationships among CAD, CAD, and CAS.