APPENDIX B
CASE STUDIES

Throughout the early stages of the life cycle, as part of the system engineering process, there are a number of applications of different tools that can facilitate the conductance of trade-off studies. Of particular interest here are some of the tools that address the downstream aspects of system support but can be effectively utilized earlier. In Figure B.1, seven abbreviated examples have been selected to illustrate the utilization of analytical methods in the engineering decision-making process.[1]

B.1 FAILURE MODE, EFFECTS, AND CRITICALITY ANALYSIS (FMECA)

B.1.1 Definition of the Problem

Company ABC, a manufacturer of gaskets for automobiles, was experiencing problems related to declining productivity and increased product costs. At the same time, competition was increasing and the company was losing its share of the market. As a result, the company decided to implement a *continuous process improvement program* with the objective of identifying potential problem areas and their impact and criticality on both internal company operations and the product being delivered to the customer. To aid in facilitating this objective, the company's manufacturing operations were evaluated using the failure mode, effects, and criticality analysis (FMECA).

[1]Case studies B.1, B.2, and B.3 were taken in part from B. S. Blanchard, D. Verma, and E. L. Peterson, *Maintainability: A Key to Effective Serviceability and Maintenance Management*, (New York: John Wiley & Sons, Inc., 1995).

Analysis Tools	Description of Application
1 Failure Mode, Effects, and Criticality Analysis (FMECA)	Identification of potential product and/or process failures, the expected modes of failure and "causes," failure effects and mechanisms, anticipated frequency, criticality, and the steps required for compensation (i.e., the requirement for redesign and/or the accomplishment of preventive maintenance). An Ishikawa "cause-and-effect" diagram may be used to facilitate the identification of "causes," and a Pareto analysis may help in identifying those areas requiring immediate attention.
2 Fault-Tree Analysis (FTA)	A deductive approach involving the graphical enumeration and analysis of different ways in which a particular system failure can occur, and the probability of its occurrence. A separate fault tree may be developed for every critical failure mode, or undesired top-level event. Attention is focused on this top-level event and the first-tier causes associated with it. Each of these causes is next investigated for its causes, and so on. The FTA is narrower in focus than the FMECA and does not require as much input data.
3 Reliability-Centered Maintenance (RCM)	Evaluation of the system/process, in terms of the life cycle, to determine the best overall program for preventive (scheduled) maintenance. Emphasis is on the establishment of a cost-effective preventive maintenance program based on reliability information derived from the FMECA; that is, failure modes, effects, frequency, criticality, and compensation through preventive maintenance.
4 Maintenance Task Analysis (MTA)	Evaluation of those *maintenance* functions that are to be allocated to the human. Identification of maintenance functions/tasks in terms of task times and sequences, personnel quantities and skill levels, and supporting resources requirements (i.e., spares/repair parts and associated inventories, tools and test equipment, facilities, transportation and han-

Figure B.1 Design analysis methods (case study applications).

Analysis Tools	Description of Application
	dling requirements, technical data, training, and computer software). Identification of high resource-consumption areas.
B.5 Level-of-Repair Analysis (LORA)	Evaluation of maintenance policies in terms of levels of repair; that is, should a component be repaired in the event of a failure or discarded and, given the "repair" option, should the repair be accomplished at the intermediate level of maintenance, at the supplier's factory, or at some other level? Decision factors include economic, technical, social, environmental, and political considerations. The emphasis here is based on life-cycle cost factors.
B.6 Design Evaluation of Alternatives	Evaluation of alternative design configurations using multiple criteria. Weighting factors are established to specify levels of importance.
B.7 Life-Cycle Cost Analysis (LCCA) Refer to Appendix C	Determination of the system/product/process life-cycle cost (design and development, production and/or construction, system utilization, maintenance and support, and retirement/disposal costs); high-cost contributors; cause-and-effect relationships; potential areas of risk; and identification of areas for improvement (i.e., cost reduction).

Figure B.1 (*Continued*)

B.1.2 The Analysis Process

An initial step included the identification of the major functions performed in the overall gasket manufacturing process by completing a functional flow diagram in accordance with the procedures described in Section 2.7 (Chapter 2). In this instance, there were 13 major functions that were subject to evaluation. For each function, required input factors and expected outputs were identified, along with the appropriate metrics. This led to the initial selection of 1 of the 13 functions, based on a perception by company personnel as to the area causing the most problems. Given this selection, the sequence of steps conveyed in Figure B.2 was followed in completing an FMECA of the selected function.

Figure B.3 represents the function, or portion of the overall manufacturing process, that was selected for evaluation. Note that although the emphasis is on the manufacturing process and its impact on the gasket, one must also consider the impact of a faulty gasket on the automobile. Thus, the FMECA needs to address both the *process* and the *product.*

As shown in Figure B.2, the approach selected for conducting the FMECA was in accordance with the practices followed in the automotive industry.[2] This included the following:

1. Identifying the different failure modes; that is, the manner in which a system element fails to accomplish its function.
2. Determining the cause(s) of failure; that is, the factor(s) responsible for the occurrence of each failure. An Ishikawa *cause-and-effect,* or *fishbone,* diagram, as illustrated in Figure B.4, was utilized to help establish the relationships between failures and their possible causes.[3]
3. Determining the effects of failure; that is, the effects on subsequent functions/processes, on the next higher-level functional entity, and on the overall system.
4. Identifying failure detection means; that is, the current controls, design features, or verification procedures that will result in the detection of potential failure modes.
5. Determining the severity of a failure mode; that is, the seriousness of the effect or impact of a particular failure mode. The degree of severity was converted quantitatively on a scale of 1 to 10, with *minor* effects being 1, *low* effects being 2 to 3, *moderate* effects being 4 to 6, *high* effects being 7 to 8, and *very high* effects being 9 to 10. The level of severity was related to issues pertaining to safety and the degree of customer dissatisfaction.
6. Determining the frequency of occurrence; that is, the frequency of occurrence of each individual failure mode or the probability of failure. A scale of 1 to 10 was applied with *remote* (failure is unlikely) being 1, *low* (relatively few failures) being 2 to 3, *moderate* (occasional failures) being 4 to 6, *high* (repeated failures) being 7 to 8, and *very high* (failure is almost inevitable) being 9 to 10. These rating factors were based on the number of failures per segment of operating time.
7. Determining the probability that a failure will be detected; that is, the probability that the design features/aids and/or verification procedures will detect potential failure modes in time to prevent a system-level failure. For a process application, this refers to the probability that a set of process controls currently in place will be in a position to detect and isolate a failure before it is transferred to the subsequent processes or to the ultimate product output. This probability is once again rated on a scale of 1 to 10, with *very high* being 1 to 2, *high*

[2]Three references were used, including (1) *Potential Failure Mode and Effects Analysis;* Instruction Manual, Ford Motor Company, 1988; (2) *Failure Mode and Effects Analysis.* Instruction Manual, Saturn Quality System, Saturn Corporation, 1990; and (3) *Potential Failure Mode and Effects Analysis (FMEA),* Reference Manual FMEA-1, developed by FMEA teams at Ford Motor Company, General Motors, Chrysler, Goodyear, Bosch, and Kelsey-Hayes, under the auspices of the American Society of Quality Control (ASQC).

[3]K. Ishikawa, *Introduction to Quality Control* (London: Chapman and Hall, 1991).

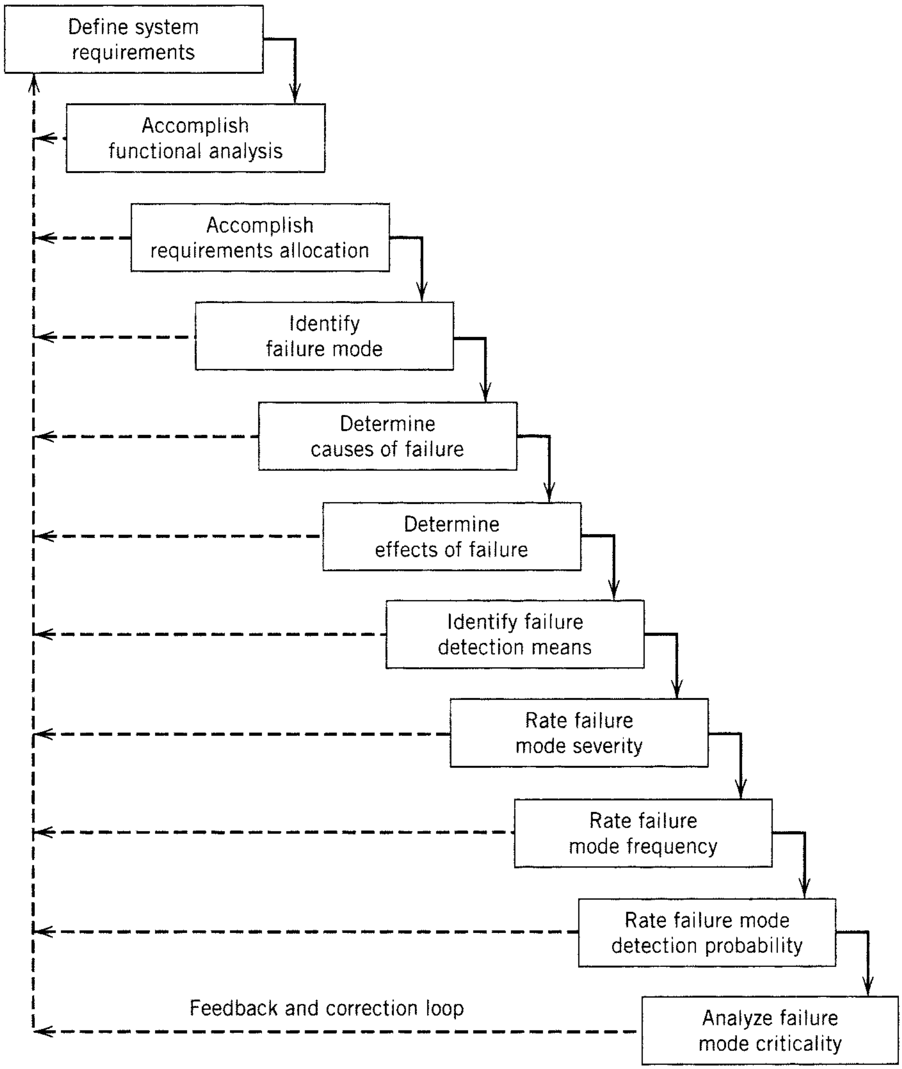


Figure B.2 General approach to conducting a FMECA.

being 3 to 4, *moderate* being 5 to 6, *low* being 7 to 8, *very low* being 9, and *absolute certainty of nondetection* being 10.

8. Analyzing failure mode criticality; that is, a function of severity (item 5), the frequency of occurrence of a failure mode (item 6), and the probability that it will be detected in time to preclude its impact at the system level (item 7). This resulted in the determination of the *risk priority number* (RPN) as a metric for evaluation. RPN can be expressed as:

$$\text{RPN} = (\text{severity rating})(\text{frequency rating})(\text{probability of detection rating}) \tag{B.1}$$

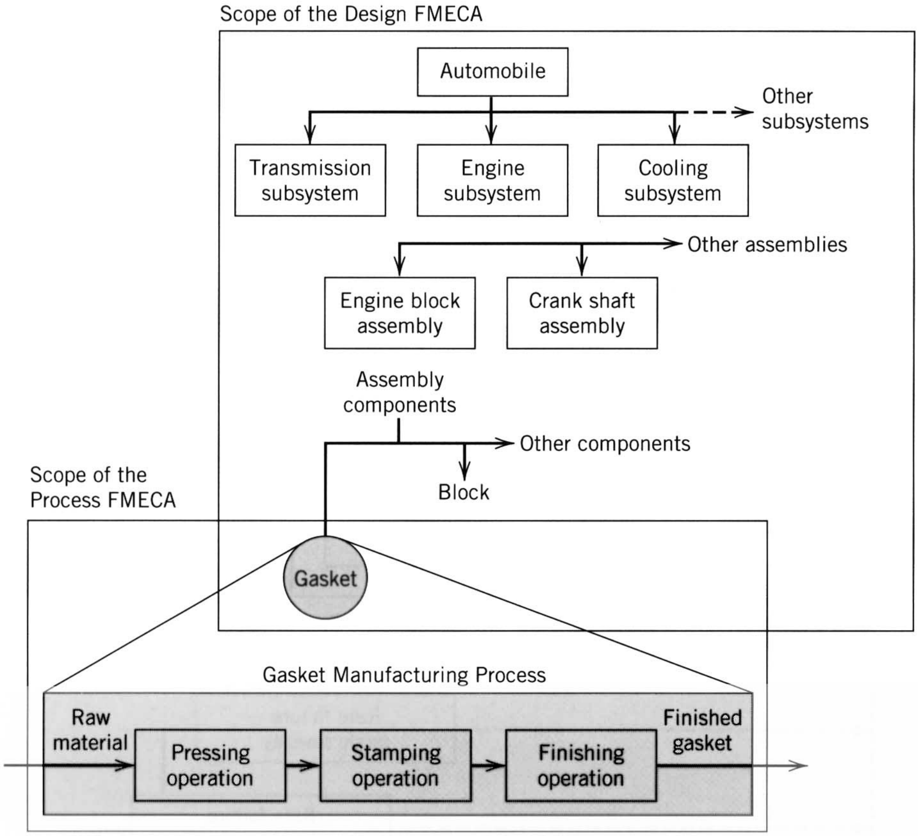


Figure B.3 Design and process FMECA focus and scope.

The RPN reflects failure-mode criticality. On inspection, one can see that a failure mode with a high frequency of occurrence, with significant impact on system performance, and that is difficult to detect is likely to have a very high RPN.

9. Identifying critical areas and recommending modifications for improvement; that is, the iterative process of identifying areas with high RPNs, evaluating the causes, and initiating recommendations for process/product improvement.

Figure B.5 shows a partial example of the format used for recording the results of the FMECA. The information was derived from the functional flow diagram and expanded to include the results from the steps presented in Figure B.2. Figure B.6 lists the resulting RPNs in order of priority (relative to requiring attention), and Figure B.7 presents the results in the form of a Pareto analysis.

B.1.3 The Analysis Results

After having completed the FMECA on the function identified in Figure B.3, Company ABC proceeded to evaluate each of its other 12 major functions/processes in a

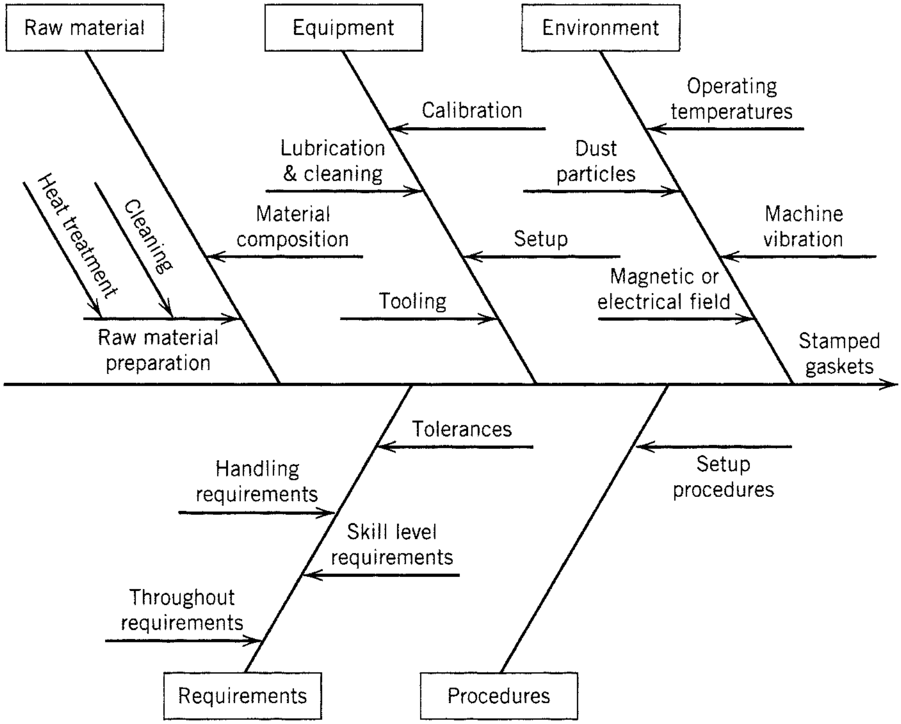


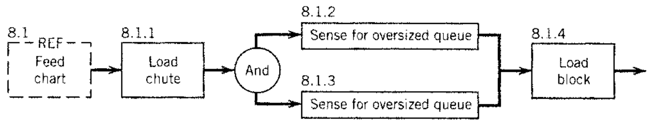
Figure B.4 The Ishikawa cause-and-effect (fishbone) diagram.

similar manner, utilizing a *team* approach. The activity was very beneficial overall, the individuals participating in the effort learned more about their own activities, and numerous changes were initiated for purposes of improvement.

B.2 FAULT-TREE ANALYSIS (FTA)

B.2.1 Definition of the Problem

During the very early stages of the system design process, and in the absence of the information required to complete a FMECA (discussed in Section B.1), a fault-tree analysis (FTA) was conducted to gain insight into critical aspects of system design. A fault-tree analysis is a deductive approach involving the graphical enumeration and analysis of the different ways in which a particular system failure can occur and the probability of its occurrence. A separate fault tree is developed for every critical failure mode or undesired top-level event. The emphasis is on this top-level event and the first-tier causes associated with it. Each of these causes is next investigated for *its* causes, and so on. This top-down hierarchy, illustrated in Figure B.8, and the associated probabilities, is called a *fault tree.* Figure B.9 presents some of the symbology used in the development of such a structure.



Process Failure Mode and Effects Analysis

Reference Number	Process Description	Potential Failure Mode	Potential Cause of Failure	Potential Effect(s) of Failure at Federal Mongul	Potential Effect(s) of Failure at Customer	Current Controls	Occurrence	Beverity FM	Beverity C	Detection	RPN	Recommended Action(s) and Status	Responsible Activity
8.1.2	Sense for oversized queue	A) Change in free spread	1) Sensor fails	a) Up process jams		a) Machine shops	1	1		1	1		
				b) Height variations		b) 1 Pc/5 min	1	7		3	21		
					c) Bearing loose when installed in engine	c) 2 Pcs/half hr	1		7	5	35		
			1) Sensor dirty	a) Up process jams		a) Machine shops	1	1		1	1		
				b) Height variations		b) 1 Pc/5 min	1	7		3	21		
					c) Bearing loose when installed in engine	c) 2 Pcs/half hr	1		7	5	35		
			1) Improper setup	a) Up process jams		a) Machine shops	1	1		1	1		
				b) Height variations		b) 1 Pc/5 min	1	7		3	21		
					c) Bearing loose when installed in engine	c) 2 Pcs/half hr	1		7	5	35		
8.1.3	Sense for undersized queue	A) Up mislocated	1) Sensor fails	a) Up process jams		a) 100% visual	2	1		1	2		
					b) Fillet ride	b) 5 Pcs/half hr	2		3	7	42		
			2) Sensor dirty	a) Up process jams		a) 100% visual	2	1		1	2		
					b) Fillet ride	b) 5 Pcs/half hr	2		3	7	42		
			3) Improper setup	a) Up process jams		a) 100% visual	2	1		1	2		
					b) Fillet ride	b) 5 Pcs/half hr	2		3	7	42		
		B) Facing/back damage	1) Sensor fails		a) Rejected at assembly	a) 100% visual	3		5	4	60		
			2) Sensor dirty		a) Rejected at assembly	a) 100% visual	3		5	4	60		
			3) Improper setup		a) Rejected at assembly	a) 100% visual	3		5	4	60		
8.1.4	Load block	A) Up mislocated	1) "Hold down" not set properly	a) Up smashed in broache		a) 5 Pcs/half hr	3	7		7	147		
				b) Up process jams		b) 100% visual	3	1	3	7	21		
					c) Fillet ride	c) 5 Pcs/half hr	3			7	63		
			2) Loose load block	a) Up smashed in broache		a) 5 Pcs/half hr	2	7		7	96		
				b) Up process jams		b) 100% visual	2	1	3	7	14		
					c) Fillet ride	c) 5 Pcs/half hr	2		5	7	42		
		B) Facing/back damage	1) Misaligned pusher		a) Rejected at assembly	a) 100% visual	4			4	80		

Figure B.5 Sample FMECA worksheet.

Causes	Risk Priority Numbers (RPNs)
Chip breaker angle ground incorrectly	273
Hold-down not set correctly	210
Undersize sensor fails	200
Undersize sensor dirty	200
Undersize sensor not positioned properly	200
Loose load block	161
Sharp die edge	120
Improper projection angle/resharpening of punch	108
Oversize sensor fails	105
Oversize sensor dirty	105
Oversize sensor not positioned properly	105
Improper sharpening of insert	93
Misaligned pusher	80
Worn tooling	72
Adapter reground to wrong dimension	60
Insert loose	60
Slivers in adapter	60
Insert off location	60
Worn/loose insert	60
Burrs from punch process caught	40
Ram stroke too long	36
Ram stroke too short	21
Broken/loose punch	12
Setscrew fault	12
Insufficient stroke by ram/punch	12
Broken pressure spring	10
Total	2475

Figure B.6 Risk priority numbers (RPNs).

B.2.2 The Analysis Process

One of the outputs from an FTA is the probability of occurrence of the top-level event or failure. If the probability factor is unacceptable, the causal hierarchy developed provides engineers with insight into aspects of the system to which redesign efforts may be directed or for which compensatory provisions may be provided. The logic used in developing and analyzing a fault tree has its foundations in Boolean algebra. Axioms from Boolean algebra are used to collapse the initial version of the fault tree to an equivalent reduced tree with the objective of deriving *minimum cut sets*. Minimum

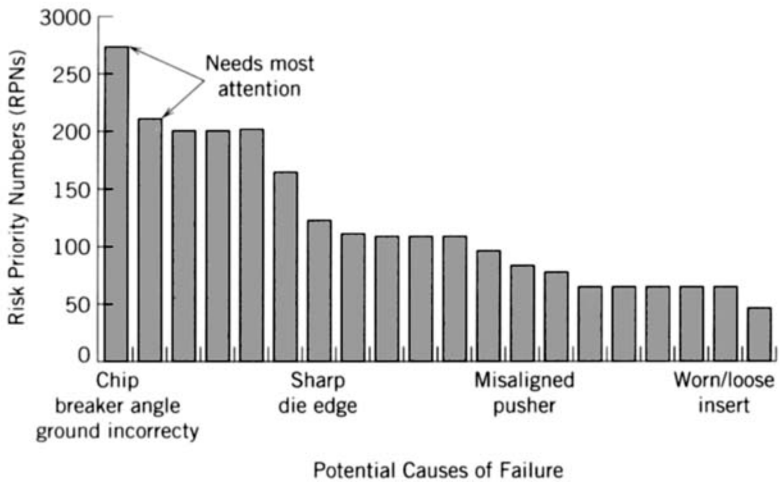


Figure B.7 Partial Pareto analysis.

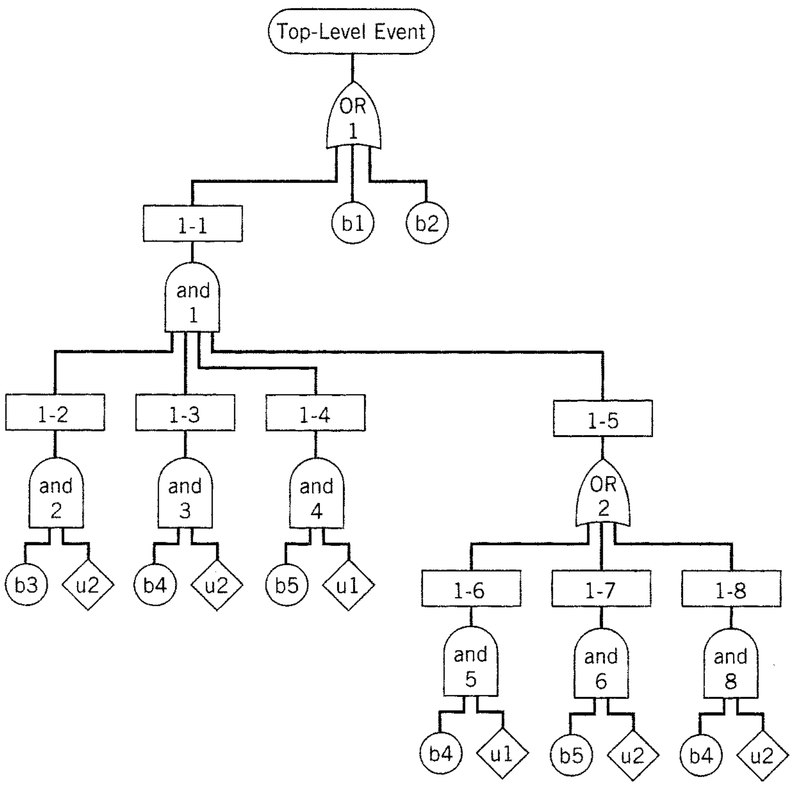


Figure B.8 An illustrative fault tree.

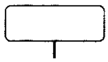
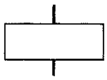
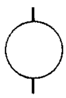
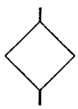
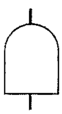
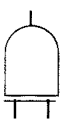
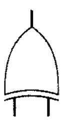
Fault Tree Symbol	Discussion
	The ellipse represents the *top-level event.* Obviously, the ellipse always appears at the very top of a fault tree.
	The rectangle represents an *intermediate fault event.* A rectangle can appear anywhere in a tree except at the lowest level in the hierarchy.
	A circle represents the *lowest-level failure event,* also called a *basic event.* Basic events are likely to appear at the lowest level in a fault tree.
	The diamond represents an *undeveloped event.* Undeveloped events could be further broken down, but are not for the sake of simplicity. Very often, complex undeveloped events are analyzed through a separate fault tree. Underdeveloped events appear at the lowest level in a fault tree.
	This symbol, sometimes called the house, represents an *input event.* An input event refers to a signal or input that could cause a system failure.
	This symbol represents the *AND logic gate.* In this case the output is realize only after all the associated inputs have been received.
	This symbol represents the *OR logic gate.* In this case any one or more of the inputs need to be received for the output to be realized.
	This symbol represents the *ORDERED AND logic gate. In* this case, the output is realized only after all the associated inputs have been received in a particular predetermined order.
	This symbol represents the *EXCLUSIVE OR logic gate.* In this case, one and only one of the associated inputs needs to be received for the input to be realized.

Figure B.9 Fault-tree constructive symbology.

cut sets are unique combinations of basic failure events that can cause the undesired top-level event to occur. These minimum cut sets are necessary to evaluate a fault tree from a qualitative and quantitative perspective. The basic steps in conducting an FTA are as follows:

1. Identify the top-level event. It is essential that the analyst be quite specific in defining this event. For example, it may be delineated as the "system catches

fire," rather than the "system fails." Further, the top-level event should be clearly observable and unambiguously definable and measurable. A generic and non-specific definition is likely to result in a broad-based fault tree with a scope that is too wide and lacking in focus.

2. Develop the fault tree. Once the top-level event has been satisfactorily defined, the next step is to construct the initial causal hierarchy in the form of a fault tree. Once again, a technique such as Ishikawa's cause-and-effect diagram can be beneficial (refer to Figure B.4). In developing the fault tree, all hidden failures must be considered and incorporated.

   For the sake of consistency and communication, a standard symbology to develop the fault tree is recommended. Figure B.9 depicts and defines the symbology to comprehensively represent the causal hierarchy and interconnects associated with a particular top-level event. In Figure B.8, the symbols OR1 and OR2 represent the two OR logic gates, "and 1" through "and 8" represent eight AND logic gates, 1-1 through 1-8 represent eight intermediate fault events, b1 through b5 represent five basic events, and u1 and u2 represent two undeveloped failure events. In constructing a fault tree, it is important to break every branch down to a reasonable and consistent level of detail.

3. Analyze the fault tree. The third step in conducting the FTA is to analyze the initial fault tree developed. A comprehensive analysis of a fault tree involves both a quantitative and a qualitative perspective. The important steps in completing the analysis of a fault tree are as follows:
   (a) *Delineate the minimum cut sets.* As part of the analysis process, the minimum cut sets in the initial fault tree are first delineated. These are necessary to evaluate a fault tree from a qualitative and/or quantitative perspective. The objective of this step is to reduce the initial tree to a simpler equivalent reduced fault tree. The minimum cut sets can be derived using two different approaches. The first approach involves a graphical analysis of the initial tree, an enumeration of all the cut sets, and the subsequent delineation of the minimal cut sets. The second approach, on the other hand, involves translating the graphical fault tree into an equivalent Boolean expression. This Boolean expression is then reduced to a simpler equivalent expression by eliminating all the redundancies. For example, the fault tree depicted in Figure B.8 can be translated into a simpler and equivalent fault tree, through Boolean reduction, as depicted in Figure B.10.
   (b) *Determine the reliability of the top-level event.* This is accomplished by first determining the probabilities of all relevant input events, and the subsequent consolidation of these probabilities in accordance with the underlying logic of the tree. The reliability of the top-level event is computed by taking the product of the reliabilities of the individual minimum cut sets.
   (c) *Review analysis output.* If the derived top-level probability is unacceptable, necessary redesign or compensation efforts will have to be initiated. The development of the fault tree and subsequent delineation of minimum cut sets provides engineers and analysts with the kind of foundation needed for making sound decisions.

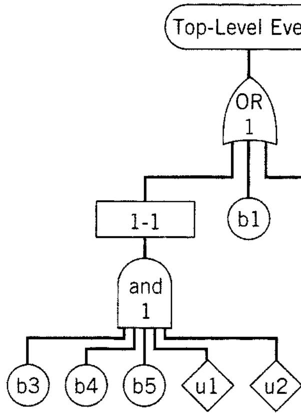


Figure B.10 A reduced equivalent fault tree (refer to Figure B.8).

B.2.3 The Analysis Results

An FTA can be effectively applied in the early phases of design to specific areas where potential problems are suspected. It is narrow in focus and easier to accomplish than an FMECA, requiring less input data to complete. For large and complex systems, which are highly software-intensive and where there are many interfaces, the use of the FTA is often preferred in lieu of the FMECA. The FTA is most beneficial if conducted, not in isolation, but as part of an overall system analysis process.[4]

B.3 RELIABILITY-CENTERED MAINTENANCE (RCM)

B.3.1 Definition of the Problem

Reliability-centered maintenance (RCM) is a systematic approach to develop a focused, effective, and cost-efficient preventive maintenance program and control plan for a system or product. This technique is best initiated during the early system design process and evolves as the system is developed, produced, and deployed. However, the technique can also be used to evaluate preventive maintenance programs for existing systems, with the objective of continuous product/process improvement.

The RCM technique was developed in the 1960s primarily through the efforts of the commercial airline industry.[5] The approach is through a structured decision tree that leads the analyst through a "tailored" logic in order to delineate the most applicable preventive maintenance tasks (their nature and frequency). The overall process involved in implementing the RCM technique is illustrated in Figure B.11. Note that the functional analysis and the FMECA are necessary inputs to the RCM, and that

[4]Reliability Analysis Center (RAC), *Fault Tree Analysis Application Guide* (Rome, NY: Rome Air Development Center, 1990). An excellent "how-to" source for the application of FTA depicting numerous case studies.

there are trade-offs resulting in a balance between preventive maintenance and the accomplishment of corrective maintenance. Figure B.12 presents a simplified RCM decision logic, where system safety is a prime consideration along with performance and cost.

B.3.2 The Analysis Process

The major steps in accomplishing an RCM analysis include the following:

1. Identify the critical system functions and/or components—For example, airplane wings, car engine, printer head, video head, and so on. Criticality in terms of this analysis is a function of the failure frequency, the failure effect severity, and the probability of detection of the relevant failure modes. The concept of criticality is discussed in more detail in Section B.1. This step is facilitated through outputs from the system functional analysis (see Section 2.7) and the failure mode, effects, and criticality analysis (FMECA). This is also depicted in Figure B.11, Blocks 1.0 to 4.0.

2. Apply the RCM decision logic and preventive maintenance (PM) program development approach. The critical system elements are subjected to the tailored RCM decision logic. The objective here is to better understand the nature of failures associated with the critical system functions or components. In each case, and whenever feasible, this knowledge is translated into a set of preventive maintenance tasks, or a set of redesign requirements. A simplified illustrative RCM decision logic is depicted in Figure B.12. Numerous decision logics, with slight variations to the original MSG-3 logic and tailored to better address certain types of systems, have been developed and are currently being utilized.[6]

These slight variations notwithstanding (as illustrated in Figure B.12), the first concern is whether a *failure is evident or hidden.* A failure can become evident through the aid of certain color-coded visual gauges and/or alarms. It may also become evident if it has a perceptible impact on system operation and performance. On the other hand, a failure may not be evident (i.e., hidden) in the absence of an appropriate

[5]A maintenance steering group (MSG) was formed in the 1960s that undertook the development of this technique. The result was a document entitled *747 Maintenance Steering Group Handbook: Maintenance Evaluation and Program Development (MSG-1),* published in 1968. This effort, focused on a particular aircraft, was next generalized and published in 1970 as *Airline/Manufacturer Maintenance Program Planning Document-MSG2.* The MSG-2 approach was further developed and published in 1978 as *Reliability Centered Maintenance,* Report Number A066-579, prepared by United Airlines, and in 1980 as *Airline/Manufacturer Maintenance Program Planning Document-MSG3.* The MSG-3 report has been revised and is currently available as *Airline/Manufacturer Maintenance Program Development Document (MSG-3), 1993.* These reports are available from the Air Transport Association.

[6]RCM decision logics, with some variations, have also been proposed in (1) MIL-STD-2173(AS), "Reliability-Centered Maintenance Requirements for Naval Aircraft. Weapons Systems, and Support Equipment"; (2) AMC-P-750-2, *Guide to Reliability-Centered Maintenance;* (3) John Moubray, *Reliability-Centered Maintenance,* 2d ed. (New York: Industrial Press, 1997); and (4) Smith, A. M., Reliability-Centered Maintenance, New York, McGraw-Hill, Inc., 1993.

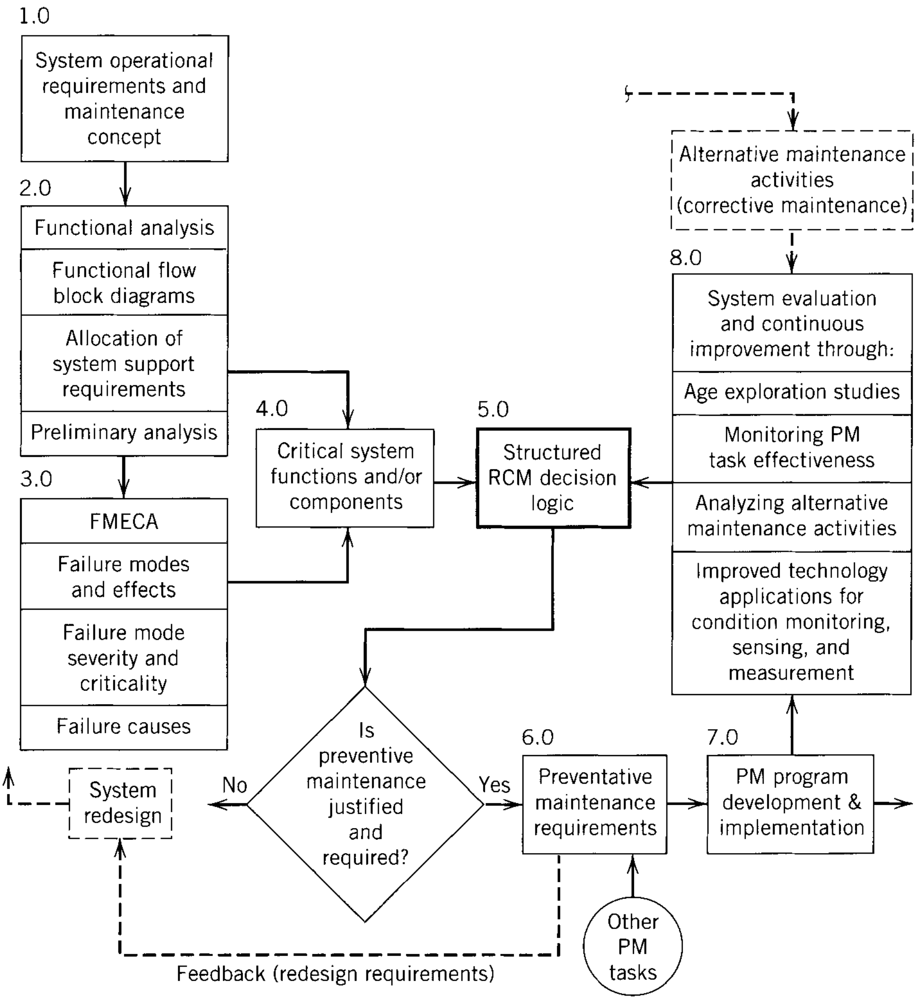


Figure B.11 Reliability-centered maintenance analysis process.

alarm, and even less so if it does not have an immediate or direct impact on system performance. For example, a leaking engine gasket is not likely to reflect an immediate and evident change in an automobile's operation, but it may in time and, after most of the engine oil has leaked, cause engine seizure. In the event that a failure is not immediately evident, it may be necessary to either initiate a specific fault-finding task as part of the overall PM program or design in an alarm that signals a failure (or pending failure).

The next concern is whether the failure is likely to compromise personal safety or system functionality. Queries exist in the decision logic to clarify this and other likely impacts of failures. This step in the overall process can be facilitated by the results of

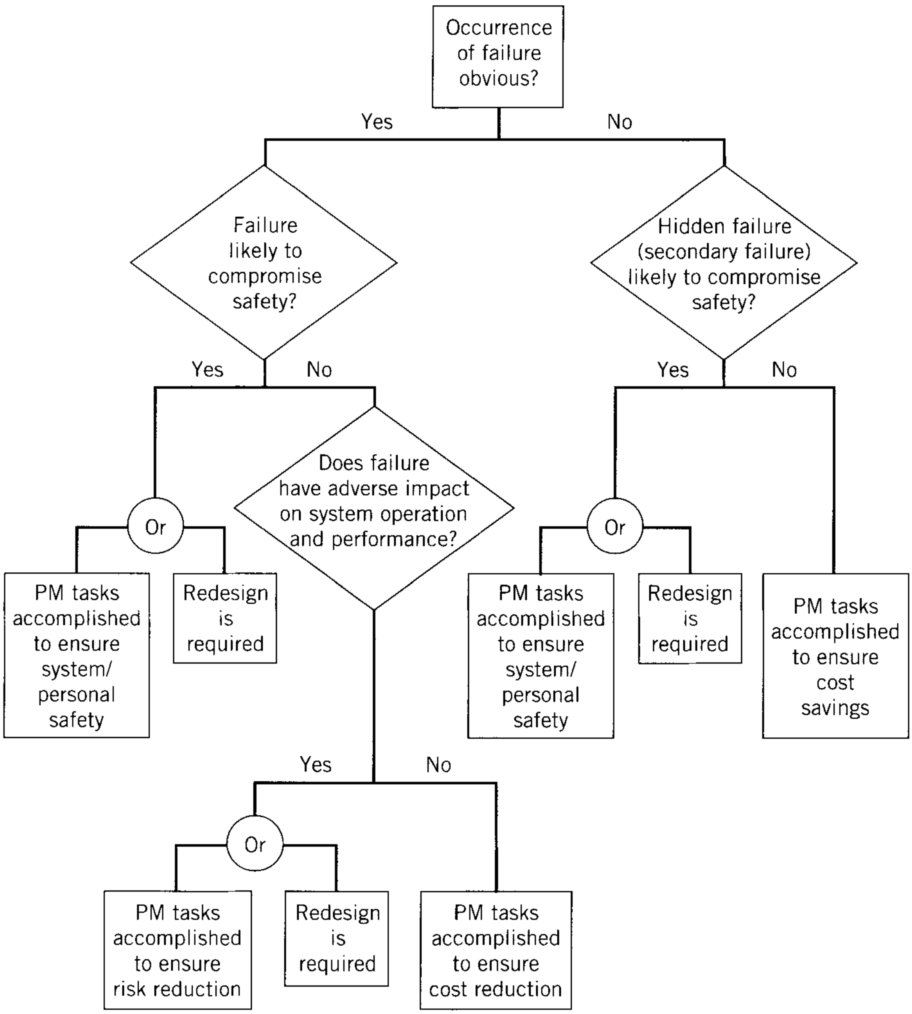


Figure B.12 Simplified RCM decision logic.

the FMECA (Section B.1). The objective is to better understand the basic nature of the failure being studied. Is the failure likely to compromise the system or personnel safety? Does it have an operational or economic impact? For example, a failure of an aircraft wing may be safety-related, whereas a certain failure in the case of an automobile engine may result in increased oil consumption without any operational degradation and will therefore have an economic impact. In another case, a failed printer head may result in a complete loss of printing capability and may be said to have an operational impact, and so on.

Once the failure has been identified as a certain type, it is then subjected to another set of questions. However, in order to answer this next set of questions adequately, the analyst must thoroughly understand the nature of the failure from a *physics-of-failure* perspective. For example, in the event of a crack in an airplane wing, how fast is this crack likely to propagate? How long before such a crack causes a functional failure?

These questions have an underlying objective of delineating a feasible set of compensatory provisions or preventive maintenance tasks. Is a lubrication or servicing task applicable and effective, and, if so, what is the most cost-effective and efficient frequency? Will a periodic check help preclude a failure, and at what frequency? Periodic inspections or checkouts are likely to be most applicable in situations where a failure is unlikely to occur immediately, but is likely to develop at a certain rate over a period of time. The frequency of inspections can vary from very infrequently to continuously, as in the case of condition monitoring. Some of the more specific queries are presented in Figure B.12. In each case, the analyst must not only respond with a "yes" or "no," but should also give specific reasons for each response. Why would lubrication either make, or not make, any difference? Why would periodic inspection be a *value-added* task? It may be that the component's wear-out characteristics have a predictable trend, in which case inspections at predetermined intervals could preclude corrective maintenance. Would it be effective to discard and replace certain system elements in order to upgrade the overall inherent reliability? And, if so, at what intervals or after how many hours of system operation (e.g., changing the engine oil after 3000 miles of driving)? Further, in each case a trade-off study, in terms of the benefit/cost and overall impact on the system, needs to be accomplished to determine the trade-offs between performing a task and not performing it.

In the event that a set of applicable and effective preventive maintenance requirements are delineated, they are input to the preventive maintenance program development process and subsequently implemented, as shown in Figure B.11, blocks 5.0 to 7.0. If no feasible and cost-effective provisions or preventive maintenance tasks can be identified, a redesign effort may have to be initiated.

3. Accomplish PM program implementation and evaluation. Very often, the PM program initially delineated and implemented is likely to have failed to consider certain aspects of the system, delineated a very conservative set of PM tasks, or both. Continuous monitoring and evaluation of preventive maintenance tasks along with all other (corrective) maintenance actions is imperative in order to realize a cost-effective preventive maintenance program. This is depicted in Figure B.11, block 8.0. Further, given the continuously improving technology applications in the field of condition monitoring, sensing, and measurement, PM tasks need to be reevaluated and modified whenever necessary.

Often, when the RCM technique is conducted in the early phases of the system design and development process, decisions are made in the absence of ample data. These decisions may have to be verified and modified, whenever justified, as part of the overall PM evaluation and continuous improvement program. Age exploration studies are often conducted to facilitate this process. Tests are conducted on samples of unique system elements or components with the objective of better understanding their reliability and wear-out characteristics under actual operating conditions. Such studies can aid the evaluation of applicable PM tasks and help delineate any dominant failure modes associated with the component being monitored and/or any correlation between component age and reliability characteristics. If any significant correlation between age and reliability is noticed and verified, the associated PM tasks and their frequency may be modified and adapted for greater effectiveness. In addition, redesign efforts may be initiated to account for some, if any, of the dominant component failure modes.

B.3.3 The Analysis Results

Quite often in the early design process, as system components are being selected, the issue of maintenance is ignored altogether. If maintenance is addressed, however, the designer may tend to specify components requiring some preventive maintenance (usually recommended by the manufacturer). If this is done, the perception is that such PM recommendations are based on actual knowledge of the component in terms of its physical characteristics, expected modes of failure, and so on. It is also believed that the more preventive maintenance required, the better the reliability. In any event, there is often a tendency to overspecify the need for PM because of the reliability issue, particularly if the component *physics-of-failure* characteristics are not known and the designer assumes a conservative approach, just in case.

Experience indicates that although the accomplishment of some selective preventive maintenance is essential, the overspecification of PM activities can actually cause a degradation of system reliability and can be quite costly. The objective is to specify the correct amount of PM, to the depth required, and at the proper frequency; that is, *not too much or too little*. Further, as systems age, the required amount of PM may shift from one level to another. The application of RCM methods on a continuing basis is highly recommended, particularly in evaluating systems from a life-cycle cost perspective.

B.4 MAINTENANCE TASK ANALYSIS (MTA)

B.4.1 Definition of the Problem

Company DEF has been manufacturing Product 12345 for the past few years. The costs have been higher than anticipated, and international competition has been increasing. As a result, company management has decided to conduct an evaluation of the overall production capability, identify "high-cost" contributors through the accomplishment of a life-cycle cost analysis, and identify possible problem areas where improvement can be realized. One area for possible improvement is the manufacturing test function where frequent failures have occurred during Product 12345 test. By reducing maintenance costs, it is likely that one can reduce the overall cost of the product and improve the company's competitive position in the marketplace. With the objective of identifying some "specifics," a detailed maintenance task analysis of the manufacturing test function is accomplished. Specific recommendations for improvement are being solicited.

B.4.2 The Analysis Process

In response, a detailed maintenance task analysis is performed, using the format included in Appendix E of B. S. Blanchard, *Logistics Engineering and Management*, 5th ed. (Upper Saddle River, NJ: Prentice-Hall, 1998). The format, as adapted for the purpose of this evaluation, includes the following general steps:

1. Review of historical information covering the performance of the manufacturing test capability indicated the frequent loss of power during the final testing of Product 12345. From this, a typical "symptom of failure" was identified, and a sample logic troubleshooting flow diagram was developed, as shown in Figure B.13.

2. The applicable "go/no-go" functions, identified in Figure B.13, are converted to the task analysis format in Figures B.14 and B.15. The functions are analyzed on the basis of determining task requirements (task durations, parallel-series relationships, sequences), personnel quantity and skill-level requirements, spare/repair part requirements, test and support equipment requirements, special facility requirements, technical data requirements, and so on. The intent in Figure B.14 is to lay out the applicable maintenance tasks required, determine the anticipated frequency of occurrence, and identify the logistic support resources that are likely to be necessary for the performance of the required maintenance. This information, in turn, can be evaluated on the basis of cost.

3. Given the preliminary results of the analysis in terms of the layout of expected maintenance functions/tasks, the next step is to evaluate the information presented in Figures B.14 and B.15 and suggest possible areas where improvement can be made.

B.4.3 The Analysis Results

A review of the information presented in Figures B.14 and B.15 suggests that the following areas be investigated further:

1. With the extensive resources required for the repair of Assembly A-7 (e.g., the variety of special test and support equipment, the necessity for a "clean room" facility for maintenance, the extensive amount of time required for the removal and replacement of CB-1A5, etc.), it may be feasible to identify Assembly A-7 as being nonrepairable. In other words, the analyst should investigate the feasibility of whether the assemblies of Unit B should be classified as "repairable" or "discard at failure."

2. For Tasks 01 and 02, a "built-in test" capability exists at the organizational level for fault isolation to the Subsystem. However, fault isolation to the unit requires a special system tester (0-2310B), and it takes 25 minutes of testing plus a highly skilled (supervisory skill) individual to accomplish the function. In essence, one should investigate the feasibility of extending the built-in test down to the unit level and eliminate the need for the special system tester and the high-skill-level individual.

3. The physical removal of Unit B from the system and its replacement takes 15 minutes, which seems rather extensive. Although perhaps not a major item, it would be worthwhile investigating whether the removal/replacement time can be reduced (to less than 5 minutes, for example).

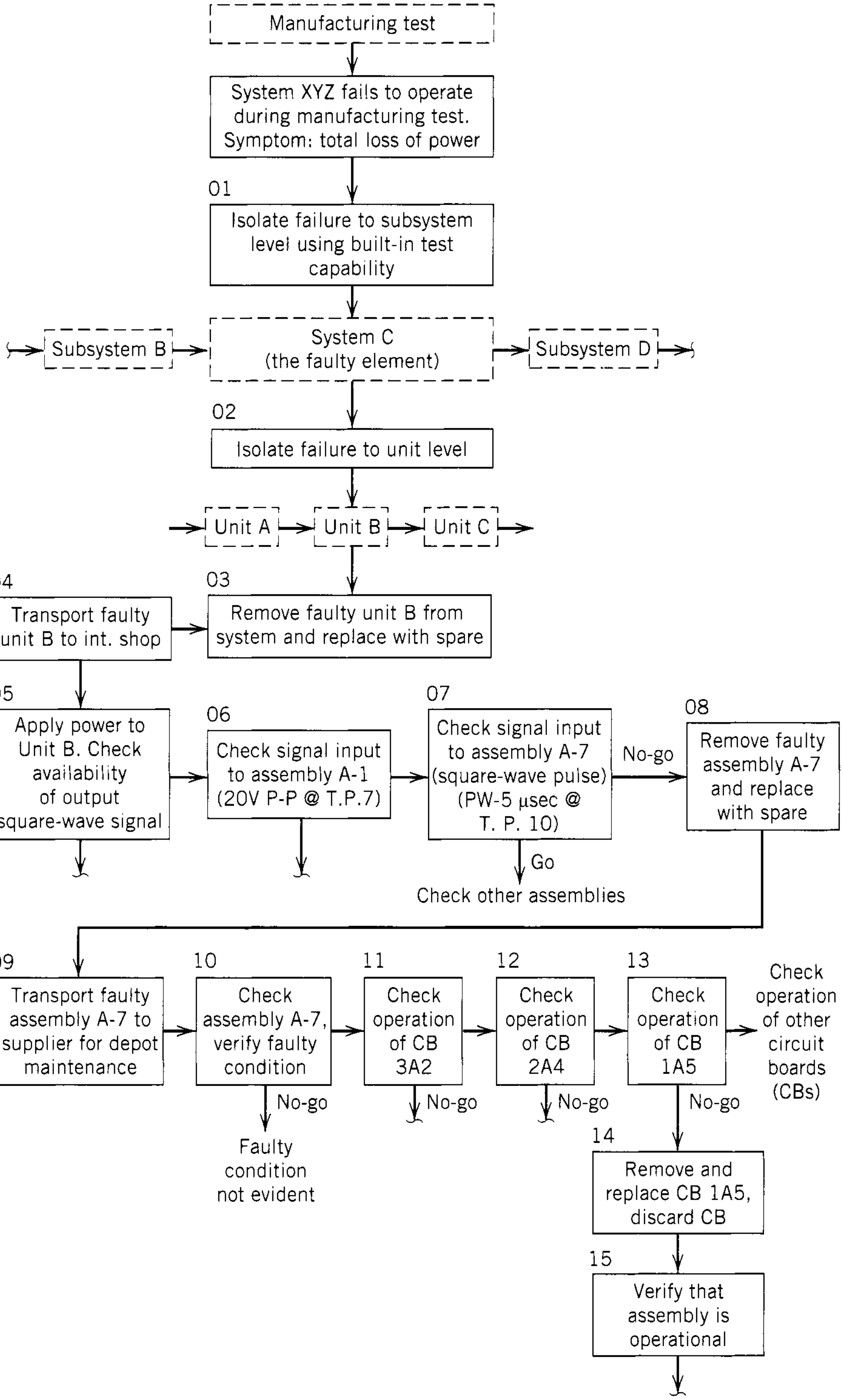


Figure B.13 Abbreviated logic troubleshooting flow diagram.

1. System: XYZ	2. Item name/part no.: Manufacturing Test/A4321		3. Next higher assy.: Assembly and test		4. Description of requirement: During manufacturing and test of Product 12345 (Serial No. 654), System XYZ failed to operate. The symptom of failure was "loss of total power output." Requirement: Troubleshoot and repair system.
5. Req. No.: 01	6. Requirement: Diag./Repair	7. Req. Freq.: 0.00450	8. Maint. Level: Org/Inter.	9. Ma. Cont. No.: A12B100	

10. Task Number	11. Task Description	12. Elapsed time - minutes (2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38)	13. Total elap. time	14. Task Freq.	Personnel Man-min			
					15. B	16. I	17. S	18. Total
01	Isolate failure to subsystem level		5	0.00450	5	-	-	5
	(Subsystem C is faulty)							
02	Isolate failure to unit level	1	25		-	25	-	25
	(Unit B is faulty)	2					25	25
03	Remove Unit B from system and	(2nd cycle)	15		15	-	-	15
	replace with a spare Unit B							
04	Transport faulty unit to int. shop		30		30	-	-	30
05	Apply power to faulty unit. Check	(3rd cycle)	20		-	20	-	20
	for output squarewave signal							
06	Check signal input to Assembly A-1		15		-	15	-	15
	(20v P-P @ T.P.7)							
07	Check signal input to Assembly A-7	(4th cycle)	20		-	20	-	20
	(squarewave, PW-5μsec @T.P. 2)							
08	Remove faulty A-7 & replace		10		10	-	-	10
09	Transport faulty Assembly A-7 to	14 calendar days in transit						
	supplier for depot maintenance							
10	Check A-7 & verify faulty condition	(5th cycle)	25		-	-	25	25
11	Check operation of CB-3A2		15		-	-	15	15
12	Check operation of CB-2A4		10		-	-	10	10
13	Check operation of CB-1A5	(6th cycle)	20		-	-	20	20
14	Remove and replace faulty CB-1A5	(7th cycle)	40		-	40	-	40
	Discard faulty circuit board							
15	Verify that assembly is operational		15		-	-	15	15
	and return to inventory							
		Total	265	0.00450	60	120	110	290

Figure B.14 Maintenance task analysis (Part 1).

1. Item name/Part No.: Manufacturing Test/A4321			2. Req No.: 01	3. Requirement: Diagnostic Troubleshooting and repair		4. Req. Freq.: 0.00450	5. Maint. level: Organization, Intermediate, Depot	6. Ma. Cont. No.: A12B100
7. Task No.	8. Qty. per Assy.	Replacement Parts 9. Part nomenclature 11. Part number	10. Rep. Freq.	Test & Support/Handling Equipment 12. Qty.	13. Item part nomenclature 15. Item part number	14. Use time (min)	16. Description of Facility Requirements	17. Special Technical Data Instructions
01	-	-	-	1	Bulit-in test equip. A123456	5	-	Organizational Maintenance
02				1	Special system tester 0-2310B	25	-	
03	1	Unit B B180265X	0.01866	1	Standard tool kit STK-100-B	15	-	
04	-	-	-	1	Standard cart (M-10)	30	-	Intermediate maintenance
05	-	-	-	1	Special system tester I-8891011-A	20	-	
06	-	-	-	1	Special system tester I-8891011-A	15	-	
07	-	-	-	1	Special system tester I-8891011-A	20	-	
08	1	Assembly A-7 MO-2378A	0.00995	1	Special extractor tool EX20003-4	10	- -	Refer to special removal instructions
09	-	-	-	1	Container, special handling T-300A	14 days	-	Normal trans. environment
10	-	-	-	1	Special system tester I-8891011-B	25	Clean room environment	Supplier (depot) maintenance
11	-	-	-	1	C.B. test set D-2252-A	15		
12	-	-	-	1	C.B. test set D-2252-A	10		
13	-	-	-	1	C.B. test set D-2252-A	20		
14	1	CB-1A5 GDA-221056C	0.00450	1	Special extractor tool EX45112-63 Standard tool kit STK-200	40		
15	-	-	-	1	Special system tester I-8891011-B	15		Return operating assy. to inventory

Figure B.15 Maintenance task analysis (Part 2).

4. In Tasks 10 to 15, a special clean-room facility is required for maintenance. Assuming that the various assemblies of Unit B are repaired (versus being classified as "discard at failure"), then it would be worthwhile to investigate changing the design of these assemblies so that a clean-room environment is not required for maintenance. In other words, can the expensive maintenance facility requirement be eliminated?

5. There is an apparent requirement for a number of new "special" test equipment/tool items; that is, special system tester 0-2310B, special system tester I-8891011-A, special system tester I-8891011-B, CB test set D-2252-A, special extractor tool EX20003-4, and special extractor tool EX45112-63. Usually, these *special* items are limited as to general application for other systems and are expensive to acquire and maintain. Initially, one should investigate whether these items can be eliminated; if test equipment/tools are required, can *standard* items be utilized (in lieu of special items)? Moreover, if the various special testers are required, can they be integrated into a "single" requirement? In other words, can a single item be designed to replace the three special testers and the CB test set? Reducing the overall requirements for special test and support equipment is a major objective.

6. For Task 09, there is a special handling container for the transportation of Assembly A-7. This may impose a problem in terms of the availability of the container at the time and place of need. It would be preferable if normal packaging and handling methods could be utilized.

7. For Task 14, the removal and replacement of CB-1A5 takes 40 minutes and requires a highly skilled individual to accomplish the maintenance task. Assuming that Assembly A-7 is repairable, it would be appropriate to simplify the circuit board removal/replacement procedure by incorporating plug-in components, or at least simplify the task to allow a person with a basic skill level to accomplish it.

B.5 LEVEL-OF-REPAIR ANALYSIS (LORA)

B.5.1 Definition of the Problem

In the design of system components, one of the decision factors relates to the question, Should the component be designed to be "repairable," or should it be designed to be "discarded" in the event of failure? If it is designed to be repairable, at what level of maintenance should the repair be accomplished? Although these questions can be applied to any component of the system (e.g., equipment, unit, assembly, module, and element of software), this case study applies to the design of Assembly A-1. This assembly is one of 15 assemblies in Unit B of System XYZ. The objective is to evaluate design alternatives for the assembly on the basis of economic criteria, as shown in Figure B.16.

B.5.2 The Analysis Process

The accomplishment of a level-of-repair analysis requires that the item being evaluated be presented in terms of a system operational requirement, a maintenance con-

Evaluation Criteria	Repair at Intermediate Cost ($)	Repair at Depot Cost ($)	Discard at Failure Cost ($)	Description and Justification
1. Estimated acquisition cost for Assembly A-1 (to include design and development, production cost)	1,700/Assembly or 102,000 (47.8%)	1,700/Assembly or 102,000 (54.7%)	1,600/Assembly or 96,000 (19.5%)	Acquisition cost is based on 60 systems. Assembly design and production costs are less in the discard case (simplified configuration).
2. Maintenance labor cost	12,240 (5.7%)	18,360 (9.8%)	Not applicable	Based on 452,600 hours of operation and a maintenance rate of 0.00045, the estimated quantity of maintenance actions is 204. When repair is accomplished, one (1) technician is assigned on a full-time basis. The $\overline{Mct}$ is 3 hours. The labor rate is $20/hour for intermediate and $30/hour for depot.
3. Supply support – spare assemblies	8,500 (4%)	17,000 (9.1%)	326,400 (66.4%)	For intermediate maintenance, 5 spare assemblies are required to compensate for turnaround time, the maintenance queue, etc. 10 spares are required for depot maintenance. 100% spares are required for the discard case.
4. Supply support – spare components	10,200 (4.8%)	10,200 (5.5%)	Not applicable	Assume $50 per maintenance action.
5. Supply support – inventory maintenance	3,740 (1.8%)	5,440 (2.9%)	65,280 (13.3%)	Assume 20% of the inventory value (spare assemblies and spare components).
6. Special test and support equipment	60,000 (28.1%)	12,000 (6.4%)	Not applicable	Special test equipment is required in the repair case. The acquisition cost is $12,000 per installation. There are five (5) installations at intermediate and one(1) at depot.
7. Transportation and handling	Negligible	12,240 (6.6%)	Not applicable	Transportation costs at the intermediate level are negligible. For depot maintenance, assume 408 one-way trips at $150/100 pounds. One assembly weighs 20 pounds.
8. Maintenance training	4,500 (2.1%)	900 (0.5%)	Not applicable	Assume 10 students for 3 days at $150 per student day for intermediate, and 2 students for 3 days at $150 per student day for depot.
9. Maintenance facilities	5,612 (2.6%)	1,918 (1%)	Not applicable	Assume $1.00 per direct maintenance manhour for intermediate, and $1.50 per direct manhour for depot. Also, assume an initial fixed cost of $1,000 per installation.
10. Technical data	6,100 (2.9%)	6,100 (3.3%)	Not applicable	For repair case, assume $1,000 for the cost of preparation of maintenance instructions. Also, assume $25 per maintenance action for maintenance data.
11. Disposal	408)0.2%)	408 (0.2%)	4,080 (0.8%)	Assume $20 per assembly and $2 per component as the cost of disposal.
Total Estimated Cost	$213,300	$186,566	$491,760	

Figure B.16 Repair versus discard evaluation (Assembly A-1).

cept, and a program plan. In this instance, it is assumed that System XYZ is installed in an aircraft. When a maintenance action is required, there is a built-in test capability within the aircraft that allows one to isolate the fault to Unit A, Unit B, or Unit C. The applicable unit is removed, replaced with a spare, and the faulty item is transported to the intermediate-level maintenance shop for corrective maintenance. In the maintenance shop, fault isolation is accomplished within the unit to the assembly level. The faulty assembly is removed, replaced with a spare, and the unit is checked out and returned to the inventory as an operational spare. The basic question pertains to the disposition of the assembly.

In approaching this problem, the first step is to accomplish a level-of-repair analysis on Assembly A-1 as an individual entity. Subsequently, the results of this part of the analysis have to be viewed in the context of the whole; that is, the results of similar analyses involving Assemblies A-2, A-3, . . . , and A-15, and the applicable assemblies of Unit A and Unit C. There is usually a feedback effect between the individual assembly analysis, the unit-level analysis, and the overall maintenance concept for the system as a whole.

For completing the level-of-repair analysis on Assembly A-1, the following information is provided:

1. System XYZ is installed in each of 60 aircraft, which are distributed equally at five operating sites over an eight-year time period. System utilization is on the average of 4 hours per day, and the total operating time for all systems is 452,600 hours.

2. As stated earlier, System XYZ includes three units: Unit A, Unit B, and Unit C. Unit B includes 15 assemblies, one of which is Assembly A-1. The estimated acquisition cost for Assembly A-1 (including design and development cost and production cost) is $1700 each if the assembly is designed to be repairable, and $1600 each if the assembly is designed to be discarded at failure. The design for repairability considers the incorporation of diagnostic provisions, accessibility, internal labeling, and so on, which is apt to be more expensive in terms of design and production costs.

3. The estimated failure rate (or corrective maintenance rate) of Assembly A-1 is 0.00045 failure per hour of system operation. When failures occur, repair is accomplished by a single technician who is assigned for the duration of the allocated active maintenance time. The estimated corrective maintenance downtime ($\overline{M}ct$) is three hours. The loaded labor rate is $20 per labor hour for intermediate-level maintenance and $30 per labor hour for depot-level maintenance.

4. Supply support includes three categories of cost: the cost of spare assemblies in inventory, the cost of spare components to enable the repair of faulty assemblies, and the cost of inventory management and maintenance. Assume that 5 spare assemblies will be required in inventory when maintenance is accomplished at the intermediate level, and that 10 spare assemblies will be required when maintenance is accomplished at the depot level. For component spares, assume that the average cost of material consumed per maintenance action is $50. The estimated cost of inventory maintenance is assumed to be 20% of the inventory value (the summation of the costs for assembly and component spares).

5. When assembly repair is accomplished, special test and support equipment is required for fault diagnosis and assembly checkout. The cost per test station is $12,000, which includes acquisition cost and amortized maintenance cost. This cost is that part of the total cost that is attributed to the maintenance requirement for Assembly A-1, and there are five test stations required for intermediate-level maintenance.

6. Transportation and handling cost is considered as being negligible when maintenance is accomplished at the intermediate level. However, assembly maintenance accomplished at the depot level will involve an extensive amount of transportation. For depot maintenance, assume $150 per 100 pounds per one-way trip (independent of distance), and that the packaged assembly weighs 20 pounds.

7. The allocation for Assembly A-1 relative to maintenance facility cost is categorized in terms of an initial fixed cost and a sustaining recurring cost proportional to facility utilization requirements. The initial fixed cost is $1000 per installation, and the assumed usage cost allocation is $1.00 per direct maintenance labor hour at the intermediate level and $1.50 per direct labor hour at the depot level.

8. Technical data and maintenance software requirements include the maintenance instructions to be included in the technical manuals to support assembly repair activities, and the failure reporting and maintenance data covering each maintenance action in the field. Assume that the cost for preparing and distributing maintenance instructions (and supporting computer software) is $1000, and that the cost for field maintenance data is $25 per maintenance action.

9. There will be some initial formal training costs associated with maintenance personnel in considering the assembly repair option. Assume 30 student-days of formal training for the intermediate level of maintenance (for the five sites in total) and 6 student-days for depot-level maintenance. The cost of training is $150 per student-day. The requirement for replenishment training as a result of attrition or turnover is considered as being negligible.

10. As a result of maintenance, there will be a requirement for disposal and/or the recycling of material. The assumed disposal cost is $20 per assembly and $2 per component.

The objective is to evaluate Assembly A-1 based on the information provided. Should Assembly A-1 be designed for (1) repair at the intermediate level of maintenance, (2) repair at the depot level of maintenance, or (3) discard at failure?

B.5.3 The Analysis Results

Figure B.16 presents a worksheet with the results from the evaluation of Assembly A-1. Based on the information shown, it is recommended that the assembly be *repaired at the depot level of maintenance.*

Prior to making a final decision, however, one should review the data in Figure B.16 in terms of "high-cost" contributors and the sensitivities of various input factors. Some of the initial assumptions may have a great impact on the analysis results and, perhaps, should be challenged. The analyst may also wish to review the source of prediction data covering reliability, maintainability, and some of the input cost factors.

Given that the repair policy decision for Assembly A-1 is verified in terms of its evaluation in an "isolated" sense (i.e., a decision has been made relative to the results of the individual analysis in Figure B.16), then it is essential that this decision be reviewed in context with other assemblies of System XYZ and with the maintenance concept. Figure B.17 reflects the results of individual level-of-repair analyses accomplished for each of the major assemblies in Unit B. The same approach used for Assembly A-1 is used for the evaluation of Assemblies A-2 through A-15.

As shown in Figure B.17, there are two major choices: (1) Adopt the individual repair policy for each assembly (i.e., a "mixed" overall policy) and (2) adopt a uniform overall policy for *all* assemblies based on the lowest total policy cost (i.e., repair at

Assembly Number	Repair Policy			Decision
	Repair at Intermediate	Repair at Depot	Discard at Failure	
A-1	$213,300	$186,566	$491,760	Repair-Depot
A-2	130,800	82,622	75,440	Discard
A-3	215,611	210,420	382,452	Repair-Depot
A-4	141,633	162,912	238,601	Repair-Intermediate
A-5	132,319	98,122	121,112	Repair-Depot
A-6	112,189	96,938	89,226	Discard
A-7	125,611	142,206	157,982	Repair-Intermediate
A-8	99,812	131,413	145,662	Repair-Intermediate
A-9	128,460	79,007	66,080	Discard
A-10	167,400	141,788	314,560	Repair-Depot
A-11	185,850	142,372	136,740	Discard
A-12	135,611	122,453	111,502	Discard
A-13	105,667	113,775	133,492	Repair-Intermediate
A-14	111,523	89,411	99,223	Repair-Depot
A-15	142,119	120,813	115,723	Discard
Policy Cost	$2,147,905	$1,920,808	$2,679,555	Repair-Depot

Figure B.17 Summary of repair-level decisions.

depot). Both options must be reviewed in terms of the feedback effects that occur, life-cycle cost implications, and associated risks.

Figure B.18 illustrates the basic process that has been discussed herein. There are many candidate items that can be evaluated in terms of repair-versus-discard decisions. Quite often, such decisions will be made based on "noneconomic" criteria. It may not be technically feasible to repair an item at the intermediate level. Safety criteria and/or the need for a specialized repair facility dictates that repair must be accomplished at the depot level. The proprietary aspects of a product dictate that an item must be repaired at the producer's facility (i.e., depot). The approach used in this example deals with those components for which economic evaluation is feasible. As shown in the figure, there are some decisions that may initially be clear-cut, and there are other decisions where a more in-depth analysis is required.

B.6 DESIGN EVALUATION OF ALTERNATIVES

B.6.1 Definition of the Problem

Company DEF is responsible for the design and development of a major system, which, in turn, comprises a number of large subsystems. Subsystem XYZ is to be procured from an outside supplier, and there are three different configurations being evaluated for selection. Each of the configurations represents an existing design, with some redesign and additional development necessary to be compatible with the requirements for the new system. The evaluation criteria include various parameters, such as performance, operability, effectiveness, design characteristics, schedule, and cost. Both qualitative and quantitative considerations are covered in the evaluation process.

B.6.2 The Analysis Process

The analyst commences with the development of a list of evaluation parameters, as depicted in Figure B.19. In this instance, there is no single parameter (or figure of merit) that is appropriate by itself, but there are 11 factors that must be considered on an integrated basis. Given the evaluation parameters, the next step is to determine the level of importance of each. Quantitative weighting factors from 0 to 100 are assigned to each parameter in accordance with the degree of importance. The Delphi method, or an equivalent evaluation technique, may be used to establish the weighting factors. The sum of all weighting factors is 100.

For each of the 11 parameters identified in Figure B.19, the analyst may wish to develop a special checklist including criteria against which to evaluate the three proposed configurations. For instance, the parameter "PERFORMANCE" may be described in terms of degrees of desirability; that is, "highly desirable," "desirable," or "less desirable." Although each configuration must comply with a minimum set of requirements, one may be more desirable than the next when looking at the proposed performance characteristics. In other words, the analyst should break down each evaluation parameter into "levels of goodness."

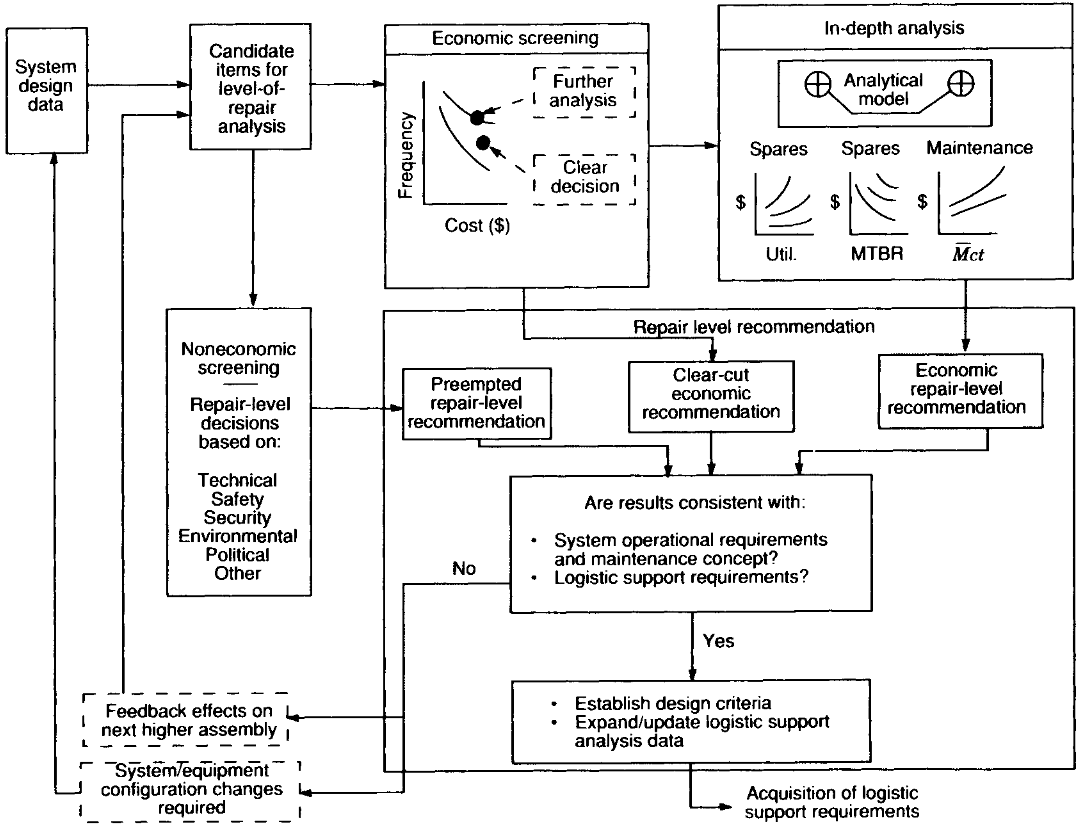


Figure B.18 Level-of-repair analysis process.

Item	Evaluation parameter	Weighting factor	Configuration A		Configuration B		Configuration C	
			Base rate	Score	Base rate	Score	Base rate	Score
1	Performance – input, output, accuracy, range, compatibility	14	6	84	9	126	3	42
2	Operability – simplicity and ease of operation	4	10	40	7	28	4	16
3	Effectiveness – Ao, MTBM, $\overline{M}ct$, $\overline{M}pt$, MDT, MLH/OH	12	5	60	8	96	7	84
4	Design characteristics – reliability, maintainability, human factors, supportability, producibility, interchange-ability	9	8	72	6	54	3	27
5	Design data – design drawings, specifications, logistics data, operating and maintenance procedures	2	6	12	8	16	5	10
6	Test aids – common and standard test equipment, calibration standards, maintenance and diagnostic computer programs	3	5	15	8	24	3	9
7	Facilities and utilities – space, weight, volume, environment, power, heat, water, air conditioning	5	7	35	8	40	4	20
8	Spare/repair parts – part type and quantity, standard parts, procurement time	6	9	54	7	42	5	30
9	Flexibility/growth potential – for reconfiguration, design change acceptability	3	4	12	8	24	6	18
10	Schedule – research and development, production	17	7	119	8	136	9	153
11	Cost – life cycle (R & D, investment, O & M)	25	10	250	9	225	5	125
Subtotal				753		811		534
Derating factor (development risk)				113 15%		81 10%		197 20%
Grand Total		100		640		730		427

Figure B.19 Evaluation summary (three alternatives).

Each of the three proposed configurations of Subsystem XYZ is evaluated independently, using the special checklist criteria. Base rating values from 0 to 10 are applied according to the degree of compatibility with the desired goals. If a "highly desirable" evaluation is realized, a rating of 10 is assigned.

The base-rate values are multiplied by the weighting factors to obtain a score. The total score is then determined by adding the individual scores for each configuration. Because some redesign is required in each instance, a special derating factor is applied to cover the risk associated with the failure to meet a given requirement. The resultant values from the evaluation are summarized in Figure B.19.

B.6.3 The Analysis Results

In Figure B.19, Configuration B represents the preferred approach, based on the highest total score of 730 points. This configuration is recommended on the basis of its inherent features relating to performance, operability, effectiveness, design characteristics, design data, and so on.