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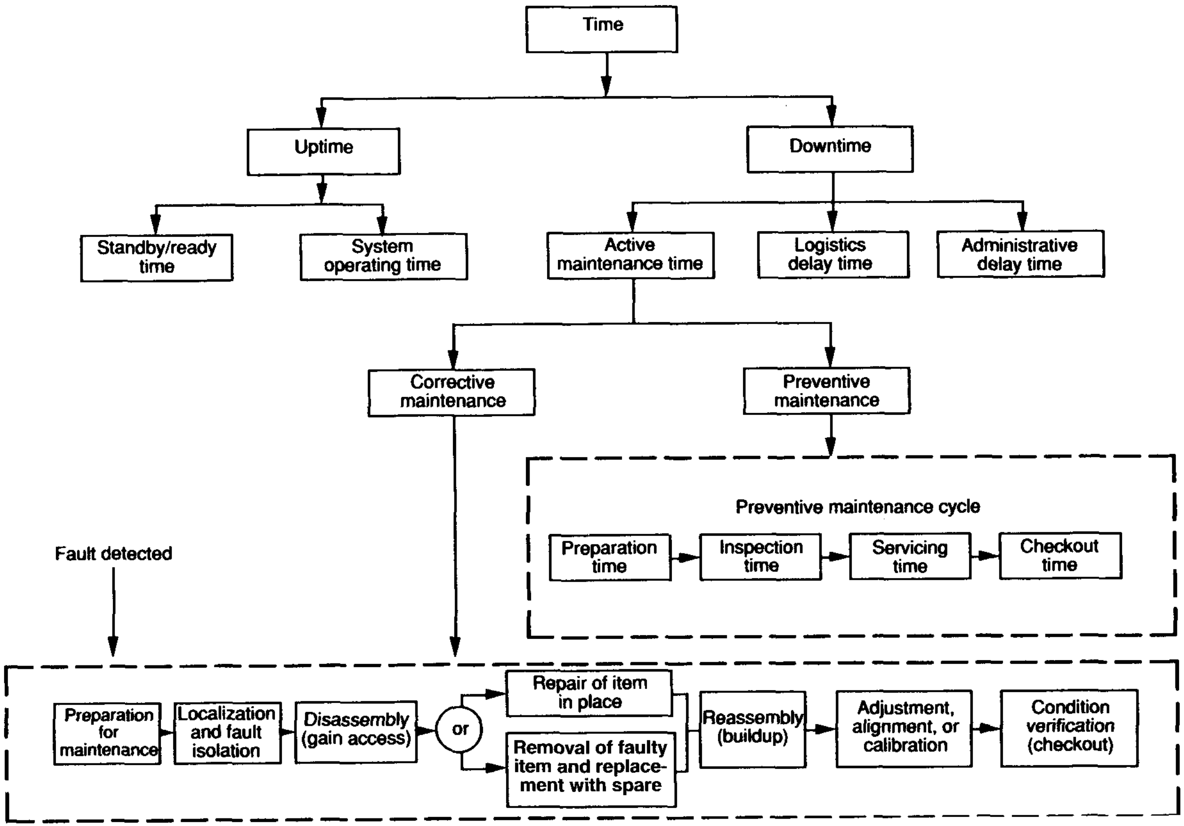


Figure 3.17 Time relationships.

1. *Active maintenance time* ($\bar{M}$): That portion of downtime when corrective and/or preventive maintenance activities are being accomplished. This factor is often expressed as

$$\bar{M} = \frac{(\lambda)(\bar{M}ct) + (fpt)(\bar{M}pt)}{\lambda + fpt} \tag{3.12}$$

   where $\bar{M}$ is the mean active maintenance time, $\bar{M}ct$ is the mean corrective maintenance time, $\bar{M}pt$ is the mean preventive maintenance time, fpt is the frequency of preventive maintenance, and λ is the failure rate (or frequency of corrective maintenance).

2. *Logistics delay time* (LDT): That portion of downtime when the system is not operational because of delays associated with the support capability; for example, waiting for a spare part, waiting for the availability of test equipment, waiting for the use of a special facility.

3. *Administrative delay time* (ADT): That portion of downtime when the necessary maintenance is delayed for reasons of an administrative nature; for example, the unavailability of personnel because of other priorities, organizational constraints, labor strikes.

In looking at these elements of downtime from the design engineer's perspective, it is quite common to address only the *active* maintenance segment (i.e., $\bar{M}$). This is because of being able to directly relate system characteristics such as diagnostic capability, accessibility, and interchangeability to downtime. The producer (i.e., contractor) is responsible for, and usually can control, this element, whereas the LDT and ADT factors are primarily influenced by the consumer (i.e., customer). From the perspective of system engineering, one needs to deal with the *entire* downtime spectrum. There is little point in constraining the design of prime equipment (i.e., an item must be designed so that it can be repaired in 30 minutes) if the support capability is such that it takes three months to acquire the necessary spare part. In essence, the entire spectrum must be considered as reflected in Figure 2.4, and each of these time elements represents an important measure.

By referring to the time relationships presented in Figure 3.17, as well as the factors in Equation (3.12), active maintenance time ($\bar{M}$) can be broken down into corrective maintenance and preventive maintenance times. The mean corrective maintenance time ($\bar{M}ct$) is expressed as

$$\bar{M}ct = \frac{\Sigma(\lambda_i)Mct_i}{\Sigma(\lambda_i)} \tag{3.13}$$

where Mct_i represents the time that it takes to progress through the corrective maintenance cycle illustrated in Figure 3.17 (for the ith item), and λ_i is the corresponding failure rate. In the event of a fixed number of maintenance actions, n, then

$$\overline{\text{M}}\text{ct} = \frac{\sum_{i=1}^{n} \text{Mct}_i}{n} \tag{3.14}$$

$\overline{\text{M}}$ct, which is a weighted average of repair times using reliability factors, is equivalent to the mean time to repair (MTTR), a measure that is commonly used for maintainability.

The time-dependency relationship between the probability of corrective maintenance and the time allocated for accomplishing corrective maintenance can be expected to produce a probability density function in one of three common forms, as illustrated in Figure 3.18:

1. *The normal distribution:* Applies to relatively simple and common maintenance actions where times are fixed with very little variation
2. *The exponential distribution:* Applies to maintenance actions involving part substitution methods of fault isolation in large systems that result in a constant failure rate
3. *The log-normal distribution:* Applies to most maintenance actions involving detailed tasks with unequal frequency and time durations

Experience has indicated that in most instances, the distribution of maintenance times for complex systems follows the log-normal approximation. From Figure 3.18, the key maintainability parameters are the mean time to repair (Point 1), the median time to repair (Point 2), and the maximum time to repair (Point 3). Whereas the "mean" value constitutes the measure that is most commonly used, the median and maximum time values are appropriate measures used in certain applications.

The median active corrective maintenance time ($\widetilde{\text{M}}$ct) is that value that divides all of the repair-time values so that 50% are less than the median and 50% are greater than the median. For the normal distribution, the median is the same as the mean, and the median in the log-normal distribution is the same as the geometric mean (MTTR_g) illustrated in Figure 3.18. The median, represented by Point 2, is calculated as

$$\widetilde{\text{M}}\text{ct} = \text{antilog} \frac{\Sigma(\lambda_i)(\log \text{Mct}_i)}{\Sigma(\lambda_i)} = \text{antilog} \frac{\sum_{i=1}^{n} \log \text{Mct}_i}{n} \tag{3.15}$$

The maximum active corrective maintenance time (M_{max}) can be defined as that value of downtime below which a designated percent of all maintenance actions can be expected to be completed. This is represented by Point 3 in Figure 3.18. Selected points, in the log-normal distribution, at the 90th or 95th percentile are generally used. The maximum corrective maintenance time is expressed as

$$\text{M}_{\text{max}} = \text{antilog}\,[\overline{\log \text{Mct}} + Z\sigma_{\log}\text{Mct}_i] \tag{3.16}$$

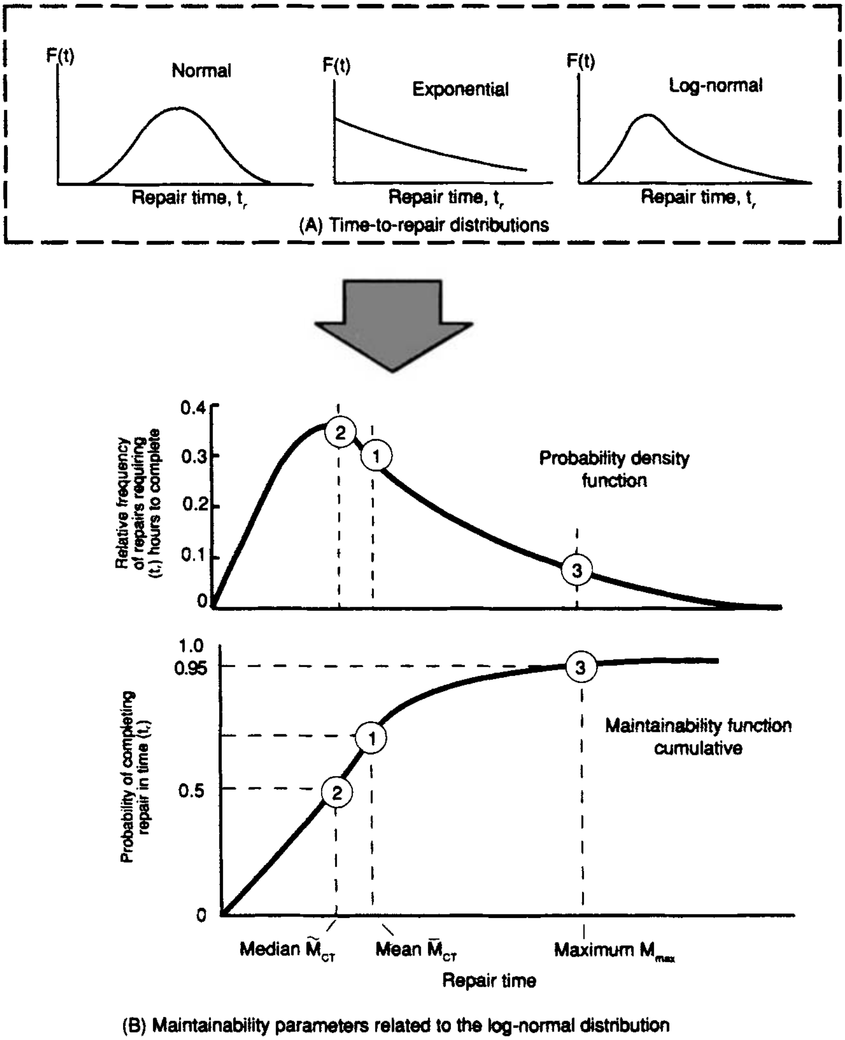


Figure 3.18 Maintainability distributions.

where $\overline{\log \text{Mct}}$ is the mean of the logarithms of Mct_i, Z is the standard variate at the point where M_{max} is defined (1.65 at 95%, 1.28 at 90%, 1.04 at 85%, and so on); refer to the normal distribution tables in any text on statistics), and σ is the standard deviation of the sample logarithms of average repair times, Mct_i.

In the area of preventive maintenance, both the mean and the median measures are used. The mean preventive maintenance time ($\overline{\text{M}}\text{pt}$) can be determined by

$$\overline{\text{M}}\text{pt} = \frac{\Sigma(\text{fpt})(\text{Mpt}_i)}{\Sigma(\text{fpt}_i)} = \frac{\sum_{i=1}^{n} \text{Mpt}_i}{n} \tag{3.17}$$

where fpt_i is the frequency of the individual (ith) preventive maintenance action and Mpt_i is the associated elapsed time to perform the preventive maintenance required.

The median value for preventive maintenance, like the requirement for corrective maintenance specified in Equation (3.15), is determined from

$$\widetilde{\text{M}}\text{pt} = \text{antilog}\,\frac{\Sigma(\text{fpt}_i)(\log \text{Mpt}_i)}{\Sigma(\text{fpt}_i)} \tag{3.18}$$

Preventive maintenance may be accomplished while the system is in full operation, or the requirements for such may result in downtime. In this instance (and in the case of corrective maintenance), only those actions that are accomplished and result in downtime are considered. Maintenance actions that do not result in system downtime are basically accounted for through the personnel labor-hour and maintenance cost measures of maintainability.[23]

Although the various measures of elapsed time are extremely important, one must also consider the maintenance labor hours expended in the process. In dealing with ease and economy in the performance of maintenance, an objective is to obtain the proper balance between elapsed time, labor hours, and personnel skills at minimum maintenance cost. Personnel time may be expressed in terms of maintenance labor hours per system operating hour (MLH/OH), maintenance labor hours per cycle of system operation (MLH/cycle), maintenance labor hours per maintenance action (MLH/MA), or maintenance labor hours per month (MLH/month). Any of these factors can be presented in terms of mean values, such as mean corrective maintenance labor hours ($\overline{\text{MLH}}_c$), which can be expressed as

$$\overline{\text{MLH}}_c = \frac{\Sigma(\lambda_i)(\text{MLH}_i)}{\Sigma(\lambda_i)} \tag{3.19}$$

where λ_i is the failure rate of the ith item and MLH_i is maintenance labor hours necessary to accomplish the related corrective maintenance actions.

The aspect of corrective maintenance having been established, the values for mean preventive maintenance labor hours and mean total maintenance labor hours (to include *all* corrective and preventive maintenance actions) can be determined in a similar manner. These factors, predicted for each level of maintenance identified in the system maintenance concept, can be utilized in determining specific maintenance and logistic support requirements and associated costs.

A third measure of maintainability (in addition to the time and labor-hour factors) is maintenance frequency. As indicated in Section 3.4.2, the frequency factors associated with primary and secondary failures are basically reflected through the relia-

[23]Although maintainability has already been defined in the broadest context, there are additional definitions that relate to a specific measure. With regard to time, it can be defined as the measure of the ability of an item to be retained in or restored to a specified condition when maintenance is performed by personnel having specified skills, using prescribed procedures and resources, at each prescribed level of maintenance and repair.

bility MTBF and λ measures. These measures are certainly important for determining the overall frequency of unscheduled maintenance; however, there are additional considerations such as manufacturing defects, operator-induced failures, maintenance-induced failures, and defects due to handling that may be relevant (refer to footnote 20 in this chapter). Moreover, one must consider the aspect of preventive maintenance. With this in mind, it is appropriate to look at the total spectrum of maintenance and the measure of mean time between maintenance (MTBM). This can be calculated as

$$\text{MTBM} = \frac{1}{1/\text{MTBM}_u + 1/\text{MTBM}_s} \tag{3.20}$$

where MTBM_u is the mean interval of unscheduled (or corrective) maintenance, and MTBM_s is the mean interval of scheduled (preventive) maintenance. The reciprocals of MTBM_u and MTBM_s are equivalent to the maintenance rates, or the maintenance actions per hour of system operation. MTBM_u should be equivalent to MTBF, assuming that the possibilities of operator-induced defects, maintenance-induced defects, and so on, have been "designed out" of the system.

Within the overall spectrum of activity represented by the MTBM factor, there are some maintenance actions that result in the removal and replacement of components and the requirement for spare parts. These actions, in response to both corrective and preventive maintenance requirements, can be measured in terms of mean time between replacement (MTBR), a factor of MTBM. In essence, the MTBM factor reflects *all* maintenance actions, some of which result in item replacements.

Figure 3.19 shows a given system where there were 100 unscheduled maintenance actions recorded over a specific segment of time. In all instances, some organizational-level maintenance was accomplished relative to diagnostics and checkout. In 25 cases, it was impossible to verify that a problem existed, as the system appeared to be operating properly when checked. Therefore, no items were removed and replaced. In the other 75 instances, a given component was suspect, resulting in a removal and replacement action. Of the components removed for higher-level maintenance (i.e., intermediate level), a problem was verified in 45 instances and repair was accomplished on-site, 12 components were sent to the factory for higher-level repair, 3 components were condemned (determined to be beyond economic repair), and there were 15 components in which no defect was noted. Of the 12 components sent to the factory, 10 were considered faulty. Through a review of these factors, it can be seen that the MTBM figure must consider all of the 100 maintenance actions, the MTBR figure can be related to the 75 replacements (at the organizational level), and the MTBF measure (as defined in a puristic reliability sense) pertains to the 58 components in which actual catastrophic failures were confirmed. From a *systems* perspective, however, there were 100 failures in total, whether they can be charged to an element of equipment, a module of software, or to a human being.

Given the definitions associated with MTBM, MTBR, MTBF, MDT, $\overline{\text{M}}\text{ct}$, $\overline{\text{M}}\text{pt}$, $\overline{\text{M}}$, and so on, it is important to relate some of these figures of merit to a higher-order system parameter. Reliability and maintainability factors, shown in Figure 2.25, are, for

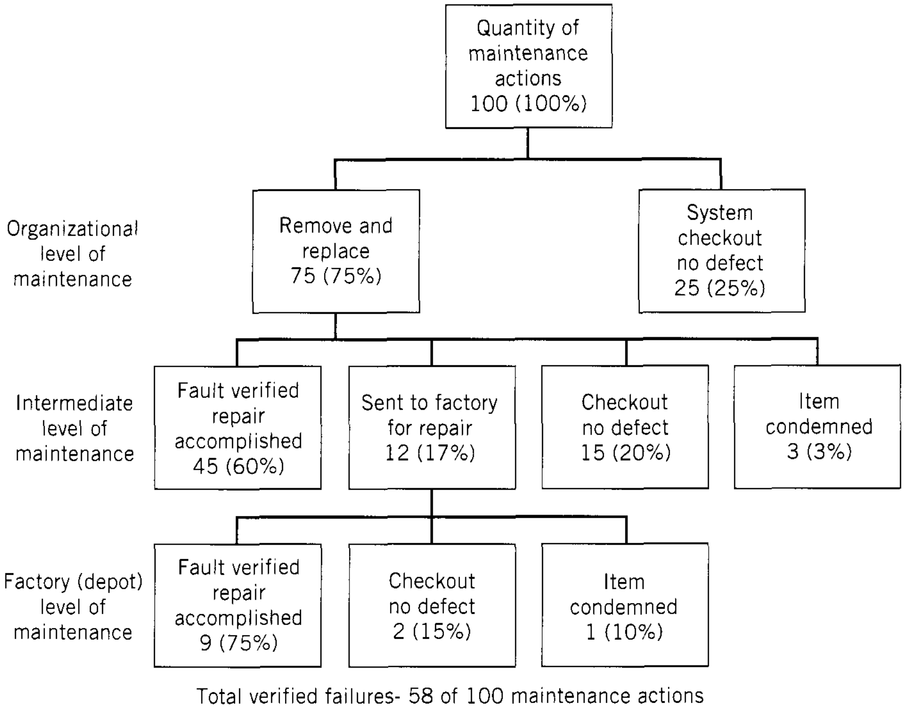


Figure 3.19 System XYZ unscheduled maintenance actions.

example, key inputs in determining system availability which, in turn, is a major element of system effectiveness. Although the specific measures may vary significantly from one system application to the next, "availability" is used quite often as a system measure. Availability can be expressed as follows:

$$A_o = \frac{\text{MTBM}}{\text{MTBM} + \text{MDT}} = \frac{\text{uptime}}{\text{uptime} + \text{downtime}} \tag{3.21}$$

where A_o is operational availability. This definition of availability relates to the consumer's operational environment where MTBM reflects *all* maintenance requirements and MDT represents *all* downtime considerations. In instances in which a producer is responsible for designing a system to meet a certain availability requirement, and the producer has no influence or control of the consumer's support structure, it may be appropriate to define availability as

$$A_a = \frac{\text{MTBM}}{\text{MTBM} + \bar{\text{M}}} \tag{3.22}$$

where A_a is achieved availability. It should be noted that the LDT and ADT factors are not considered here. Progressing one step further, there are instances in which availability is defined as

$$A_i = \frac{\text{MTBF}}{\text{MTBF} + \overline{\text{M}}\text{ct}} \tag{3.23}$$

where A_i represents inherent availability. Note that preventive maintenance is not included here. Employing this figure of merit as a system measure may be appropriate from a contractual standpoint where the producer is somewhat isolated from the consumer environment. However, in dealing with system engineering requirements, the A_o factor is more relevant than either the A_a or A_i factor.

Figure 1.3 and 2.25 show two sides of the balance. The reliability and maintainability factors described herein are significant contributors (along with performance) in measuring the *technical* effectiveness of the system. Reliability and maintainability parameters are combined to determine availability, and system availability constitutes a major input in determining system effectiveness. At the other end of the balance is life-cycle cost (LCC). LCC is a function of research and development cost, production/construction cost, operation and support cost, and retirement and disposal cost. The consequences of reliability and maintainability have a direct impact on each of these major cost categories. However, the greatest impact of these design characteristics is on operational and support costs, where the frequency of maintenance and downtime factors are significant in determining the overall support capability for the system. If these characteristics are not appropriately considered in system design, the "iceberg" effect illustrated in Figure 1.4 will likely prevail.

The material presented to this point is intended to provide a familiarization with the terms and definitions associated with maintainability. Maintainability is one of the many disciplines requiring consideration within the overall context of system engineering. A general understanding of the subject is necessary, as well as some familiarity with the activities that are usually undertaken in the performance of a typical maintainability program. Some key terms and definitions have been covered; it is now appropriate to describe related program activities.[24]

In implementing a maintainability program for a typical large-scale system, the tasks identified in Figure 3.20 are generally applicable. Although there are variations from one situation to the next, the performance of these tasks in terms of overall program phasing is assumed to be in accordance with Figure 3.21. The major program phases and system-level activities are derived from the baseline presented in Figure 1.12 (Chapter 1).

In Figure 3.20, the maintainability program tasks listed can be categorized under (1) program planning, management, and control (Tasks 1–4), (2) design and analysis (Tasks 5–12), and (3) test and evaluation (Task 13). The first category of tasks

[24]Although specific maintainability tasks should be tailored to the system and associated program needs, the tasks listed in Figure 3.20 are assumed to be typical for the purposes of discussion.

Program Task	Task Description and Application
1. Maintainability Program Plan	To develop a maintainability program plan that identifies, integrates, and assists in the implementation of all management tasks applicable in fulfilling maintainability program requirements. This plan includes a description of the maintainability organization, organizational interfaces, a listing of tasks, task schedules and milestones, applicable policies and procedures, and projected resource requirements. This plan must tie directly into the System Engineering Management Plan (SEMP).
2. Review and control of suppliers or subcontractors	To establish initial maintainability requirements and to accomplish the necessary program review, evaluation, feedback, and control component supplier/subcontractor program activities. Supplier program plans are developed in response to the requirements of the overall Maintainability Program Plan for the system.
3. Maintainability program reviews	To conduct periodic program and design reviews at designated milestones; (e.g., conceptual design review, system design reviews, equipemnt/software design reviews, and critical design review). The objective is ensure that maintainability requirements will be achieved.
4. Data collection, analysis, and corrective-action system	To establish a closed-loop system for data collection, analysis, and the initiation of recommendations for corrective action: The objective is to identify potential maintainability design problems.
5. Maintainability modeling	To develop a maintainability model for making initial numerical allocations, and for subsequent estimates to evaluate system/component maintainability. As design progresses, maintainability top-down functional block diagrams, logic troubleshooting flow diagrams, and so on, are developed and are used as a basis for accomplishing periodic predictions, logistic support analysis, and testability analysis. These should evolve directly from the system-level maintenance functional flow block diagrams.
6. Maintainability allocation	To allocate, or apportion, top system-level requirements to lower indenture levels of the system (e.g., subsystem, unit, assembly). This is accomplished to the depth necessary to provide specific criteria as an input to design.
7. Maintainability prediction	To estimate the maintainability of a system (or components thereof) based on a given design configuration. This is accomplished periodically throughout the system design and development process to determine whether the initially specified system requirements are likely to be met given the proposed design at that time.
8. Failure mode, effect, and criticality analysis (FMECA)—maintainability information	To identify potential design weaknesses through a systematic analysis approach considering all possible ways in which a component can fail (the modes of failure), the possible causes for each failure, the likely frequency of occurrence, the criticality of failure, the effects of each failure on system operation (and on various system components), and any corrective action that should be initiated to prevent (or reduce the probability of) the potential problem from occuring in the future. The objective is to determine maintainability design requirements as a result of anticipated corrective and/or preventive maintenance needs. Refer to Case Study B.1, Appendix B.
9. Maintainability analysis	To accomplish various design-related studies pertaining to equipment packaging schemes, fault-isolation and diagnostic provisions, built-in test versus external test equipment, levels of repair, component standardization, producibility considerations, and so on. Maintainability mathematical models, level-of-repair analysis models, and life-cycle cost analysis models are utilized as required.
10. Maintenance task analysis (MTA)	To evaluate design data and determine weaknesses relative to the maintainability characteristics incorporated in the design, and to determine the maintenance and support resources required for the system. Refer to Case Study B.4, Appendix B.
11. Level-of-repair analysis (LORA)	To evaluate system components to determine whether it is more economical to repair the item or to discard it in the event of failure. Refer to Case Study B.5, Appendix B.
12. Maintainability data for the detailed maintenance plan and the supportability analysis (SA)	To identify and prepare maintainability data as they apply to the various elements of logistic support—spare and repair parts, test and support equipment, personnel quantities and skill levels, training, facilities, technical manuals, and software.
13. Maintainability demonstration	To plan and implement a program where testing is accomplished (either sequential testing or a "fixed" sample size), using a preproduction prototype and considering statistical "accept" and "reject" criteria, to measure the maintainability characteristics of the system. These characteristics may include $\overline{M}ct$, MLH/OH, $\overline{M}pt$, or equivalent. This test is accomplished prior to entering production.

Figure 3.20 Maintainability engineering program tasks.

must be closely integrated with system engineering activities and reflected in the SEMP. The second group of tasks constitutes tools used in support of the mainstream design engineering effort, in response to maintainability program requirements included in the system specification and the program plan. The third area of activity, maintainability demonstration, must be integrated with system-level testing activities

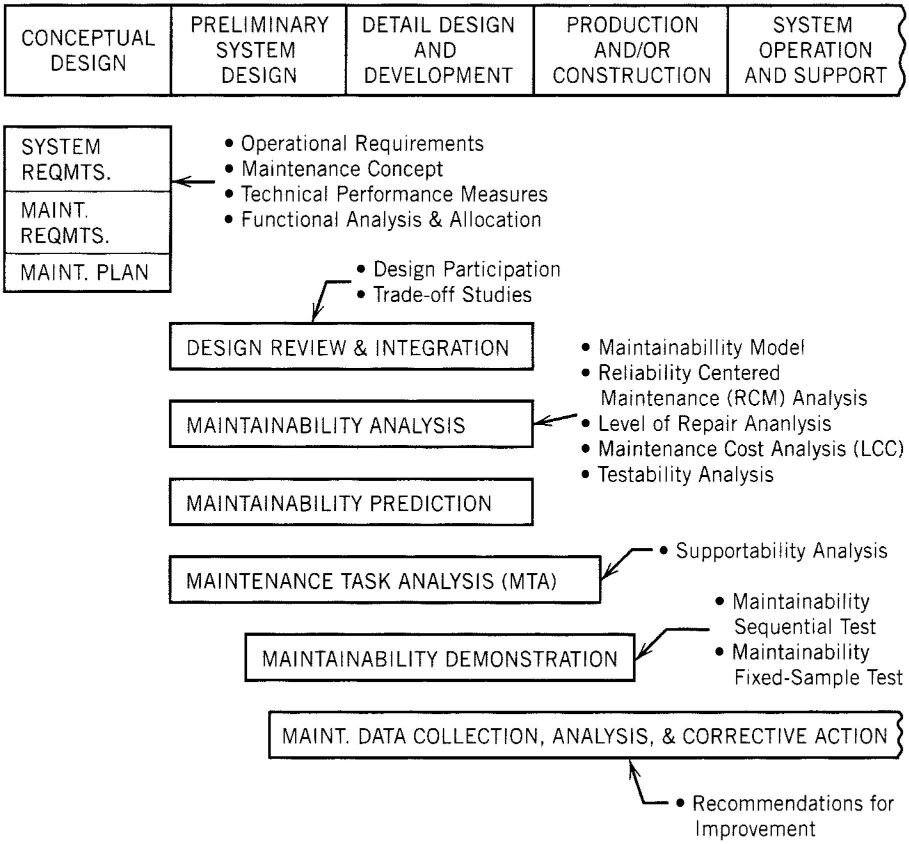


Figure 3.21 Maintainability tasks in the system life cycle.

and covered in the TEMP. Although these tasks are primarily in response to maintainability program requirements, there are many interfaces with basic design functions and with other supporting disciplines such as reliability and logistic support.

Although brief task descriptions are included in Figure 3.20, some additional comments, as they pertain to a select few, are provided for purposes of emphasis.

1. *Maintainability Program Plan:* Although the requirements for a maintainability program may specify a separate and independent effort, it is *essential* that the program plan be developed as part of, or in conjunction with, both the Reliability Program Plan (refer to Figure 3.14, Task 1) and the SEMP. Organizational interfaces, task input-output requirements, schedules, and so on, must be integrated with reliability program requirements and must be directly supportive of system engineering activities. Moreover, maintainability activities must be closely integrated with human factors and logistic support functions and must be included in the respective plans for these program areas. The SEMP is introduced in Section 1.4 (refer to Figure 1.26) and is described further in Chapter 6.

2. *Maintainability modeling:* The completion of this task, along with several others (e.g., allocation, prediction, FMECA, maintainability analysis), depends on the development of functional-level diagrams, similar to the one presented in Figure 3.22. These diagrams should evolve directly from, and must support, the system functional analysis and associated functional flow diagrams described in Section 2.7 (refer to Figures 2.11 to 2.16). The objective is to illustrate system packaging concepts, diagnostic capabilities (depths of localization and fault isolation), items that are repaired in place or removed for maintenance, and so on. The results of this task constitute a major input to the maintenance task analysis (MTA) and the supportability analysis (SA) and must be provided in a timely manner.

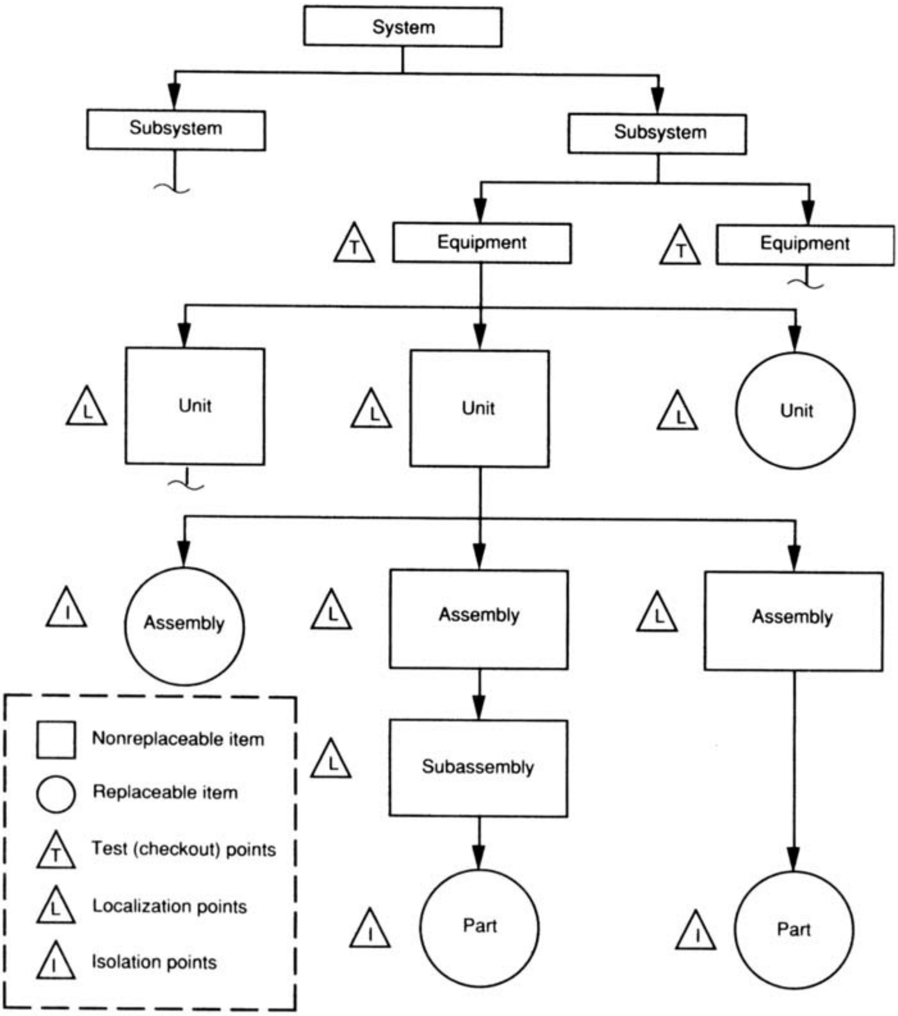


Figure 3.22 System/decomposition for maintainability analysis and prediction.

3. *Failure mode, effect, and criticality analysis* (FMECA): FMECA, as it applies to maintainability, is primarily used as an aid in the development of system packaging schemes and diagnostic routines and is employed to assist in determining critical preventive maintenance requirements. This task should be closely integrated with reliability and logistics activities, because the FMECA is also a required task in these program areas. Case Study B.1, Appendix B, describes the FMECA process.

4. *Maintainability analysis:* This includes the accomplishment of many different design-related studies dealing with system functional packaging concepts, levels of diagnostics, levels of repair, built-in versus external test, and so on. It must be accomplished in conjunction with the FMECA and maintainability modeling, and it must be coordinated with logistic support analysis (LSA) requirements. The LSA also requires a level-of-repair analysis and life-cycle cost analysis in fulfilling the requirements related to the design for supportability. Case Study B.6, Appendix B, describes an evaluation of alternative design configurations accomplished in support of a maintainability analysis effort.

5. *Maintenance task analysis* (MTA): This includes a detailed analysis and evaluation of the system to (a) assess a given configuration relative to the degree of incorporation of maintainability characteristics in design and compliance with the initially specified requirements and (b) to determine the maintenance and logistic support resources required to support the system throughout its planned life cycle. Such resources may include maintenance personnel quantities and skill levels, spares and repair parts and associated inventory requirements, tools and test equipment, transportation and handling requirements, facilities, technical data, computer software, and training requirements. Such an evaluation may be accomplished during the preliminary and detail design phases utilizing available design data as the source of information and/or through a review and assessment of an existing item using checklists as an aid. An MTA may be conducted on a commercial off-the-shelf (COTS) item in the event that the maintenance resource requirements have not already been identified. This task should be closely coordinated with human-factors activities (i.e., the operator task analysis and the development of operational sequence diagrams) and with logistics activities (i.e., the MTA is an integral part of the logistic support analysis effort). Case Study B.4, Appendix B, includes an abbreviated example of the results of an MTA.[25]

6. *Level-of-repair analysis* (LORA): This includes an evaluation of various system components to determine whether it is economically feasible to repair an item or to discard it in the event of failure. If repair is to be accomplished, should the component be repaired at the intermediate level or at the factory (i.e., depot)? A LORA may be performed initially, in the development of the system maintenance concept, to provide design guidelines for packaging, diagnostics, and so on, and later in the evaluation of a given design configuration to determine maintenance resource re-

[25]A more in-depth presentation of the MTA, its content, and the procedure for accomplishing such is included in B. S. Blanchard, *Logistics Engineering and Management*, 5th ed. (Upper Saddle River, NJ: Prentice-Hall, 1998).

quirements. The LORA should be performed in conjunction with the MTA and as part of the logistic support analysis effort. Case Study B.5, Appendix B, includes an example of the LORA process.

7. *Maintainability demonstration:* This task, usually performed as part of Type 2 testing, should be defined in the context of the *total* system test and evaluation effort. The objective of maintainability demonstration is to simulate different maintenance task sequences, record the associated maintenance times, and verify the adequacy of the resources required to support the demonstrated maintenance activities (e.g., spare/repair parts, support equipment, software, personnel quantities and skills, and data). The results from this activity should not only determine whether maintainability requirements have been met, but should also help to determine whether the supportability objectives have been met in response to logistic support requirements. Maintainability demonstration requirements must be covered in the TEMP.

In summary, the tasks identified in Figure 3.20 are generally performed in response to some detailed specification or program requirement. Like reliability tasks, these tasks are completed on a relatively independent basis for many programs. Yet the interfaces are numerous, and there are some excellent opportunities for task integration, resulting in reduced program costs. Figure 3.23 conveys an example of the relationships between selected reliability and maintainability tools. As one progresses further through this text, the opportunities for integration will become even more apparent. The intent of this section is to provide an introduction to the requirements associated with most maintainability programs.

3.4.4 Human Factors Engineering[26, 27]

Quite often in the development of a system, the emphasis is on the design of hardware and software and the *human* element tends to be ignored. For a system to be complete, the human being and the interfaces between the human and the other elements of the system (e.g., equipment, software, facilities, data, elements of support) must be addressed. Optimum hardware or software design alone will not guarantee effective results.

The requirements for the "human" (i.e., operator, maintainer, supporting personnel) stem from the functional analysis, along with the requirements for hardware, software, and so on (see Figure 1.13). From this point, operational and maintenance functions are broken down into job operations, duties, tasks, subtasks, and task elements, as illustrated in Figure 3.24. Through subsequent analyses, the various activ-

[26]The objective is to provide an introduction to human factors (or human engineering), but not to cover the subject in depth. However, for more information, three good references are (1) A. Chapanis, *Human Factors in Systems Engineering* (New York: John Wiley & Sons, Inc., 1996); (2) G. Salvendy, ed. *Handbook of Human Factors and Ergonomics*, 2d ed., (New York: John Wiley & Sons, Inc., 1997); and (3) M. S. Sanders and E. J. McCormick, *Human Factors Engineering and Design*, 7th ed., (New York: McGraw-Hill, 1992). Additional references are included in Appendix A.

[27]Although the term *human factors* is used throughout this text, other terms often applied in covering the same material include *ergonomics and human engineering*, and there are other variations of these.

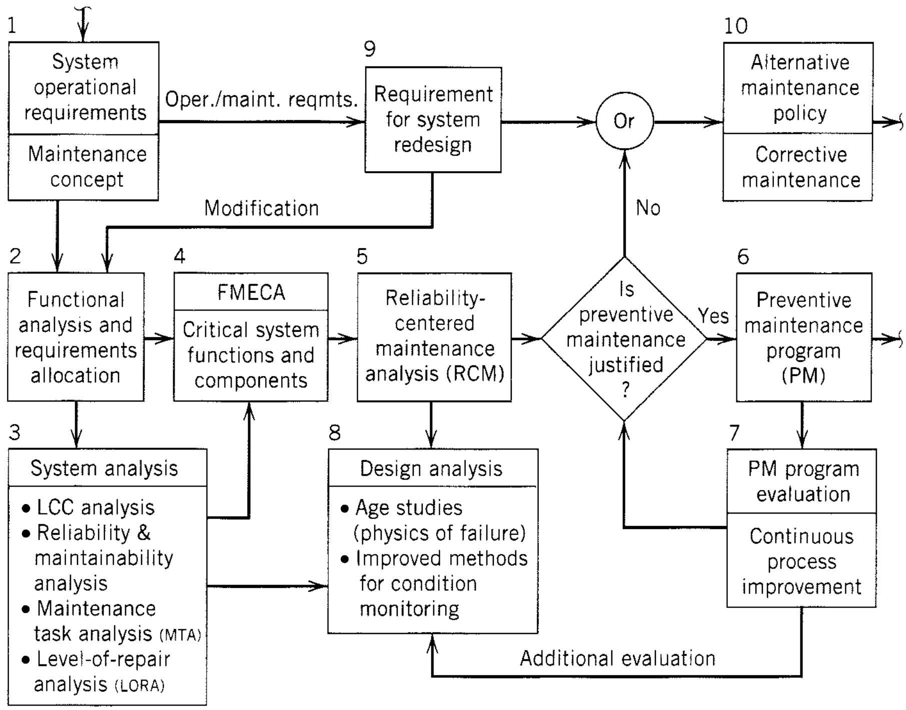


Figure 3.23 Example of the relationships between selected reliability and maintainability tools.

ities and tasks to be performed by the human are combined and related in terms of personnel types, quantities, skill levels, and proposed assigned workstations. This, in turn, leads to the definition of training requirements and the development of training support (e.g., simulators, equipment, software, facilities, data/information). As the design evolves through the steps identified in Figure 3.24, it is essential that the proper level of integration be accomplished with the development of hardware, software, and so on, as the interfaces are many and continuous.

In the development of a system for human beings, specific considerations in design must include the following factors:

1. *Anthropometric factors:* Anthropometry deals with the measurement of the dimensions and the physical characteristics of the human body (e.g., standing height, sitting height, arm reach, breadth, buttock–knee length, hand size, and weight). When establishing basic design requirements involving the human being (for work space application, work surface design, control panel layout), one obviously must take into consideration the physical dimensions of the human body. Both "structural" dimensions (when the body is fixed and in a static state) and "functional" dimensions (when the body is engaged in some physical activity and in a dynamic state) must be measured and used in designing for the performance of operational functions and main-

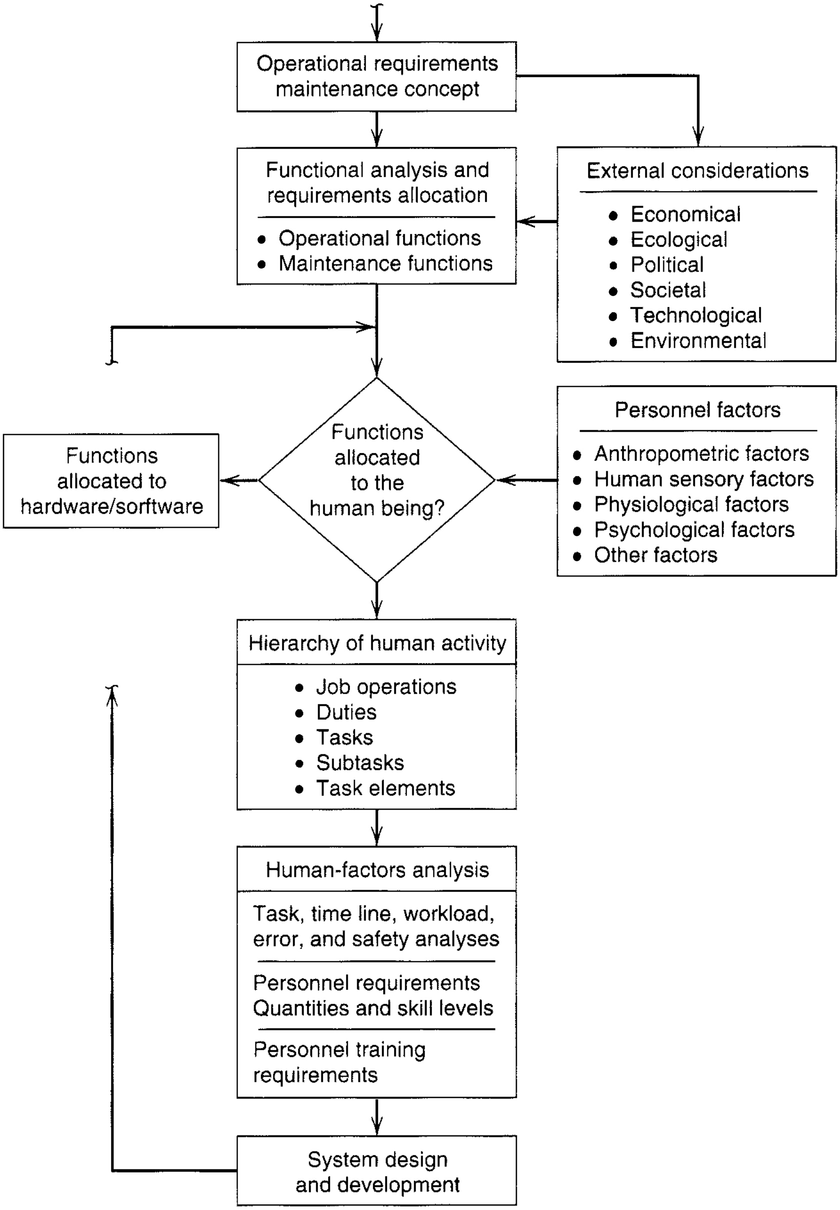


Figure 3.24 Human-factors requirements.

tenance functions. Further, the design engineer must consider both *male* and *female* dimensions, with the appropriate ranges of variability (usually from the 5th to the 95th percentiles). For instance, the height of a male may range from 63.6 in. (5th percentile) to 68.3 in. (50th percentile) or 72.8 in. (95th percentile), and the height of the female from 59.0 in. (5th percentile) to 62.9 in. (50th percentile) or 67.1 in. (95th percentile). Although the average values may be used, the design of work spaces, surfaces, and so on, must consider possible variations for both male and female operators and maintainers; for example, from the 5th percentile female to the 95th percentile male. For specific design criteria, the reader should refer to additional sources.[28]

2. *Human sensory factors:* This category relates to the human sensory capacities, particularly sight or vision, hearing, feel or touch, smell, and so on. In the design of workstations, surfaces, operator consoles, and panels, the engineer must be cognizant of the human's capability relative to sight as it pertains to vertical and horizontal fields of view, angular fields of view, the detection of certain objects from different angles, the detection of certain colors and varying degrees of brightness from different angles, and so on. The placement of panel displays and controls as a function of use and the employment of different color combinations to facilitate the accomplishment of manual tasks require knowledge of the human being's capability for seeing. In addition, the designer needs to understand the human's capacity for hearing in terms of both frequency and intensity (or amplitude). The design of work areas for oral communications and/or the use of auditory displays requires knowledge relative to the effects of noise on the performance of work. For instance, as the noise level increases, a human begins to experience discomfort and both productivity and efficiency decrease. If the noise level approaches 120 to 130 dB, then a physical sensation in some form, or pain, will likely occur. In essence, the system designer needs to integrate the capabilities of the human into the final product.[29]

3. *Physiological factors:* Although the study of physiology is obviously well beyond the scope of this text, it is appropriate to recognize the effects of environmental stresses on the human body during the performance of manual tasks. *Stress* refers to any type of external activity, or environment, that acts on an individual in such a manner as to cause a degrading impact. Some typical causes of stress are (1) high and low temperatures, or temperature extremes, (2) high humidity, (3) high levels of vibration, (4) high levels of noise, and (5) large amounts of radiation or toxic substances in the air. To varying degrees, these environmental effects will negatively impact on human performance; that is, physical fatigue will occur, motor response will be slower, mental processes will slow down, and the likelihood of error will increase. These exter-

[28]Anthropometry data are included in National Aeronautics and Space Administration (NASA), *Anthropometric Source Book.* Vol. 1; *A Handbook of Anthropometric Data,* Vol. 2; and *Annotated Bibliography,* Vol. 3; NASA Reference Publication 1024, 1978. Also refer to Kroemer and Kroemer (1997) and Sanders and McCormick (1992) in Appendix A.

[29]Human sensory factors are covered further in H. P. Van Cott and R. G. Kinkade, eds., *Human Engineering Guide to Equipment Design* (Washington, DC: U.S. Government Printing Office, 1972); and M. S. Sanders and E. J. McCormick, *Human Factors in Engineering Design.* 7th ed. (New York: McGraw-Hill, 1992).

nally related stress factors will normally result in individual human "strain." *Strain* may, in turn, have an impact on any one or more of a human's biological functions (e.g., the circulatory system, digestive system, nervous system, and respiratory system). Measures of strain may include parameters such as blood pressure, body temperature, pulse rate, and oxygen consumption. These factors of strain, caused by external stresses, will definitely have an impact on the performance of human operator and maintenance functions if the design fails to consider the physiological effects on the human.

4. *Psychological factors:* This category relates to the factors that pertain to the human mind; that is, the emotions, traits, attitudinal responses, and behavioral patterns as they relate to job performance. All other conditions may be perfect relative to completing a task in an effective manner. However, if the individual operator (or maintenance technician) lacks the proper motivation, initiative, dependability, self-confidence, communication skills, and so on, the likelihood of performing the task in an effective manner is extremely low. Generally, a person's attitude, initiative, motivation, and so on, are based on the needs and expectations of the individual. This, in turn, is a function of system design and the organizational environment within which the individual performs. If the tasks to be completed are perceived as being too complex, the individual may become frustrated, a poor attitude may develop, and errors will occur. On the other hand, if the tasks are too simple and routine, there is little challenge, boredom prevails, and errors will occur as a result of attitude. Further, as an external factor, the management style of the supervisor may cause an attitudinal problem. In any event, it is appropriate to consider the possible psychological effects on the human in the design and development of a system.[30]

In addition to considering the aforementioned general characteristics associated with the human, it is necessary to have some understanding of the human's ability to deal with and process information. Whether a function should be automated or accomplished by the human and, if accomplished by the human, to what extent, is dependent on the human's ability to detect, react, and process information. Figure 3.25 portrays a simple information-processing model, which includes four basic subsystems. The *sensing* subsystem responds to specific types of energy identified through the human senses (i.e., vision, hearing, feeling, smelling). This provides the *stimulus* to initiate some form of action. The *information-processing* subsystem addresses the human's capacity to receive and process information. Of particular interest is the type and amount of information the human can transmit (often expressed in terms of "bits") and the rate at which he or she can transmit it. The *storage* subsystem refers to the human memory and its capacity, or the ability to retrieve data and facilitate the information-processing activity. Finally, there is the *response* subsystem, which allows the accomplishment of some function/task through a combination of physical motions (i.e., the output from the model). Inherent within this model is the

[30]Additional information on human behavioral characteristics, psychological factors, motivation, attitude, leadership characteristics, and so on, may be found in most texts dealing with organizational theory, organizational dynamics, behavioral science, and related subjects.

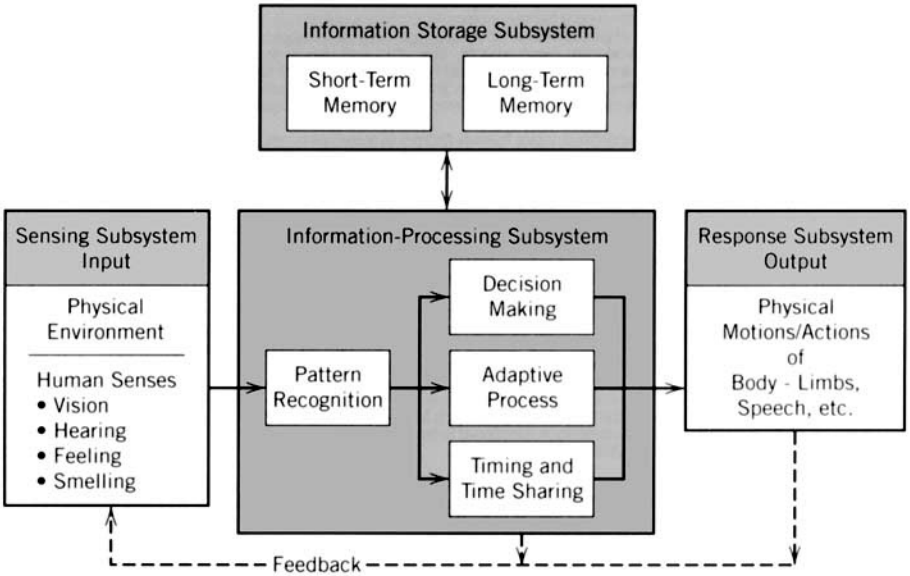


Figure 3.25 The processing of information and subsequent human response (simplified).

feedback loop, which helps to verify that the responses are accurate in terms of the original input.[31]

In the implementation of a human-factors program for a typical large-scale system, the tasks identified in Figure 3.26 are generally applicable. There are (1) program planning, management, and control tasks (Tasks 1–3), (2) design and analysis tasks (Tasks 4–13), and (3) test and evaluation tasks (Tasks 14 and 15). In addition, some of these tasks have been presented, in terms of the life cycle, in Figure 3.27. Although brief task descriptions are included in Figure 3.26, some additional comments pertaining to a few are provided for emphasis.

1. *Human-factors program plan:* Although the requirements for a human-factors program may specify a separate and independent effort, it is *essential* that the program plan be developed as part of, or in conjunction with, the Reliability Program Plan (Figure 3.14, Task 1), the Maintainability Program Plan (Figure 3.20, Task 1), and the System Engineering Management Plan (SEMP). Many of the activities in each of the plans are mutually supportive and require integration in terms of task input-output requirements, schedules, and so on.

2. *Functional analysis:* The purpose of a functional analysis (in this context) is to identify those functions that are to be performed by the human being and where there is a human-machine interface. This activity should evolve directly from, and must

[31]Figure 3.25 constitutes a modified version of Figure 2.1 in H. P. Van Cott and R. G. Kinkade, *Human Engineering Guide to Equipment Design*, rev. ed. (Washington, DC: U.S. Government Printing Office, 1972).

Program Task	Task Description and Application
1. Human Factors Program Plan	To develop a human factors program plan which identifies, integrates, and assists in the implementation of all management tasks applicable in fulfilling human factors engineering requirements. This plan includes a description of the human factors organization, organizational interfaces, a listing of tasks, task schedules and milestones, applicable policies and procedures, and projected resource requirements. This plan must tie directly into the System Engineering Management Plan (SEMP).
2. Review and control of suppliers or subcontractors	To establish initial human factors requirements and to accomplish the necessary program review, evaluation, feedback, and control of component supplier/subcontractor program activities. Supplier program plans are developed in response to the requirements of the overall Human Factors Program Plan for the system.
3. Human factors program reviews	To conduct periodic program and design reviews at designated milestones; e.g., conceptual design review, system design reviews, equipment/software design reviews, and critical design review. The objective is to ensure that human factors requirements will be achieved.
4. System analysis (mission analysis)	To determine the overall capabilities and the performance requirements for the system, and to develop appropriate mission scenarios identifying basic activity sequences. This should be accomplished as part of the system requirements definition process in conceptual design.
5. Functional analysis	To identify the major functions that the system is to perform (based on operational requirements), and to develop functional flow block diagrams defining system design requirements in functional terms. This task must "track" the system-level functional analysis.
6. Function allocation	To conduct trade-off studies, evaluate, and determine the resources required in accomplishing the functions identified through the Functional Analysis activity; i.e., determining the "HOWs" (versus the "WHATs"), particularly in situations where there are human-machine interfaces.
7. Detailed operator task analysis	To evaluate functions that are to be accomplished by the human, and to establish a hierarchical breakdown to the lowest level where human activity exists; i.e., job operation, duty, task, sub-task, and task element. Personnel quantity and skill-level requirements are identified through analysis.
8. Operational sequence diagrams	To identify the human-machine interfaces, and to develop a sequential flow of information, decisions, and actions through the generation of operational sequence diagrams (OSDs).
9. Time line analysis	To select and evaluate critical task sequences, and to verify that the necessary events can be performed and that they are compatible in terms of allocated time; i.e., can the tasks be performed within the appropriate time allotted for accomplishing the mission?
10. Workload analysis	To evaluate human operator activities throughout a given mission scenario (or through a number of designated scenarios) to determine the workload level; e.g., the relationship between the maximum time allowed and the actual time for task performance.
11. Error analysis	To systematically determine the various ways in which errors can be made by the human, and to make design recommendations to reduce the likelihood of such errors occurring in the future. This task is comparable to the reliability FMECA, except that the system/equipment failures are the result of *human* errors.
12. Safety analysis	To systematically evaluate, through cause-and-effect analysis, the effects of system/equipment failures on safety. Although safety pertains to both personnel and equipment, the aspect of *personnel* safety is emphasized herein. This task ties in directly with the reliability FMECA and the Human Factors Error Analysis.
13. Models and/or mock-ups	To develop a three-dimensional physical model or a mockup of the system (or a component thereof) to demonstrate human-machine interfaces, spatial relationships, equipment layouts, panel displays, accessibility provisions for maintenance, and so on.
14. Training program requirements	To plan and implement a formal training program. This includes the determination of personnel training requirements (quantity of personnel and the skill levels desired as an output), categories of training, training equipment, training data, training facilities, mockups and models, special training aids, and so on. The plan should include a description of the training organization, a listing of tasks, task schedules and milestones, policies and procedures, and projected resource requirements.
15. Personnel test and evaluation	To plan and implement a program to physically demonstrate human-machine interfaces, task sequences, task times, personnel quantity and skill-level requirements, the adequacy of operating procedures, the adequacy of personnel training, and so on. This test and evaluation activity is accomplished prior to entering production.

Figure 3.26 Human-factors engineering program tasks.

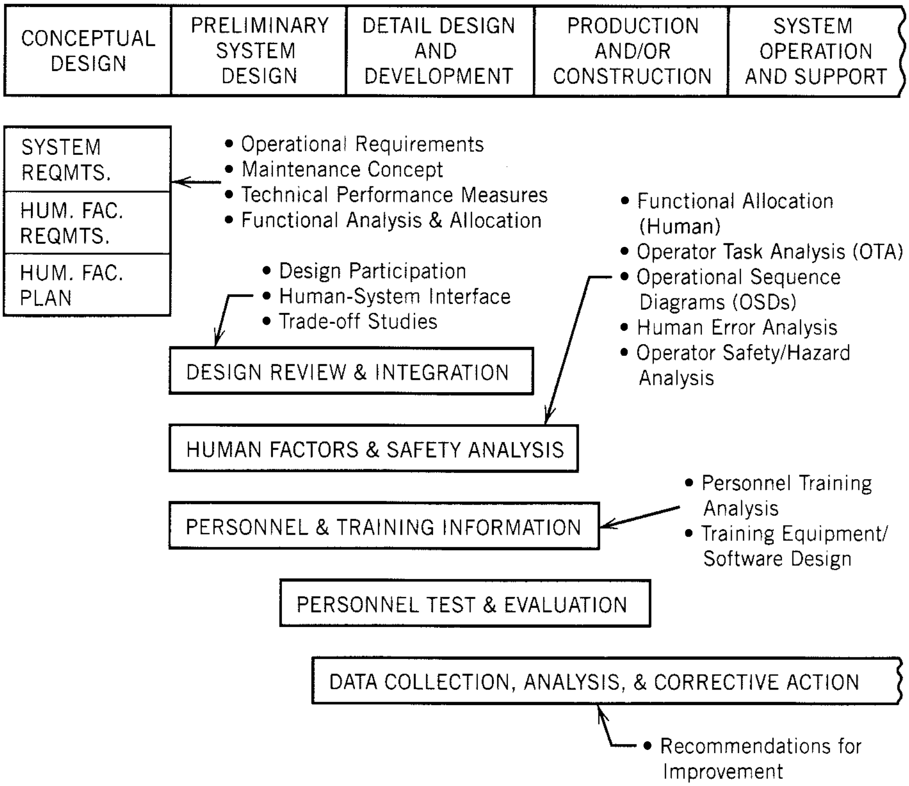
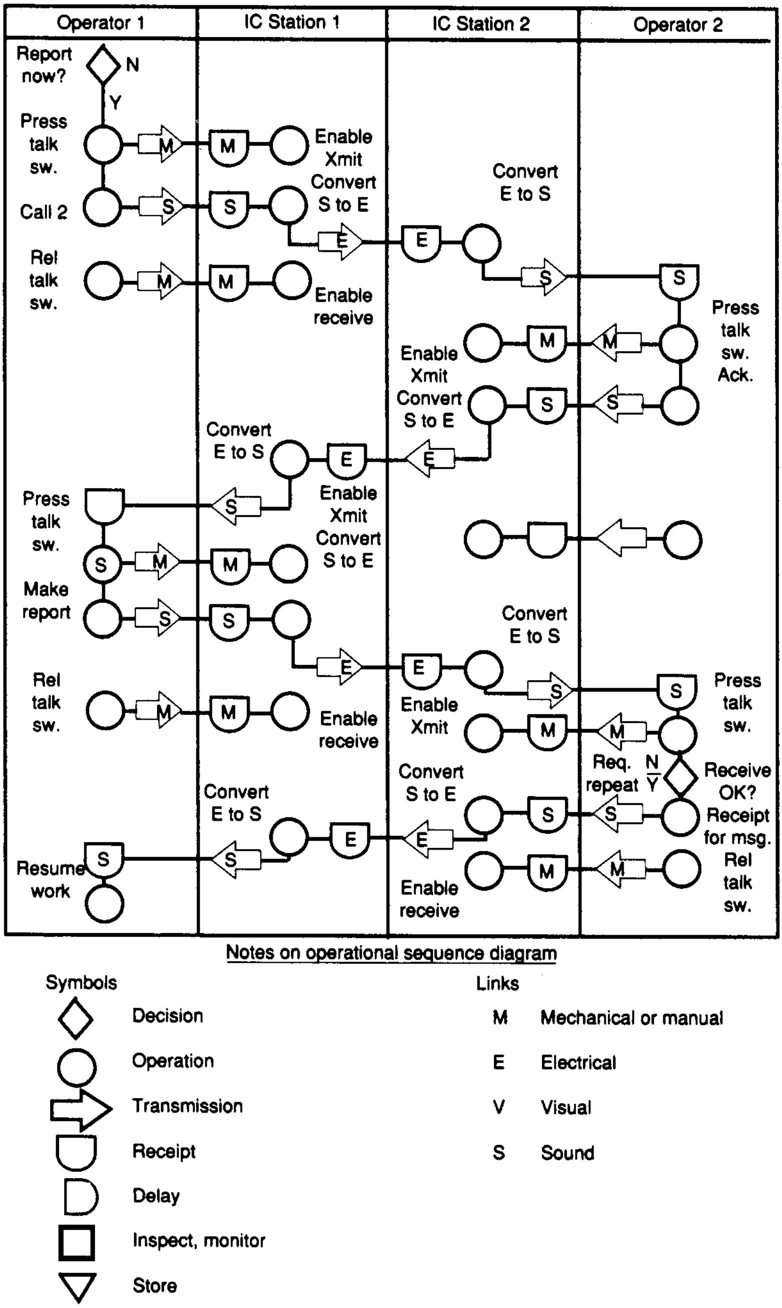


Figure 3.27 Human-factors tasks in the system life cycle.

support, the system functional analysis and associated functional flow diagrams described in Section 2.7 (refer to Figures 2.11–2.16).

3. *Detailed operator task analysis:* This part of the overall human-factors analysis effort constitutes the expansion of major functions from the system functional analysis into job operations, duties, tasks, and so on. Ultimately, this will lead to the definition of operator and maintenance personnel requirements, in terms of quantities and skill levels, and the subsequent development of training program requirements (Figure 3.26, Task 14). With the identification of personnel and training requirements, close coordination must be established with reliability, maintainability, and logistics program activities, as there are common interests in this area.

4. *Operational sequence diagrams:* As part of the human-factors design analysis effort, operational sequence diagrams (OSDs) are developed to show various groups of activities involving the human-machine interface. An example of an OSD is presented in Figure 3.28, where a communications sequence between operators and workstations is illustrated. Through a symbolic presentation, different actions are shown that, in turn, lead to the identification of specific design requirements. Of significance is the requirement that OSDs must evolve from the functional analysis.



Stations or subsystems are shown by columns; sequential time progresses down the page.

Figure 3.28 Example operational sequence diagram. *Source:* MIL-H-46855, Military Specification, "Human Engineering Requirements for Military Systems. Equipment and Facilities" (Washington, DC: Department of Defense).

5. *Personnel test and evaluation:* The purpose of this task is to demonstrate selected human activity sequences to verify operating/maintenance procedures and to ensure compatibility between the human and other elements of the system. Demonstrations are conducted using a combination of analytical computer simulations, physical mock-ups (wooden, metal, and/or cardboard), and preproduction prototype equipment. Computerized simulations may include the insertion of a 5th percentile female or a 95th percentile male into a work space, in a sitting or standing position, in order to evaluate activity sequences and space requirements. A great deal of information can be acquired through use of the appropriate computer graphics employing a three-dimensional database. Type 2 testing, using preproduction prototype equipment, may include the use of personnel, trained as recommended from the results of Task 14, in the performance of selected operator and/or maintenance task sequences accomplished in accordance with approved procedures. The conductance of such tests should not only allow for the evaluation of critical human-machine interfaces, but should provide reliability information pertaining to operator functions, maintainability data when maintenance tasks are performed, verification and validation of information in formal technical manuals/procedures, verification of the adequacy of the training program for operator and maintenance personnel, and so on. Basically, this activity must be coordinated with other testing requirements and must be covered in the TEMP.

In summary, many of the tasks identified in Figure 3.26 (and the tools/techniques used in accomplishing them) are interrelated, the interfaces are many, and they feed on one another. Figure 3.29 provides an example showing the relationships between the functional analysis, the operator task analysis (OTA), the development of operational sequence diagrams (OSDs), the development of training requirements, and the appropriate feedback loop. In addition, note that a safety/hazard analysis has been included, as personnel safety is a major issue in the design for human factors.[32]

3.4.5 Safety Engineering[33]

Safety is a system design characteristic. Certain materials selected for the design and construction of a system element may produce harmful toxic effects on the human; the placement and mounting of components may cause injuries to the operator and/or the maintainer; the use of certain fuels, hydraulic fluids, and/or cleansing liquids may result in an explosive environment; the location of certain electronic components close together may cause the generation of an electrical hazard; the performance of a series of strenuous tasks during the operation or maintenance of the system may cause personal injury; and so on.

Safety is important, both from the standpoint of the human operator and/or main-

[32]The safety/hazard analysis is discussed further in Section 3.4.5.

[33]Two good references for a more in-depth coverage of the subject are (1) H. E. Roland and B. Moriarity, *System Safety Engineering and Management*, 2d ed. (New York: John Wiley & Sons, Inc., 1990); and (2) N. J. Bahr, *System Safety Engineering and Risk Assessment: A Practical Approach* (New York: Taylor & Francis, 1997).

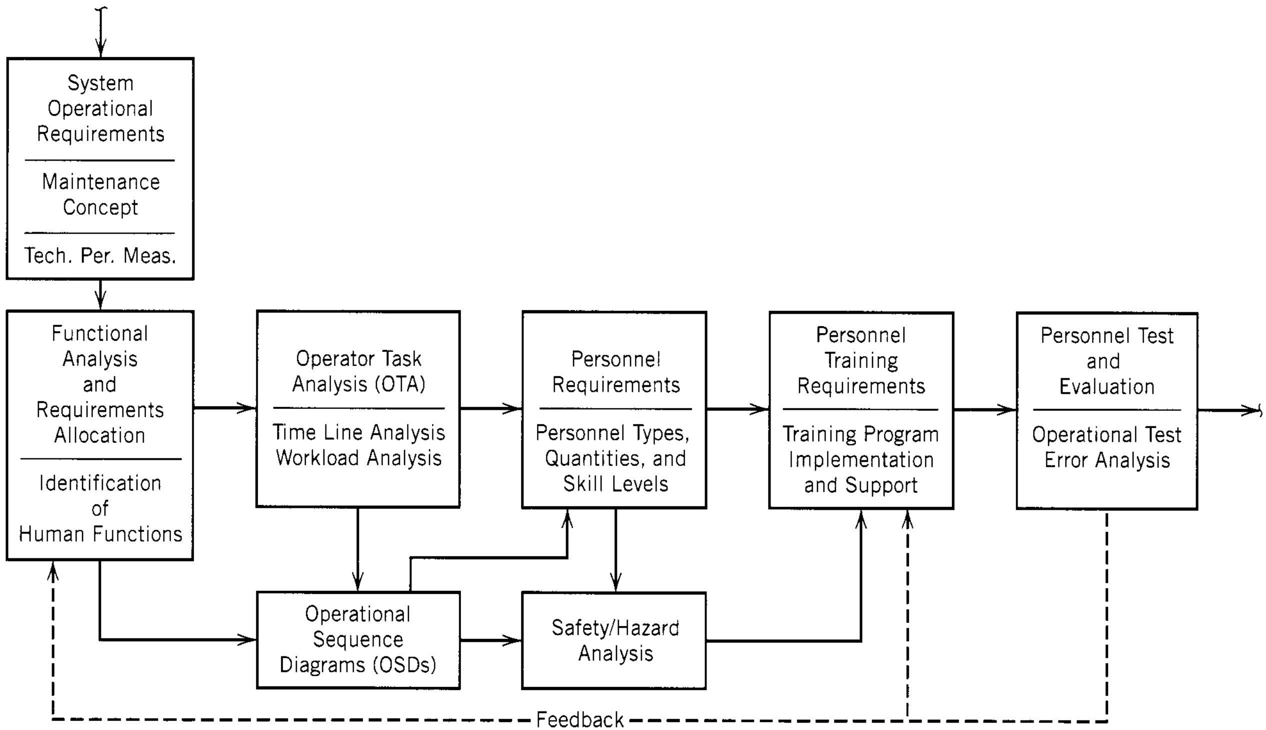


Figure 3.29 The application and relationships of selected tools/methods used for human factors in design.

tainer and from the standpoint of the equipment and other elements of the system. Through faulty design, one can create problems that may result in human injury. Moreover, problems can be created that result in damage to other elements of the system. In other words, the concerns in design deal with both personal safety and equipment safety.

Relative to the system design and development process, safety engineering requirements are comparable to those described for reliability, maintainability, and human factors (Sections 3.4.2, 3.4.3, and 3.4.4, respectively). Figure 3.30 provides a listing of safety program tasks for a typical large-scale system. There are (1) program planning, management, and control tasks (Tasks 1–3), (2) design and analysis tasks (Tasks 4–7), and (3) test and evaluation tasks (Tasks 8 and 9). There are three basic tasks shown in Figure 3.30 that require additional comment.

1. *System Safety Program Plan:* Although the requirements for this task may specify a separate and relatively independent effort, it is *essential* that the program

Program Task	Task Description and Application
1. System Safety Program Plan	To develop a system safety program plan that identifies, integrates, and assists in the implementation of all management tesks applicable in fulfilling safety engineering requirements. This plan includes a desription of the safety engineering organization, organizational interfaces, a listing of tasks, task schedules and milestones, applicable policies and procedures, and projected resource requirements. This plan must tie directly into the System Engineering Management Plan (SEMP).
2. Review and control of suppliers or subcontractors	To establish initial system safety requirements and to accomplish the necessary program review, evaluation, feedback, and control of component supplier/subcontractor program activities. Supplier program plans are developed in response to the requirements of the overall System Safety Program Plan for the system.
3. System safety program reviews	To conduct periodic program and design reviews at designated milestones, e.g., conceptual design review, system design reviews, equipment/software design reviews, and critical design review. The objective is to ensure that safety engineering requirements will be achieved.
4. Fault-tree analysis (FTA)	To accomplish a fault-tree analysis (FTA) for determining system events that may cause undesireable events (or hazards), and to establish a ranking of these undesireable events. Fault-tree diagrams are developed from early hazard analyses, critical paths are identified, and probable causes are noted (a top-down approach). This task is closely related to the reliability FMECA. Refer to Case Study B.2, Appendix B.
5. Hazard analysis	To accomplish an analysis of the system with the objective of (a) identifying all major hazards and the anticipated probability of occurance, (b) identifying the "cause" factors that will result in a hazard, (c) evaluating the impacts (effects) on the system in the event that hazards occur, and (d) categorizing the identified hazards, i.e., catastrophic, critical, marginal, negligible. This task is closely related to the reliability FMECA and the Human-Factors Safety Analysis.
6. Risk analysis	To initiate a risk management program for the evaluation and control of the probability of occurrance and the consequences of hazardous events. Risk analysis, risk assessment, and risk abatement activities are included.
7. Data collection, analysis, feedback, feedback, and corrective action	To plan and implement a data collection and reporting capability for identifying and evaluating potential areas of risk. Participate in failure analysis activity and in accident investigations as appropriate. Recommendations for corrective action are initiated in areas when potential risk exists.
8. Safety training program	To plan and implement a training program covering the procedures and steps necessary to ensure that operator and maintenance personnel are properly trained in the performance of all system functions. This includes consideration of the requirements for training materials and data, training equipment, training aids, training facilities, and so on.
9. Safety test and evaluation	To plan and implement a program to test the system (and its components) to ensure that it can be safely operated and maintained, and that all necessary safety precautions have been taken. This test and evaluation activity is accomplished prior to entering production.

Figure 3.30 Safety engineering program tasks.

plan be developed as part of, or in conjunction with, the Reliability Program Plan (Figure 3.14, Task 1), the Maintainability Program Plan (Figure 3.20, Task 1), the Human-Factors Program Plan (Figure 3.26, Task 1), and the System Engineering Management Plan (SEMP). Tasks 4 and 5 of the safety program (fault-tree analysis and hazard analysis) are closely related to the reliability FMECA, the maintainability analysis (diagnostics and testability analysis), and the human-factors safety analysis. Task 7 should tie in with the reliability FRACAS and the maintainability Task 4 (data collection and analysis). Task 8 (training program) should be related to the human-factors Task 14. Task 9 (testing) should be coordinated with reliability Tasks 18–20, maintainability Task 13, and human-factors Task 15. Many of the activities in each of the plans are mutually supportive and require integration in terms of task input-output requirements, schedules, and so on.

2. *Fault-tree analysis (FTA):* This is an ongoing top-down analytical process, using deductive analysis and Boolean methods, for determining system events that will, in turn, cause undesirable events, or hazards. Further, these events are ranked in terms of their influence in causing the potential hazards. Fault-tree logic diagrams are developed commencing with the top event and proceeding downward through successive levels of causation steps, determining at each level what the next set of events will be. Fault-tree analysis is closely related to both reliability and maintainability analysis, particularly in considering possible symptoms and frequencies of failure, diagnostic and test routines, and so on. Case Study B.2, Appendix B, describes the FTA approach.

3. *Hazard analysis:* The objective of this task is to evaluate the design and determine possible events that may result in hazards at the system level. By simulating failures, critical activities, and so on, at the component level, one can (through a cause-and-effect analysis) identify possible hazards, anticipated frequency of occurrence, and classification in terms of criticality. Recommendations for design change are made where appropriate. This task, with regard to methodology and objectives, is very closely related to the reliability FMECA (which also categorizes events in terms of criticality) and the human-factors safety analysis.

In summary, the tasks identified in Figure 3.30 are generally performed in response to some detailed program requirement and are often completed on an independent basis. However, the interfaces are numerous, and it is essential that these requirements be appropriately integrated into the overall system engineering process.

3.4.6 Security Engineering

Although not usually included within the class of the more traditional disciplines associated with engineering and the design of systems, the issue of *security* has certainly assumed a high priority in view of the continuing threats of terrorism and the terrorist acts that are taking place in today's world. Thus, there is an added dimension that must be addressed within the overall spectrum of system engineering: the *design for security.* The question at this point is, How does one design a system to preclude the planned introduction of faults/failures that will cause the system (or any portion thereof) to be completely destroyed, resulting in the damage of material, facilities, and/or the loss of life? The objective, of course, is to prevent an individual (or group of individuals) from intentionally sabotaging a system for one reason or another.[34]

Although such a problem may be caused intentionally versus inadvertently, the goal here is similar to the design objectives specified within the disciplines of human factors engineering and safety engineering. In human factors engineering, one of the objectives is to design a system to preclude the introduction of faults by the operator (or maintainer) that will result in the system's not being able to perform its mission. In safety engineering, an objective is to design a system such that faults cannot be introduced that will result in system damage and/or personal injury/death. In both cases, the major concern is related to the possibility of inducing problems in the process of performing system functions during the accomplishment of a mission, in the performance of a maintenance task, and/or in the accomplishment of a support activity. The assumptions in this case relate to the possibility that such problems may occur though some unintentional act or series of acts.

In designing for security, it is necessary to go one step further by addressing the issue of intent. The question is, What characteristics should be incorporated in the design of a system that will prevent (or at least deter) one or more individuals from *intentionally* inducing faults that will destroy the system, cause harm to personnel, and/or have an impact that will endanger society and the associated environment? In response, the design should consider the following:

1. The development and incorporation of an external security alarm capability that will detect the presence of unauthorized personnel and prevent them from operating, maintaining, and/or gaining access to the system and its elements, and one that will ultimately lead to the prevention of an "outsider" from inducing a problem that will result in system damage or destruction.

2. The incorporation of a "condition-based monitoring" capability that will enable one to check the status of the system and its elements on a continuing basis. To accomplish this requires the appropriate sensors, readout devices, inspection methods, and the like, be included that will verify that the system and its components are in the condition intended and that the appropriate diagnostics be incorporated that will lead to the correction of any problem that may exist. An objective is to initially determine (through inspection and/or test methods) that the system is in satisfactory condition and to provide the necessary subsequent controls that will ensure that this condition will continue to exist.[35]

[34]Subsequent to the "911" incident, there has been a great deal of emphasis on security and the design for security. In the defense sector, in particular, an added requirement in the development of new (and the modification of existing) systems has been the inclusion of the necessary characteristics in design to counter the threat of terrorism.

[35]A major challenge for the future is to develop the appropriate sensors and inspection methods that will allow for the proper condition-verification of *all* of the materials, cargo containers, and related items that are being transported both internally and worldwide. The current absence of such a capability constitutes a potential threat.

3. The incorporation of a built-in capability (mechanisms) that will detect and initiate an alarm in the event that problem is detected and a design that will, in the event of a problem, prevent a subsequent chain reaction of failures leading to system damage or destruction.

In other words, the designer must address such issues as (1) preventing unauthorized personnel from gaining access to the system in question, (2) being able to initially determine the condition of the system and the follow-on monitoring of its components at all times, and being able to control the processing of these components as they progress through the *forward* and *reverse* flow of activities identified in Figure 1.20, and (3) being able to both detect and subsequently prevent any failures that are induced through incorporation of the appropriate characteristics in the system design.[36]

At this point (and in summary), it should be emphasized that it is certainly easier to define a problem than to arrive at a proposed solution, and much remains to be accomplished to ensure better system security in the future. Hence, it is anticipated that a great deal of research and design effort will be expended from here on to arrive at better solutions for the problem at hand.

3.4.7 Manufacturing and Production Engineering[37]

The role of manufacturing/production may take several forms, including the construction of a single one-of-a-kind system entity and the production of a quantity of similar items. In the first case, there is an obvious strong interface between the design activity and the follow-on construction of the system, which, in turn, is based on the recommended design configuration. In the second situation, one needs to (1) design the product that is to be manufactured for *producibility* and (2) design the manufacturing/production capability to be both effective and efficient in producing that product. A major goal in the application of system engineering requirements is to address these various life-cycle activities and their interfaces, as conveyed in Figure 1.10.[38]

In regard to a product and its design configuration, a key objective is to *design for producibility*. "Producibility" is a measure of the relative ease and economy of producing an item. The characteristics of design must be such that the item can be produced easily and economically, using conventional and flexible manufacturing methods and processes without sacrificing function, performance, effectiveness, or quality. Some major objectives are as follows:

[36]An objective in system design is to determine the cause-and-effect relationships among the various system elements/components, and the effects of a system failure on the mission being accomplished. Some failures, of a more catastrophic or critical nature, will ultimately result in system damage, destruction, and/or personal injury. The goal is to design the system to prevent these failures from occurring. An excellent tool that may be utilized to facilitate this objective is the FMECA; see Case Study B.1. in Appendix B.

[37]A good reference that presents some of the current trends in manufacturing is P. M. Swamidass, *Innovations in Competitive Manufacturing* (American Management Association (AMACOM), 2002). Refer to Appendix A for additional references.

[38]When referring to a "product," the assumption is that we are dealing with a relatively large repairable entity versus a smaller nonrepairable commercial consumable item.

1. The quantity and variety of components utilized in system design should be held to a minimum. Common and standard items should be selected where possible, and there should be a number of different supplier sources available throughout the planned life cycle of the system.

2. The materials selected for constructing the system should be standard, available in the quantities desired and at the appropriate times, and should possess the characteristics for easy fabrication and processing. The design should preclude the specification of peculiar shapes requiring extensive machining and/or the application of special manufacturing methods.

3. The design configuration should allow for the easy assembly (and disassembly as required) of system elements; that is, equipment, units, assemblies, and modules. Assembly methods should be simple, repeatable, and economical and should not require the utilization of special tools and devices or high personnel skill levels.

4. The design configuration should be simple, to the extent that the system (or product) can be produced by more than one supplier, using a given data package and conventional manufacturing methods/processes. The design should be compatible with the application of computer-aided design (CAD)/computer-aided manufacturing (CAM) technology where appropriate.

Figure 3.31 presents a simplified step-by-step approach addressing some important considerations in design. Referring to the eighth block in the figure, the design review checklist in Appendix D (Item 21), or something equivalent, may be utilized to provide additional guidance in this area.

In considering the design characteristics of the manufacturing/production capability itself, there are a number of goals and objectives that are important, particularly in view of the current trends pertaining to increased globalization and greater international competition, the need for producing a wide variety of products in shorter time frames, the need to reduce product costs, and so on (refer to Section 1.1 and Figure 1.1). More specifically, there has been a great deal of emphasis on *flexibility* and *agility*. The central theme in "agile manufacturing" is to develop a capability that can react quickly in producing a wide variety of high-quality products, with continuously changing configurations, in a short time frame, with rapid response and maximum customer satisfaction as the goal. Another key objective relates to *lean production*, which emphasizes the elimination of waste in the utilization of all resources, including people and time. At the same time, there has been a great deal of activity related to improving all of the functions within the supply chain (e.g., purchasing, materials handling, transportation and distribution, customer service), as well as modernizing some of the business processes necessary in the manufacture of products. The development of electronic commerce (EC) methods has enabled the integration and rapid processing of information and data packages supporting key business operations. For example, the advent of the *Enterprise Resource Planning* (ERP) approach has enabled the integration of manufacturing operations and other functions of a given firm with suppliers and customers.

Although the aforementioned areas of activity are primarily dedicated to improv-

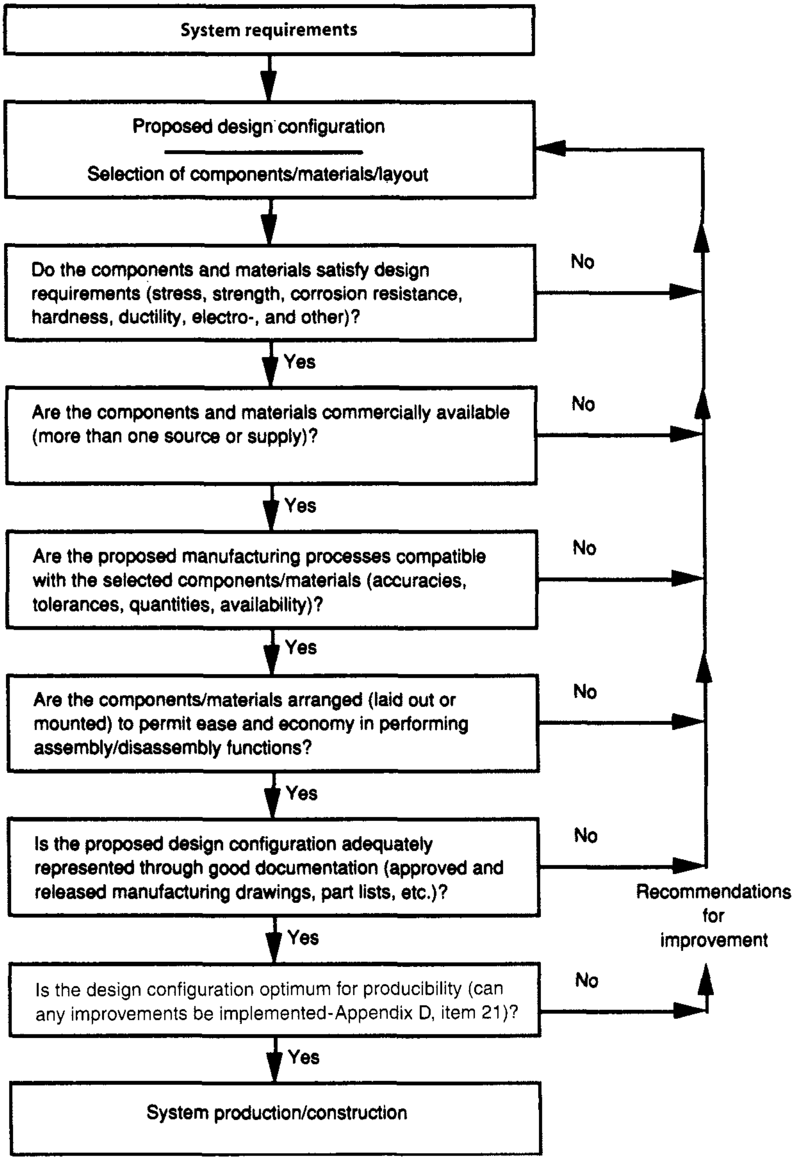


Figure 3.31 Producibility considerations.

ing the operations of a manufacturing/production capability, one must also address the life-cycle issues associated with the maintenance and support of this capability. There have been a number of instances which a relatively high percentage of the cost of a product has been be attributed to the maintenance costs associated with the equipment in the factory that is used to manufacture/produce that product, with such costs being amortized and assigned to the product. Thus, in a highly competitive environment, one must consider not only the operational issues but the maintenance and support issues as well.[39]

3.4.8 Logistics and Supportability Engineering[40]

As shown in the system "operational and maintenance" flow diagram in Figure 1.20, there are a wide variety of activities conducted throughout the system life cycle (see Sections 1.3.3 and 1.3.4). Included in the *forward* flow of activities (i.e., from the supplier to the consumer/user) are the functions identified in Figure 1.21—purchasing, materials processing and handling, inventory management, packaging and transportation, warehousing and storage, distribution, customer service, information flow, and all of the related business practices that are necessary to support the effective and efficient implementation of the supply chain. Although the product *design* and *maintenance and support* interfaces are generally not addressed within the bounds of supply chain management (SCM), there has been much progress in recent years in modernizing the physical supply and distribution channels in the interest of improving the competitive position of firms worldwide.

Included in the *reverse* flow of activities shown in Figure 1.20 (i.e., from the consumer/user to the applicable maintenance facility and back) are the maintenance and support functions identified throughout the infrastructure illustrated in Figure 1.22, along with the required resources, which include the following general categories:[41]

1. *Manpower and personnel:* Includes all personnel required in the installation, checkout, operation, handling, and sustaining maintenance of the system throughout its planned life cycle. Maintenance personnel considerations cover activities at all levels of maintenance, operation of test equipment, operation of facilities, and so on.

2. *Training, training equipment, and devices:* Includes the initial training of all system operator and maintenance personnel and the follow-on "replenishment" training to cover attrition and replacement personnel. Training equipment, training simulators, mock-ups, training data and manuals, special facilities, special devices and aids, and software to support personnel training operations are also included.

[39]Refer to Section 1.3.4 and a description of the concept of *total productive maintenance* (TPM). This concept was first introduced in 1971, primarily because of the low level of effectiveness in manufacturing products and the resulting high costs of maintenance experienced in many factories at the time. Subsequently, implementation of the principles and concepts of TPM have become popular internationally and have been adopted by many factories throughout the world today. For additional information, refer to the bibliography in Appendix A, under "Maintainability Engineering and Maintenance."

[40]To gain a complete perspective of the field of logistics (presented in a broad context), it is recommended that additional study in this area be pursued. Four good references are (1) B. S. Blanchard, *Logistics Engineering and Management,* 6th ed. (Upper Saddle River, NJ: Prentice-Hall, 1998); (2) R. H. Ballou, *Business Logistics Management: Planning, Organizing, and Controlling the Supply Chain,* 4th ed. (Upper Saddle River, NJ: Prentice-Hall, 1998); (3) J. J. Coyle, and E. J. Bardi, *Transportation* (St. Paul, MN: South-Western Publishing, 1998); and (4) *Journal of Business Logistics,* published by the Council of Logistics Management (CLM), Oak Brook, IL. Additional references are included in Appendix A.

[41]B. S. Blanchard, *Logistics Engineering and Management,* 5th ed. (Upper Saddle River, NJ: Prentice-Hall, 1998).

3. *Supply support:* Includes all spares (units, assemblies, modules, etc.), repair parts, consumables, special supplies, and related inventories needed to support prime mission-oriented equipment, software, test and support equipment, transportation and handling equipment, training equipment, and facilities. Provisioning documentation, procurement functions, warehousing, distribution of material, and personnel associated with the acquisition and maintenance of spare/repair part inventories at all support locations are also included in this category.

4. *Test and support equipment:* Includes all tools, special condition monitoring equipment, diagnostic and checkout equipment, metrology and calibration equipment, maintenance stands, and servicing and handling equipment required to support operation, transportation, and scheduled and unscheduled maintenance actions associated with the system or product. Both "peculiar" (newly developed) and common "standard" (existing and already in the inventory) items must be covered.

5. *Packaging, handling, storage, and transportation:* Includes all special provisions, materials, containers (reusable and disposable), and supplies necessary to support packaging, preservation, storage, handling, and/or transportation of prime mission-oriented equipment, test and support equipment, spares and repair parts, personnel, technical data, and mobile facilities. In essence, this category covers the initial distribution of products and the transportation of personnel and materials for maintenance purposes.

6. *Facilities:* Includes all special facilities needed for system operation and the performance of maintenance functions at each level. Physical plant, real estate, portable buildings, housing for personnel, intermediate maintenance shops, calibration laboratories, and special depot or overhaul facilities must be considered. Capital equipment and utilities (heat, power, energy requirements, environmental controls, communications, etc.) are generally included as part of facilities.

7. *Technical data:* Includes system installation and checkout procedures, operating and maintenance instructions, inspection and calibration procedures, overhaul procedures, modification instructions, facilities information, drawings and specifications, and associated databases that are necessary for the performance of system operation and maintenance functions. Information processing requirements (networks and equipment) are also included in this category.

8. *Computer resources:* Includes all software, computer equipment, tapes/disks, databases, and accessories necessary in the performance of system maintenance functions at each level. This covers condition monitoring requirements and maintenance diagnostic aids.

These basic elements of logistics and the maintenance and support infrastructure (also identified in Figure 1.23) must be completely integrated and viewed in the context of the "system" as an entity—that is, the combining and integration of all of the activities identified in Figures 1.21 and 1.22. Otherwise, there is no guarantee that system requirements will be met should a failure occur. Further, considering past experience and the downstream costs associated with system support (and the cause-and-effect relationships—refer to Figures 1.4 and 1.5), the ultimate requirements for

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these elements must be addressed in terms of the entire system life cycle, with emphasis in the early phases of design and development. More specifically, (1) the prime mission-related elements of the system must be *designed for supportability*, and (2) the logistics and maintenance support infrastructure must be designed so that it will provide for effective and efficient support through the system's planned life cycle. Thus, it is essential that these requirements be included and inherent within the system engineering process (refer to Figure 3.5).[42]

This life-cycle approach, with emphasis on system design, has been recognized in the defense sector and applied in the development of relatively large-scale defense systems through the introduction of the concept of "acquisition logistics."[43] *Acquisition logistics* can be defined as a

> multifunctional technical management discipline associated with the design, development, test, production, fielding, sustainment, and improvement modifications of cost-effective systems that achieve the user's peacetime and wartime readiness requirements. The principal objectives of acquisition logistics are to ensure that support considerations are an integral part of the system's design requirements, that the system can be cost-effectively supported throughout its life cycle, and that the infrastructure elements necessary to the initial fielding and operational support of the system are identified and developed and acquired.[44]

Inherent within the spectrum of acquisition logistics are a number of program activities, including initial planning; a variety of design-related tasks throughout the system development process; the identification, procurement, processing, distribution, and installation of the required elements of support at the appropriate consumer/user's operational sites; and the ongoing sustaining customer service and maintenance support of the system throughout its planned life cycle. An abbreviated discussion of key activities follows.

1. *Integrated logistic support plan (ILSP).* An ILSP (or a planning document of an equivalent nature) is usually initiated during the conceptual design phase and updated in preliminary system design; it covers all planning activities, design activities, procurement and acquisition activities, and sustaining support activities. Often included are individual subplans covering the different elements of the maintenance and support infrastructure and related life-cycle activities—for example, detailed maintenance concept/plan (including applicable logistics performance factors); reli-

[42]Although the term *supportability* is primarily used through this text, similar terms such as *serviceability* and *sustainability* are also used interchangeably; for example, the former primarily in the commercial sector and the latter, assuming some recent emphasis, in the defense sector. Independent of such, the objective is to design the system so that it can be supported effectively and efficiently throughout its programmed life cycle.

[43]DOD 5000.2-R, *Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs* (Washington, DC: Office of the Secretary of Defense, April 5, 2002), Section C5.2.3.5.4.

[44]MIL-HDBK-502, *Acquisition Logistics* (Washington, DC: Department of Defense, May 30, 1997), Section 4.1.