14

PRODUCTION

14.1 SYSTEMS ENGINEERING IN THE FACTORY

The production phase of the system life cycle represents the culmination of the system development process, leading to the manufacture and distribution of multiple units of the engineered and tested system. The objective of this phase is to embody the engineering designs and specifications created during the engineering development stage into identical sets of hardware and software components, and to assemble each set into a system suitable for delivery to the users. Essential requirements are that the produced system performs as required, is affordable, and functions reliably and safely as long as required. To fulfill these requirements, systems engineering principles must be applied to the design of the factory and its operations.

Most of the discussion in this chapter is concerned with the production of hardware system elements. On the other hand, as noted in Chapter 11, almost all modern products are controlled by embedded microprocessors. Thus, production tests necessarily include testing the associated software.

This chapter is organized in four main sections. It begins with Engineering for Production, which describes where production considerations must be applied during

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each phase of system development in order to ensure that the end product is both affordable and satisfies performance and reliability goals. The section Transition from Development to Production describes the problems typically encountered in the transfer of responsibility from the engineering to the manufacturing organizations and the role of systems engineering in their resolution. Production Operations describes the organization of the overall system manufacturing program as a complex system in its own right, especially as it is typically distributed among a team of contractors. The final section, Acquiring a Production Knowledge Base, describes the scope of knowledge that development systems engineers need to acquire in order to lead properly a system development effort, together with some of the means by which it may be best obtained.

Place of the Production Phase in the System Life Cycle

The production phase is the first part of the postdevelopment stage of the system life cycle. This relation is shown in Figure 14.1, which is a functional flow diagram relating the production phase to the preceding integration and evaluation phase and to the succeeding phase, operation, and support. The inputs from integration and evaluation are specifications and the production system design; the outputs are operational documentation and the delivered system.

Figure 14.2 shows the timing of the production phase relative to its preceding and succeeding phases. As in the case of the integration and evaluation phase, there is a considerable overlap between the end of each phase and the beginning of the next. Overlap between the end of integration and evaluation and the beginning of the production phase is necessary to order long-lead materials, to acquire factory tooling and test equipment, and to prepare production facilities for operations. Similarly, the initial produced systems are expected to be placed in operation while the production of subsequent units is continuing.

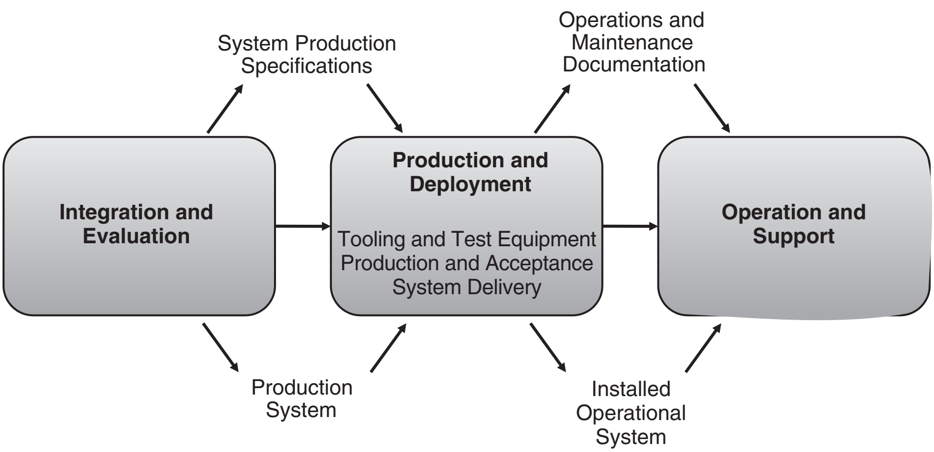

Figure 14.1. Production phase in a system life cycle.

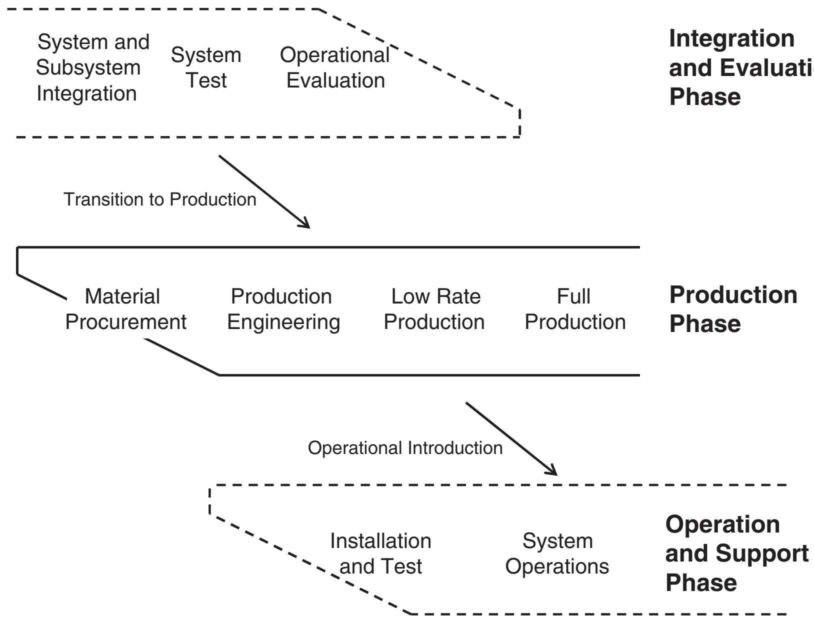

Figure 14.2. Production phase overlap with adjacent phases.

Design Materialization Status

The materialization status of the system would seem to be off the scale of previous diagrams, such as Table 13.1 and its predecessors, because the prior phases of the system development process have essentially fully "materialized" the system components and the system as a whole. However, since the majority of complex systems are made from components produced at a variety of locations, the process of materialization cannot be considered completed until the components are assembled at a central location and are accepted as a total system. This dispersal of manufacturing effort creates stress on vendor coordination, interface control, integration testing, and calibration standards. These will be discussed further in a subsequent section.

14.2 ENGINEERING FOR PRODUCTION

During the development stages of the system life cycle, and especially during concept development, the technical effort is focused primarily on issues related to achieving the performance objectives of the system. However, unless the final product is also affordable and functions reliably, it will not meet its operational need. Since these latter factors are strongly influenced by the choice of system functions and especially by their physical implementation, they must be considered from the beginning and throughout the development process. The process of introducing production considerations during development is generally referred to as “concurrent engineering” or “product development.” This section addresses how this process is applied during each phase of system development.

The accepted method of incorporating production considerations into the development process is to include such production specialists and other specialty engineers as members of the system design team. These may include experts in such specialties as reliability, producibility, safety, maintainability, and user interfaces, as well as packaging and shipping.

To make the contributions of these experts effective, it is necessary to bring them into active participation in the system design process. In this connection, it is essential to apply their specialized knowledge to the system requirements, as well as to interpret their specialty languages to other members of the system design team. Without systems engineering leadership, communication skills, and insistence on system balance, the concurrent engineering process is not likely to be effective.

Concurrent Engineering throughout System Development

The following paragraphs describe examples of the application of concurrent engineering in successive phases of system development, as well as the role of systems engineers in making these applications effective. As may be expected, this effort grows in relevancy as the system design progresses; however, it must be initiated at the outset of the program and effectively implemented throughout even the earliest phases.

Needs Analysis. Production and reliability considerations apply in the needs analysis for both needs-driven and technology-driven situations. The decision to begin a new system development must consider its feasibility to be produced as a reliable and affordable entity. Making such a decision relies heavily on systems engineering analyses, together with first-hand knowledge of the postulated development and manufacturing processes.

Concept Exploration. A principal product of the concept exploration phase is a set of system performance requirements that will serve as a basis for selecting the most desirable system concept from among competing candidates. In framing these requirements, a balance must be struck among performance, cost, and schedule goals—a balance requiring a total system perspective in which production processes are essential factors.

As will be discussed in the section on production operations, just as technology is advancing rapidly in solid-state electronics, communications, system automation, materials, propulsion, and many other system component areas, it is similarly revolutionizing production processes. A clear sense of the status and trend of manufacturing technology is a necessary element in the formulation of realistic system requirements. Systems engineering must make informed evaluations of the contributions by production specialists. For example, the selection of materials will be influenced by the difficulty and cost of production processes.

Concept Definition. Perhaps the most critical contribution of systems engineering is in the selection and definition of the preferred system conceptual design. At this point in the development, a clear concept of the implementation of the system in hardware and software is required to develop credible estimates of manufacturing and life cycle costs.

The selection of the proposed system design requires a balance among many factors, and for most of these, the assessment of risk is a central factor. As noted in Chapter 8, taking advantage of advancing technology necessarily involves some degree of risk both in terms of component design and process design. The estimates of risks are influenced by the nature and maturity of the associated manufacturing methods, which must be heavily weighted in trade-off analyses of alternative system configurations. In bringing the experience of production experts to bear on these judgments, systems engineers must serve as informed translators and mediators between them and design engineers and analysts.

Advanced Development. The advanced development phase provides an opportunity to reduce program risks by conducting analyses, simulations, experiments, and demonstrations of critical subsystems or components. Similarly, new production processes and materials must be validated before acceptance. Because of the expense involved in all such activities, especially experiments and demonstrations, the decision as to which ones warrant such validation must be made with full knowledge of the nature and extent of the risks, the magnitude of the gains expected from the use of the proposed processes and materials, and the scope of experimentation necessary to settle the issue. Again, this is a major systems engineering issue requiring expertise in production as well as in system design and performance.

This phase must provide a suitable basis for defining production processes, critical materials, tooling, and so on, through trade studies that consider the risks and costs of alternative approaches. Systems engineering must be intimately involved in the planning and evaluation of such studies to ensure their appropriate integration into the overall plans for the engineering design phase. In this connection, critical attention must be given to the impact of manufacturing methods on the compatibility of component interfaces in order to minimize production, assembly, and testing problems.

Engineering Design. The engineering design phase is where production factors become especially prominent in the detailed design of system components. Component and subcomponent interface tolerance specifications must be compatible with the capabilities of manufacturing processes and allocated costs. The design and construction of factory test equipment must also be accomplished during this phase so as to be ready when production is authorized.

During this phase, design engineers obtain major inputs from specialty engineers applying their experience in the areas of producibility, reliability, maintainability, and safety. In this collective effort, systems engineers serve as mediators, interpreters, analysts, and validators of the final product. To play these roles, the systems engineers must have a sufficient understanding of the intersecting disciplines to effect meaningful communication across technical specialties and to guide the effort toward the best available outcome.

An important part of the engineering design phase is the design and fabrication of production prototypes to demonstrate the performance of the product, as it will be manufactured. The degree to which the prototype fabrication methods are selected to duplicate the actual manufacturing tooling and process control is a matter requiring systems engineering judgment as well as design and manufacturing considerations.

Usually, many components of a complex system are designed and manufactured by subcontractors. The selection of component contractors must involve the evaluation of their manufacturing as well as engineering capabilities, especially when the components involve advanced materials and production techniques. Systems engineers should be able to help judge the proficiency of candidate sources, be key participants in source selection and in setting the requirements for product acceptance, and serve as technical leads in subcontracting.

Such knowledge is also essential for leading the interface definition effort among component suppliers, the specification of interface tolerances, and the definition of component test equipment design and calibration standards for use in both development and production acceptance testing.

The above considerations all affect production cost estimates, which systems engineers must contribute to and evaluate; considerations of uncertainty and risks must also be given due weight in forming the final cost and schedule estimates.

Integration and Evaluation. Unexpected incompatibilities at component interfaces are often first brought to light during the integration of prototype system components and subsequent system testing. These problems are normally corrected through component redesign, refinement of component test equipment, and so on, prior to final release for production. Nevertheless, during the subsequent assembly and test of the production system, design changes introduced to correct these incompatibilities, together with other "minor" changes and adjustments introduced to facilitate production and test activities, may themselves produce new areas of incompatibility. Accordingly, systems engineers should monitor the initial production assembly and test activities so as to alert program management to any problem areas that must be addressed prior to deployment of the product. In order to identify and expeditiously deal with such problems at the earliest possible time, systems engineers must be knowledgeable of both factory production and test acceptance processes. In some cases, acceptance test procedures are written by systems engineers.

Application of Deployment Considerations in System Development

It has been stressed in previous chapters that the system design must consider system behavior throughout the total life cycle. In many systems, the deployment or distribution process subjects the system and its constituent components to substantial environmental stresses during transportation, storage, and installation at the operational site. While these factors are considered during system definition, in many instances, they are not quantitatively characterized until the advanced development phase or sometimes even later. It is therefore mandatory that the deployment of the system be planned in detail as early in the development process as possible. Factors such as the risk of exposure to environments that might affect system performance or reliability must be assessed and reflected either in the system design requirements or in restrictions to be observed during the deployment process. In some cases, protective shipping containers will be required. In those cases where problem areas still exist, provision should be made for their resolution through further analysis and/or experimentation.

In many cases, the predecessor system provides a prime source of information regarding the conditions that a new system may encounter during its transit from producer to user. When the operational site and the system physical configuration are the same or similar to that of the new system, the deployment process can be quantitatively defined.

14.3 TRANSITION FROM DEVELOPMENT TO PRODUCTION

Transition in Management and Participants

As may be inferred from the life cycle model, wholesale changes in program management focus and participants necessarily take place when the production of a new system is initiated. These areas are briefly summarized below.

Management. The management procedures, tools, experience base, and skills needed for successful program direction and control during the production phase differ materially from those needed during system development. Accordingly, the production of a new system is almost always managed by a team different from the one that directed the earlier engineering development, integration, and test efforts. Moreover, the production contract is sometimes completed among several companies, some of which may have been only peripherally involved in the system development. For all these reasons, there is normally little carryover of key personnel from the engineering into the production phase. At best, selected members of the development engineering team may be made available when requested to provide technical assistance to the production organization. Production funding is usually embodied in a contract separate from the one that was in force during engineering development and is administered separately to provide its own audit trail and future costing data.

Program Focus. As noted earlier, the production phase is focused on producing and distributing identical copies of the product design. The stress is on efficiency, economy, and product quality. Automated manufacturing methods are employed where practicable. Configuration control is extremely tight.

Participants. The participants in this phase are very different from those who were involved in the development effort. Specifically, the great majority of participants in this phase are technicians, many of whom are highly skilled as automatic equipment and factory test operators. The engineering participants are chiefly concerned with process design, tool and test equipment design and calibration, quality control, factory supervision, and troubleshooting. Most are specialists in their respective disciplines. However, as stated earlier, to effect a successful transition into production, there must also be an experienced team of systems engineers guiding the process.

Problems in the Transition Process

The transition of a new system from development to production can be a particularly difficult process. Many of the associated problems can be ascribed to the factors that were first cited in Chapter 1 (i.e., advancing technology, intercompany competition, and technical specialization) as dictating the need for a special systems engineering activity. These factors are further discussed below.

Advancing Technology. It was seen that while the incorporation of technological advances in the design of new systems is often necessary to achieve the desired gain in capability and thus preclude premature obsolescence, this also incurs the risk of introducing unanticipated complications in both the development and production processes. Although the development process provides methods for the identification and reduction of performance problems, production-related difficulties are frequently not revealed until production prototypes have been fabricated and tested. By that time, remedial action is likely to cause severe and very expensive delays in production schedules. Systems engineering expertise is crucial, both for anticipating such unintended results insofar as possible and for quickly identifying and resolving those that still do unexpectedly occur.

An example of technological advances that must be considered in the transition process is that of the speed of digital processors, accompanied by reductions in size and cost. The pressure to install the latest products can be irresistible but comes at a price of changes in packaging, testing, and sometimes software revision.

Competition. Competition puts stresses on the transition process from several directions. Competition for funds often results in insufficient effort being budgeted for production preparation; moreover, it almost always eliminates the availability of reserve funding to deal with unexpected problems, which always arise in the development of complex systems. This results in too little testing of production prototypes, or delay of their fabrication until after the time that decisions on tooling, materials, and other production factors have to be made. Despite slippages in production preparation, production schedules are frequently held firm to avoid the external appearance of program problems, which are likely to cause customer concern and possibly even direct intervention. Competition for experienced staff within the organization can also result in reassignment of key engineers to a higher priority activity, even though they may have been counted on for continued commitment to the project. Competition for facilities may delay the availability of the facilities needed for the start of production. These are only examples of the competing forces that must be dealt with in managing the transition process.

Specialization. The transition from development to production also involves transfer of prime technical responsibility for the system from specialists in engineering and development to specialists in manufacturing. Moreover, at this point, the primary location of activity also shifts to the manufacturing facilities and their supporting organizations, which typically are separated physically from and managerially independent of engineering—an arrangement that can and often does severely attenuate essential communications between the engineering and production organizations. Systems engineers with some knowledge of production are frequently the only individuals who can communicate effectively between engineering and production personnel.

The above problems are rendered still more difficult by the usual dispersion of development and production of major components and subsystems among several specialized subcontractors. Coordination during the production phase in such cases is many times more complicated than during development because of the need to closely synchronize the timing and tempo of fabrication and testing with system assembly and delivery schedules. For these reasons, successful prototypes do not necessarily guarantee successful production systems.

Product Preparation

The importance of the above transition process in commercial development and production has led the National Society of Professional Engineers (NSPE) to dedicate a separate phase in their system life cycle to "commercial validation and production preparation." The engineering activities during this phase of development are stated to include the following:

- Complete a preproduction prototype.
- Select manufacturing procedures and equipment.

Demonstrate the effectiveness of

- final product design and performance;
- installation and start-up plans for the manufacturing process, selection of production tools and technology;
- selection of materials, components, and subsystem vendors and logistics; design of a field support system; and
- preparing a comprehensive deployment/distribution plan.

Either as part of the production plan or separately, other associated activities must also be defined or refined at this time. These include

- logistic support plans,
- configuration control plans, and
- document control plans and procedures.

Production Configuration Management

The forces of advancing technology, competition, and specialization all exert pressure to make changes in the engineering design of the system, especially at the component and subcomponent levels. As noted previously, new technology offers opportunities to introduce higher performance or cheaper elements (e.g., new materials, commercial off-the-shelf [COTS]). Moreover, competition presses for less costly designs, and engineers at component producers may petition to adapt designs to fit their particular production tooling. All of these factors tend to produce numerous engineering change proposals (ECPs), each of which must be analyzed and accepted, modified, or rejected. The system contractor's systems engineers play a crucial role in analyzing these proposals, planning and overseeing test efforts where required and recommending the appropriate action on change proposals. The time available for such action is very short and the stakes are very high. Intercontractual pressures often complicate the decision process.

Viewed in this light, the transition from engineering design to production is the most critical period in the configuration management process and calls for effective analytical, engineering, and communication skills on the part of systems engineers and project managers. Above all, documentation must not be allowed to lag significantly behind the change process, and all concerned must be kept in the communication loop. Systems engineering is the keeper of the integrity of the design.

It follows that the configuration management process does not stop when production begins; it continues even more intensively throughout the production process. At the beginning of production, component interface incompatibilities that have not been previously detected and eliminated (or inadvertently have been created in product design) will be revealed and must be dealt with quickly. Each incompatibility requires a decision as to whether it can be remedied in parallel with continuing production or if production should be interrupted, and if so, at what point. Because of their impact on cost and schedule, such decisions are made at management levels, but the most critical inputs are provided by systems engineering. These inputs come from close teamwork between the configuration management team and supporting systems and production engineering staffs. If, as often happens, communication between the production and engineering organization is poor, the above process will be inefficient and costly.

14.4 PRODUCTION OPERATIONS

Planning the development and evaluation of a major new system requires well thought-out and documented plans, such as the systems engineering management plan (SEMP) and the test and evaluation master plan (TEMP), which are promulgated widely to coordinate the efforts of the system development. For the same reasons, the production phase must have a formal system production plan to provide a blueprint of the organization, tasks, and schedules for system production.

Production Planning

The key elements of a production plan include the following subplans and sections:

- responsibility and delivery schedule for each major subassembly (component);
- manufacturing sites and facilities;
- tooling requirements, including special tools;
- factory test equipment;
- engineering releases;
- component fabrication;
- components and parts inspection;
- quality control;
- production monitoring and control assembly;
- acceptance test;
- packaging and shipping;
- discrepancy reports;
- schedule and cost reports; and
- production readiness reviews.

Preparation of the production plan should begin during engineering design and forms the basis for initiating production. It must be a living document and must evolve during the production process. Lessons learned should be documented and passed on to future programs. Systems engineers not only contribute to the plan but, in the process, also benefit by learning about the diverse activities that must be managed during production.

Production Organization as a Complex System

The manufacture of a new complex system typically requires the coordinated efforts of a team of contractors with extensive facilities, equipment, and technical personnel, usually distributed geographically but working to unified specifications and schedules. As in an engineered system, all these subsystems and their elements must work together effectively and efficiently to perform their collective mission—the production of units of a system of value to its users. The planning, design, implementation, and operation of this production system are tasks of comparable complexity to that required to develop the system itself.

Figure 14.3 is a schematic representation of the configuration of the facilities for producing a typical new complex system. The large blocks correspond to the engineering and production facilities of the prime contractor. The blocks on the left represent suppliers of newly developed components, while those at the top represent suppliers of standard components. The suppliers of developed components are shown to have engineering elements that operate under the technical direction of the prime contractor.

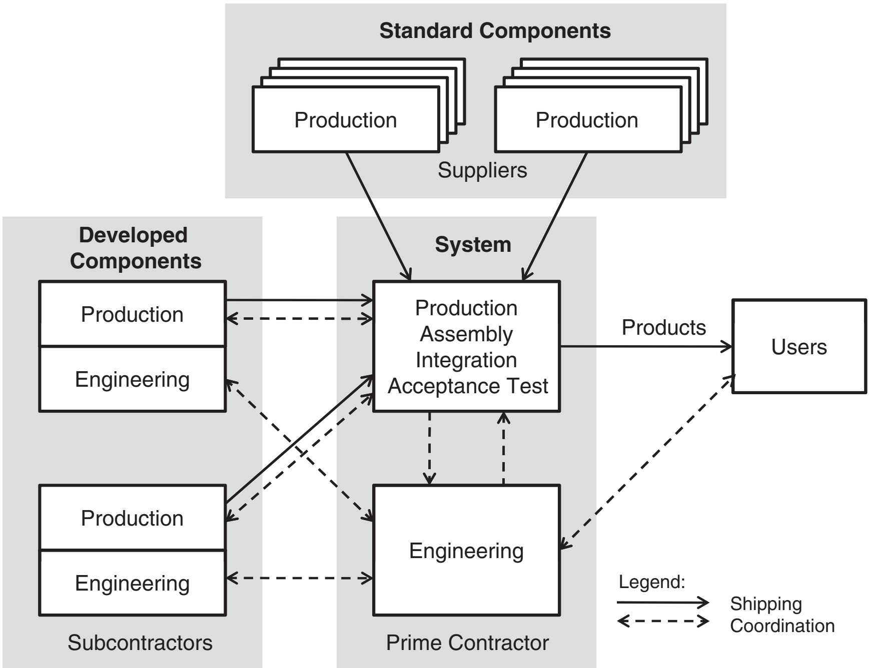

Figure 14.3. Production operation system.

Whether or not the component suppliers are owned by the prime contractor, they are to all intents separate organizations that have to be technically coordinated by the prime contractor's engineering organization. It is seen that this combination of facilities must itself be managed as an integrated system, with strict control of all of the interfaces with respect to product performance, quality, and schedule.

The overall task of bringing this entity into being is usually led by a management team assembled by the prime production contractor. While systems engineers do not lead this effort, they must be important contributors because of their broad knowledge of the system requirements, architecture, risk elements, interfaces, and other key features.

The "architecting" of the production system is complicated by a number of factors, including

1. *Advancing Technology*, especially of automated production machinery, which raises issues as to when to introduce the most recent development and into which processes; similar decisions are required on the extent and timing of introducing advanced materials;
2. *Requirement to Ensure Compatibility of New Processes with Workforce Organization and Training*—in numerous cases, technology-driven changes have resulted in decreases in productivity;

3. *Design of Communications among Distributed Production Facilities*—a balance between lack of information exchange and information overload is crucial;
4. *Factory and Acceptance Test Equipment*—in a distributed system, there must be a highly coordinated set of component test equipment that ensures identical acceptance criteria at component manufacturers and at the integration and assembly facility, as well as conformity of system-level acceptance test equipment with the integrated component tolerance structure;
5. *Manufacturing Information Management*—in any complex system, an enormous amount of data must be collected at all system levels in order to effectively govern and control the manufacturing and assembly process; the database management system required to deal with this information is a large software system in its own right and therefore requires an expert staff for its implementation and operation;
6. *Provisions for Change*—for production operations expected to extend for a period of years, the facilities need to be designed to adapt to variations in rates of production and to the introduction of design changes; many systems are first produced at low rates to validate the process on when production is stretched out for funding reasons; accommodation of the process to these changes while maintaining an efficient operation is an important goal.

All of the above problems require the application of systems engineering principles to obtain effective solutions.

Component Manufacture

We have seen that the building blocks of complex systems are components representing different specialized product lines. These are integrated from subcomponents into complete units, tested, and shipped to a system assembly plant or to spare parts distribution facilities. Thus, the manufacturing process takes place at a number of separate facilities, many of which are usually under different company managements. As noted in the previous section, the management of such a distributed operation poses special problems. An example is the necessity for extremely tight coordination between the component manufacturers and the system producer of production schedules, testing, inspection, and quality control activities. The difficulty of managing a distributed production process for a new and complex system necessitates an integrated team effort in which systems engineers play an essential role in helping to deal rapidly and efficiently with such inadvertent incompatibilities as may be encountered.

Component manufacturing is the place where most special tooling, such as automatic material forming, joining, and handling machinery, is required. The use of automation can substantially reduce the cost of production, but at the same time may involve large development costs and extensive worker training. If newly introduced, it can also cause start-up delays. Thus, the introduction of special tooling for component manufacture must be closely coordinated by the production contractor to minimize scheduling problems.

Production tolerances require special attention because they are directly affected by tooling, as well as by any minor changes that may be made to reduce production costs. Since these may affect both the ability to interface with components made by another contractor and also system performance, systems engineering oversight by the production contractor is necessary.

Usually, the company that produces a given new system component is also the one that developed it. However, the organizational separation of the company's manufacturing from its engineering operation creates the potential for mistakes in the design of production tooling and test equipment resulting from imperfect communications. Incompatibilities inadvertently introduced by design changes made in the interest of cost reduction or other worthy objectives may consequently pass unnoticed until final component testing or even until system assembly. A degree of systems engineering oversight is important, especially to ensure compatibility between the test equipment at component manufacturers and that which will be used at the integration facility for component acceptance. This should also include provisions for and periodic revalidation of common calibration standards.

The establishment of commercial standards at the part and subcomponent levels has greatly simplified many aspects of production and integration of electronic and mechanical components. Economies of scale have reduced costs and have enabled a broad degree of interchangeability, especially in component containers, mounting, and interconnections.

System Acceptance Tests

Before each production system is accepted by the customer for delivery, it must pass a formal systems acceptance test. This is usually an automated end-to-end test with go–no go indications of key system performance.

For a complex system, the design and development of suitable acceptance test procedures and equipment is a major task requiring strong systems engineering leadership. The test must determine that the requirement of ensuring that the product is properly constructed meets the key requirements and is ready for operational use. Its results must be unequivocal, regarding success or failure, and must require minimum interpretation. At the same time, the test must be capable of being performed relatively quickly without adding materially to the total cost of manufacturing. Such a balance requires the application of systems engineering judgment as to what is essential to be tested and what is not.

The system acceptance test is usually witnessed by representative(s) of the customer and is signed off on successful completion.

Manufacturing Technology

The explosive advance of modern technology has had dramatic impacts on products and the process of production. Microelectronic chips, high-speed computing devices, low-cost optics, piezoelectrics, and microelectromechanical devices are but a few of dozens of technological advances that have radically changed the composition of components and the way they are made. Even more changes in manufacturing methods and equipment have been produced by the wholesale replacement of human factory operators by automatic controls and robotics. The new methods have greatly increased speed, precision, and versatility of machining and other processes. Of comparable importance is the reduction of the time to convert a machine from one operation to another from days or weeks to minutes or hours. These changes have resulted in major economies at nearly every aspect of manufacture. They have also made it possible to produce higher-quality and more uniform components.

Prior to the widespread application of computer-aided manufacture (CAM) and component design, control of interfaces had to rely on inspection and testing using a multiplicity of special tools and fixtures. Today's computer-controlled manufacture and assembly, as well as the use of computer-based configuration management tools that can be electronically coordinated among organizations, make the management of interfaces of components built remotely far easier than in the past. However, to effectively implement this degree of automation requires planning, qualified staff, and significant funding. This, in turn, requires systems engineering thinking on the part of those organizing the production system.

14.5 ACQUIRING A PRODUCTION KNOWLEDGE BASE

For inexperienced systems engineers, the acquisition of knowledge regarding the production phase that is both broad enough and sufficiently detailed to influence effectively the development process can appear to be an especially daunting task. However, this task is basically similar to that of broadening the knowledge base in diverse engineering specialties, in the elements of program management, and in the interorganizational communications that every systems engineer must accomplish over time. Some of the most effective means for acquiring this knowledge are summarized below.

Systems Engineering Component Knowledge Base

In order to guide the engineering of a new system, systems engineers must acquire a basic level of knowledge concerning the basic design and production processes of system components. This means that systems engineers must appreciate the impact of production factors on the suitability of particular components to meet the requirements for their use in a specific system application. To make the acquisition of such a knowledge base more achievable, the following considerations may be helpful:

1. Focus on those components that use advanced technology and/or recently developed production processes. This means that attention to mature components and established production processes may be relaxed.
2. Focus on previously identified risk areas as they may affect or be affected by production.

3. For these identified risk areas, identify and establish contact with sources of expert knowledge from key in-house and contractor engineers. This will be invaluable in helping solve problems that may arise later.

The type and extent of the necessary knowledge base will vary with the system and component areas. Some examples are described below.

Electronics Components. Modern electronics is largely driven by semiconductor technology, so familiarity with the nature of circuit chips, circuit boards, solid-state memories, microprocessors, and gate arrays is necessary, though only to the level of understanding what they are, what they do, and how they should, and even more importantly, should not be used. Their development is in turn driven by commercial technology, and in many instances, their capability is multiplying according to Moore's law. It is therefore important to have a feel for the current state of the art (e.g., component densities, processor speeds, chip capabilities) and its rate of change.

Electro-optical Components. In communications and displays, electro-optical components play key roles, thanks to advances in lasers, fiber optics, and solid-state electro-optical elements. Their development is also driven by commercial applications and is advancing rapidly in the above areas.

Electromechanical Components. As their name implies, these components combine the features of electrical and mechanical devices (e.g., antennae, motors). Their characteristics tend to be peculiar to the specific application and can best be learned on a case-by-case basis.

Mechanical Components. Most applications of mechanical components are mature. However, several areas are moving rapidly. These include advanced materials (e.g., composites, plastics), robotics, and micro devices. Their design and production have been revolutionized by computer-aided engineering (CAE) and CAM.

Thermomechanical Components. Most of these components relate to energy sources and thermal controls. For this reason, safety is frequently a key issue in their system applications, as is the related function of control.

Software Components. Software, and embedded firmware derived from it, is rapidly becoming part of virtually every device (e.g., communications, transportation, toys). The process of designing and producing reliable software is also advancing as rapidly. The production aspects of software and firmware are of course very different from hardware. Every systems engineer should understand the general capabilities, including the advantages and limitations, of software quality and software design and implementation, as well as the basic differences between computer-based software and firmware. Software is treated in greater depth in Chapter 11.

Production Processes

Production processes are not the responsibility of systems engineers. Nevertheless, the general nature of these processes and typical problems associated with them must be understood by systems engineers to give them the knowledge to resolve problems that occur in production, especially during start-up.

Observing Production Operations. The factory floor is often the most illuminating source of insight concerning the manufacturing process, especially when observation is supplemented by questioning factory personnel. Opportunities to observe production operations occur naturally during site visits, production planning, and other activities, but these are seldom adequate to provide even a superficial understanding of manufacturing processes. Systems engineers should endeavor to schedule special factory tours to acquire a first-hand feel of how the factory operates. This is especially important because of the rapid advances in manufacturing tools and processes brought about by increasing automation. Because the initial production of new components is likely to run into problems with tools, processes, materials, parts availability, quality control, and so on, it is important to develop a feel for the nature of the associated activities and possible means for problem resolution. Of course, the best opportunity to learn production processes is a short assignment in the manufacturing organization.

Production Organization. It has been previously noted that the organization and management of the production process of a major system is different from the organization and management of the system development process. It is important for systems engineers to be acquainted with the differences, both generically and for the specific system under development. While this is of most immediate concern for program management, it strongly influences how the transition from engineering to production should be planned, including the transfer of design knowledge from design engineers to production engineers. In particular, in many companies, the communications between engineering and production personnel are often formal and largely inadequate. When this is the case, company management should provide special means to establish adequate communication across this critical interface—a function in which systems engineers can play a leadership role. Failure to bridge this potential communication gap properly has been a major contributor to critical delays and near failures in the production of numerous major systems.

Production Standards. Virtually all types of manufacturing are governed by industry or government standards. The U.S. government is replacing most of its own standards by those developed by industry, as well as moving to utilize COTS parts and components insofar as is practicable. These standards are primarily process oriented and define all aspects of production. Systems engineers must be familiar with the standards that are applicable to components and subsystems in their own system domain and with the way in which these standards are applied to the manufacturing process. These standards are often indicative of the quality of the components that are likely to be produced, and hence of the degree to which oversight, special testing, and other management measures will be required. While the decisions regarding such actions are the responsibility of program management, systems engineering judgment is a necessary ingredient.

14.6 SUMMARY

Systems Engineering in the Factory

The objectives of the production phase are to produce sets of identical hardware and software components, to assemble components into systems meeting specifications, and to distribute produced systems to customers.

Essential requirements are that the produced system performs as required, is affordable, and functions reliably and safely as long as required.

Engineering for Production

Concurrent engineering, or product development, has the following features: it is the process of introducing production considerations during development. Production specialists and other specialty engineers are key members of the design team. Therefore, systems engineers must facilitate communications among team members.

The decision to begin new system development must demonstrate its need, technical feasibility, and affordability. The formulation of realistic system requirements must include a clear sense of the status and trend in manufacturing technology. As technology evolves, requirements must also evolve to stay consistent.

Production risks are influenced by the nature and maturity of the associated manufacturing methods and are heavily weighted in trade-off analyses of system alternatives.

Successful production requires that new production processes and materials are validated before acceptance, that component interfaces are compatible with manufacturing processes, and that factory test equipment is validated and ready. The latter is typically demonstrated by production prototypes that have demonstrated product performance.

Unexpected incompatibilities at component interfaces have the following features:

- They are often first discovered during the integration of prototype components.
- Corrections of incompatibilities may themselves produce new areas of incompatibility.

Systems engineers must be knowledgeable of factory production and test acceptance processes. Direction and control of production differs from system development in the following: (1) different tools, experience base, and skills; and (2) a different team of specialists—few key personnel carry over from development.

Production risks are frequently not revealed until production prototypes are fabricated and tested. Remedial action is likely to cause expensive delays; therefore, systems engineering expertise is crucial for resolution.

Transition from Development to Production

Stresses on the transition from development to production result from

- insufficient funding for production preparation,
- little or no reserve funds for unexpected problems,
- too little testing of production prototypes, and
- schedules held firm even though problems exist.

The transition to production is a most critical period for continuity of operations and features must be recognized. The transition transfers responsibility from development to manufacturing specialists. And manufacturing facilities are typically separate and independent of engineering. Therefore, communication is difficult between engineering and production personnel. Consequently, systems engineers are needed for facilitating communications. Finally, a system production plan is required as a blueprint for transition.

The transition to production is critical to the configuration management process because documentation cannot lag behind the change process; systems engineering is the keeper of the integrity of the design.

Production Operations

The planning, design, implementation, and operation of a "production system" is a task of comparable complexity to developing the system itself. Architecting of the production system requires

- acquisition of extensive tooling and test equipment,
- coordination with component manufacturing facilities,
- organization of a tight configuration management capability,
- establishment of an effective information system with enginery organization,
- training the production staff in the use of new tooling,
- accommodation of both low and high production rates, and
- promotion of flexibility to accommodate future product changes.

Specialized components often represent different product lines and pose special problems. Tight coordination is needed between component manufacturing and system producers, in production schedules, testing, inspection, and quality control. Establishment of commercial standards at the part and subcomponent levels leads to greatly simplified production and integration of components.

Computer-controlled manufacturing methods greatly increase speed, precision, and versatility of factory operations. They reduce time to reconfigure machines between operation modes, and produce higher-quality parts and more uniform components. This often leads to major cost savings.

Acquiring a Production Knowledge Base

Systems engineers must acquire a basic knowledge concerning production processes to be capable of guiding the engineering of a new system. They must focus on advanced technology and new production processes, as well as risk areas as they may be affected by production.

PROBLEMS

14.1 Because complex systems contain a large number of subsystems, components, and parts, it is usually necessary to obtain a significant number of them from outside subcontractors and vendors. In many cases, it is possible to make these items either in-house or procure them elsewhere. Both approaches have advantages and disadvantages. Discuss the main criteria that are involved in deciding which approach is best in a given case.

14.2 One of the requirements of a good systems engineer who is engaged in developing systems which have significant components that are manufactured is that he or she be knowledgeable about factory production and acceptance test processes. Give two examples that illustrate the importance of this knowledge in achieving on-time delivery of the final product.

14.3 Configuration management is particularly important during the transition from system development to production. Identify four specific areas where close attention to configuration management is crucial during this phase transition and explain why.

14.4 Discuss how the planning, design, implementation, and operation of a production system is a task of comparable complexity to that required to develop the actual system itself.

14.5 Describe the process referred to as concurrent engineering, its objectives, use of interdisciplinary integrated product teams (IPTs), and its place in the system life cycle. Describe the role of systems engineers on the teams. Describe what problems you would expect to be encountered in assembling an IPT and in making its effort productive and how they might be handled.

14.6 Discuss four typical problems that make the transition from development to production difficult and the approaches to minimizing them.

14.7 Production is typically the responsibility of a division of a company independent of the development organization. It has been stated that the transition to production and the production process itself requires systems engineering expertise in certain critical areas. List some instances where systems engineering expertise in the production organization is required in the production of medical devices (e.g., implantable pacemakers).

14.8 Discuss the principal areas in which CAM has revolutionized the manufacture of automobiles.

FURTHER READING

B. Blanchard and W. Fabrycky. *System Engineering and Analysis*, Fourth Edition. Prentice Hall, 2006, Chapters 16 and 17.

G. E. Dieter and L. C. Schmidt. *Engineering Design*, Fourth Edition. McGraw-Hill, 2009, Chapter 13.

International Council on Systems Engineering. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, INCOSE-TP-2003-002-03.2, Sections 4 and 9. July, 2010.

Systems Engineering Fundamentals. Defense Acquisition University (DAU Press), 2001, Chapter 7.