accomplish this result. In the acquisition of major systems, the satisfactory completion of this process leads to a commitment to proceed with engineering development and a possible ultimate production of the new system.

The final chapter in this part describes the process and activities involved in engineering-level decision making. A detailed description of the trade-off analysis is provided to provide formality to a systems engineer's thinking about decisions.

6

NEEDS ANALYSIS

6.1 ORIGINATING A NEW SYSTEM

The primary objective of the needs analysis phase of the system life cycle is to show clearly and convincingly that a valid operational need (or potential market) exists for a new system or a major upgrade to an existing system, and that there is a feasible approach to fulfilling the need at an affordable cost and within an acceptable level of risk. It answers the question of why a new system is needed and shows that such a system offers a sufficient improvement in capability to warrant the effort to bring it into being. This is achieved, in part, by devising at least one conceptual system that can be shown to be functionally capable of fulfilling the perceived need, and by describing it in sufficient detail to persuade decision makers that it is technically feasible and can be developed and produced at an acceptable cost. In short, this whole process must produce persuasive and defensible arguments that support the stated needs and create a “vision of success” in the minds of those responsible for authorizing the start of a new system development.

Systems Engineering Principles and Practice, Second Edition. Alexander Kossiakoff, William N. Sweet, Samuel J. Seymour, and Steven M. Biemer

Place of the Needs Analysis Phase in the System Life Cycle

The exact beginning of the active development of a new system is often difficult to identify. This is because the earliest activities in the origin of a new system are usually exploratory and informal in nature, without a designated organizational structure, specified objectives, or established timetable. Rather, the activities seek to determine whether or not a dedicated effort would be warranted, based on an assessment of a valid need for a new system and a feasible technological approach to its implementation.

The existence of a discrete phase corresponding to that defined as *needs analysis* in Chapter 4 is more characteristic of need-driven system developments than of those that are technology driven. In defense systems, for example, "material solution analysis" (see Department of Defense [DoD] life cycle of Fig. 4.1) is a required prerequisite activity for the official creation of a specific item in the budget for the forthcoming fiscal year, thereby allocating funds for the initiation of a new system project. Within this activity, a need determination task produces an initial capability description (ICD), which attests to the validity of the system objective or need, and gives evidence that meeting the stated objective will yield significant operational gains and is feasible of realization. Its completion culminates in the first official milestone of the defense acquisition life cycle.

In a technology-driven system development, typical of new commercial systems, the needs analysis phase is considered to be part of the conceptual development stage (Fig. 4.2). However, in this case too, there must be similar activities, such as market analysis, assessment of competitive products, and assessment of deficiencies of the current system relative to the proposed new system, that establish a bona fide need (potential market) for a product that will be the object of the development. Accordingly, the discussion to follow will not distinguish between needs-driven and technology-driven system developments except where specifically noted.

The place of the needs analysis phase in the system life cycle is illustrated in Figure 6.1. Its inputs are seen to be *operational deficiencies* and/or *technological opportunities*.

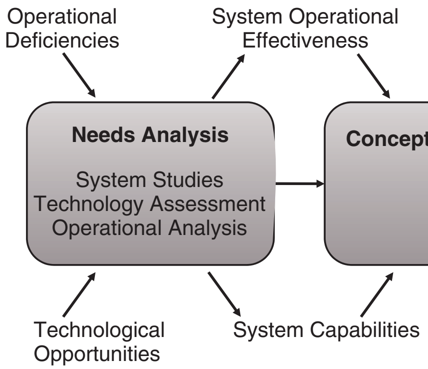

Figure 6.1. Needs analysis phase in the system life cycle.

Its outputs to the following phase, *concept exploration*, are an estimate of *system operational effectiveness* that specify what results a new system should achieve to meet the identified need, together with *system capabilities*, the output of various operational analyses and system studies, which provide evidence that an affordable system capable of meeting the effectiveness target is feasible.

As discussed above and depicted in the figure, the impetus for the initiation of a new system development generally comes from one of two sources: (1) the perception of a serious deficiency in a current system designed to meet an important operational need (need driven) or (2) an idea triggered by a technological development whose application promises a major advance over available systems in satisfying a need (technology driven). Either of these may then lead to investigations and analyses that eventually culminate in a program to develop a new system. Quite often, both factors contribute to the final decision.

Examples of New System Needs

The automobile industry is a prime example where changing conditions have forced the need for system improvements. Government laws require manufacturers to make substantial improvements in fuel economy, safety, and pollution control. Almost overnight, existing automobile designs were rendered obsolete. These regulations posed a major challenge to the automobile industry because they required technically difficult trade-offs and the development of many new components and materials. While the government gave manufacturers a number of years to phase in these improvements, the need for innovative design approaches and new components was urgent. In this case, the need for change was triggered by legislative action based on the needs of society as a whole.

Examples of technology-driven new systems are applications of space technology to meet important public and military needs. Here, the development of a range of advanced devices, such as powerful propulsion systems, lightweight materials, and compact electronics, made the engineering of reliable and affordable spacecraft a practical reality. In recent years, satellites have become competitive and often superior platforms for communication relays, navigation (GPS), weather surveillance, and a host of surveying and scientific instruments.

A more pervasive example of technology-driven system developments is the application of computer technology to the automation of a wide range of commercial and military systems. Information systems, in particular (e.g., banking, ticketing, routing, and inventory), have been drastically altered by computerization. System obsolescence in these cases has come not from recognized deficiencies but rather from opportunities to apply rapidly advancing technology to enhance system capabilities, to reduce cost, and to improve competitive position.

External Events. As will be seen later in this section, analysis of needs goes on more or less continuously in most major mission or product areas. However, external events often precipitate intensification and focusing of the process; this results in the formulation of a new operational requirement. In the defense area, this may be an intelligence finding of a new potential enemy threat, a local conflict that exposes the deficiency in a system, a major technological opportunity uncovered in a continuing program of concept exploration, or a major deficiency uncovered in periodic operational testing. In the civil products area, a triggering event might be a sudden shift in customer demand or a major technological change, such as the discovery of a radically new product, or an opportunity to automate a labor-intensive process. The drastic increase in the price of petroleum has triggered an intensive and successful effort to develop more fuel-efficient commercial aircraft: the wide-bodied jets.

Competitive Issues

Going from a perceived need to the initiation of a development program requires more than a statement of that need. Regardless of the source of funding (government or private), there is likely to be competition for the resources necessary to demonstrate a bona fide need. In the case of the military, it is not unusual for competition to come from another department or service. For example, should maritime superiority be primarily a domain of the surface or air navy, or a combination of the two? Should cleaner air be achieved by more restrictions on the automobile engine combustion process or on the chemical composition of the fuel? The answers to these types of questions can have a major impact on the direction of any resulting development. For these reasons, strong competition can be expected from many sectors when it is publicly known that a new system development is under consideration. The task of sorting out these possibilities for further consideration is a major systems engineering responsibility.

Design Materialization Status

As described in Chapter 4, the phases of the system development process can be considered as steps in which the system gradually materializes, that is, progresses from a general concept to a complex assembly of hardware and software that performs an operational function. In this initial phase of the system life cycle, this process of materialization has only just started. Its status is depicted in Table 6.1, an overlay of Table 4.1 in Chapter 4.

The focus of attention in this phase is on the system operational objectives and goes no deeper than the subsystem level. Even at that level, the activity is listed as "visualize" rather than definition or design. The term *visualize* is used here and elsewhere in the book in its normal sense of "forming a mental image or vision," implying a conceptual rather than a material view of the subject. It is at this level of generality that most designs first originate, drawing on analogies from existing system elements.

Table 6.1 (and Table 4.1) oversimplifies the representation of the evolving state of a system by implying that all of its elements begin as wholly conceptual and evolve at a uniform rate throughout the development. This is very seldom, if ever, the case in practice. To take an extreme example, a new system based on rectifying a major deficiency in one of the subsystems of its predecessor may well retain the majority of the other subsystems with little change, except perhaps in the selection of production parts.

TABLE 6.1. Status of System Materialization at the Needs Analysis Phase

	Phase					
	Concept development			*Engineering development*		
Level	Needs analysis	Concept exploration	Concept definition	Advanced development	Engineering design	Integration and evaluation
System	Define system capabilities and effectiveness	Identify, explore, and synthesize concepts	Define selected concept with specifications	Validate concept		Test and evaluate
Subsystem		Define requirements and ensure feasibility	Define functional and physical architecture	Validate subsystems		Integrate and test
Component			Allocate functions to components	Define specifications	Design and test	Integrate and test
Subcomponent		Visualize		Allocate functions to subcomponents	Design	
Part					Make or buy	

Such a new system would start out with many of its subsystems well advanced in materialization status, and with very few, if any, in a conceptual status.

Similarly, if a new system is technology driven, as when an innovative technical approach promises a major operational advance, it is likely that parts of the system not directly involved in the new technology will be based on existing system components. Thus, the materialization status of the system in both examples will not be uniform across its parts but will differ for each part as a function of its derivation. However, the general principle illustrated in the table is nevertheless valuable for the insight it provides into the system development process.

Applying the Systems Engineering Method in Needs and Requirements Analysis

Being the initial phase in the system development cycle, the needs analysis phase is inherently different from most of the succeeding phases. There being no preceding phase, the inputs come from different sources, especially depending on whether the development is needs driven or technology driven, and on whether the auspices are the government or a commercial company.

Nevertheless, the activities during the needs analysis phase can be usefully discussed in terms of the four basic steps of the systems engineering method described in Chapter 4, with appropriate adaptations. These activities are summarized below: the generic names of the individual steps as used in Figure 4.12 are listed in parentheses.

Operations Analysis (Requirements Analysis). Typical activities include

- analyzing projected needs for a new system, either in terms of serious deficiencies of current systems or the potential of greatly superior performance or lower cost by the application of new technology;
- understanding the value of fulfilling projected needs by extrapolating over the useful life of a new system; and
- defining quantitative operational objectives and the concept of operation.

The general products of this activity are a list of *operational objectives* and *system capabilities*.

Functional Analysis (Functional Definition). Typical activities include

- translating operational objectives into functions that must be performed and
- allocating functions to subsystems by defining functional interactions and organizing them into a modular configuration.

The general product of this activity is a list of initial *functional requirements*.

Feasibility Definition (Physical Definition). Typical activities include

- visualizing the physical nature of subsystems conceived to perform the needed system functions and

- defining a feasible concept in terms of capability and estimated cost by varying (trading off) the implementation approach as necessary.

The general product of this activity is a list of initial *physical requirements*.

Needs Validation (Design Validation). Typical activities include

- designing or adapting an effectiveness model (analytical or simulation) with operational scenarios, including economic (cost, market, etc.) factors;
- defining validation criteria;
- demonstrating the cost-effectiveness of the postulated system concept, after suitable adjustment and iteration; and
- formulating the case for investing in the development of a new system to meet the projected need.

The general product of this activity are a list of operational *validation criteria*.

Given a successful outcome of the needs analysis process, it is necessary to translate the operational objectives into a formal and quantitative set of *operational requirements*. Thus, this phase produces four primary products. And since three of these have the name "requirements" as part of their description, it can be confusing to separate the three. The primary output of the needs analysis phase is the set of operational requirements. But let us introduce four types of requirements so as not to confuse the reader.

Operational Requirements. These refer largely to the mission and purpose of the system. The set of operational requirements will describe and communicate the end state of the world after the system is deployed and operated. Thus, these types of requirements are broad and describe the overall objectives of the system. All references relate to the system as a whole. Some organizations refer to these requirements as capability requirements, or simply required capabilities.

Functional Requirements. These refer largely to what the system should do. These requirements should be action oriented and should describe the tasks or activities that the system performs during its operation. Within this phase, they refer to the system as a whole, but they should be largely quantitative. These will be significantly refined in the next two phases.

Performance Requirements. These refer largely to how well the system should perform its requirements and affect its environment. In many cases, these requirements correspond to the two types above and provide minimal numerical thresholds. These requirements are almost always objective and quantitative, though exceptions occur. These will be significantly refined in the next two phases.

Physical Requirements. These refer to the characteristics and attributes of the physical system and the physical constraints placed upon the system design. These may include appearance, general characteristics, as well as volume, weight, power, and material and external interface constraints to which the system must adhere. Many organizations do not have a special name for these and refer to them simply as *constraints*, or even *system requirements*. These will be significantly refined in the next two phases.

For new start systems, the first iteration through the needs and requirements analysis phase results in a set of operational requirements that are rather broad and are not completely defined. In the military, for example, the requirements-like document that emerges from the needs analysis is formally known as the ICD. This term is also used in the non-DoD community as a generic description of capabilities desired. In either case, the ICD document contains a broad description of the system concept needed and focuses on operational, or capability, requirements. Only top-level functional, performance, and physical requirements are included. Later documents will provide detail to this initial list.

The elements of the systems engineering method as applied to the needs analysis phase described above are displayed in the flow diagram of Figure 6.2. It is a direct adaptation of Figure 4.12, with appropriate modifications for the activities in this phase. Rectangular blocks represent the four basic steps, and the principal activities are shown as circles, with the arrows denoting information flow.

The inputs at the top of the diagram are operational deficiencies and technological opportunities. Deficiencies in current systems due to obsolescence or other causes are need drivers. Technological opportunities resulting from an advance in technology that offers a potential major increase in performance or a decrease in cost of a marketable system are technology drivers. In the latter case, there must also be a projected concept of operation for the application of the new technology.

The two middle steps are concerned with determining if there is at least one possible concept that is likely to be feasible at an affordable cost and at an acceptable risk. The validation step completes the above analysis and also seeks to validate the significance of the need being addressed in terms of whether or not it is likely to be worth the investment in developing a new system. Each of these four steps is further detailed in succeeding sections of this chapter.

6.2 OPERATIONS ANALYSIS

Whether the projected system development is need driven or technology driven, the first issue that must be addressed is the existence of a valid need (potential market) for a new system. The development of a new system or a major upgrade is likely to be very costly and will usually extend over several years. Accordingly, a decision to initiate such a development requires careful and deliberate study.

Analysis of Projected Needs

In the commercial sector, market studies are continuously carried out to assess the performance of existing products and the potential demand for new products. Customer reactions to product characteristics are solicited. The reason for lagging sales is sys-

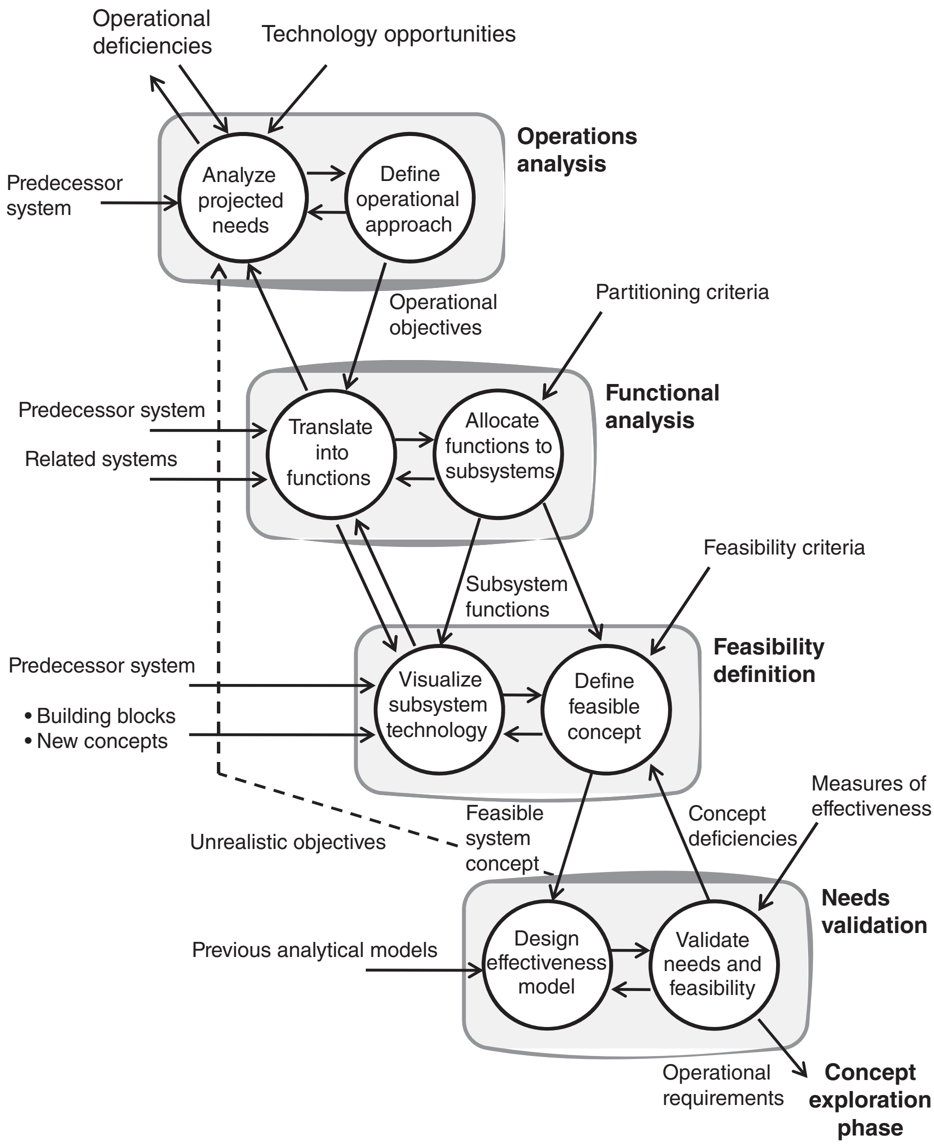

Figure 6.2. Needs analysis phase flow diagram.

tematically probed. The strengths and weaknesses of competing systems and their likely future growth are analyzed.

For military systems, each service has one or more systems analysis organizations whose responsibility is to maintain a current assessment of their operational capability and readiness. These organizations have access to intelligence assessments of changes in the military capability of potential adversaries that serve as inputs to effectiveness studies. In addition, periodic operational tests, such as simulated combat at sea, landing operations, and so on, serve to provide evidence of potential deficiencies that may signal the need for developing a more capable system. A particularly important consideration is whether or not modification of doctrine, strategy, or tactics can better meet the need with existing assets, thus reducing the urgency of acquiring expensive new assets.

Deficiencies in Current Systems. In virtually all cases, the need addressed by a projected new system is already being fulfilled, at least in part, by an existing system. Accordingly, one of the first steps in the needs analysis process is the detailed identification of the perceived deficiencies in the current system. If the impetus for the new system is technology driven, the current system is examined relative to the predicted characteristics achieved with the prospective technology.

Since the development of a successor system or even a major upgrade of an existing system is likely to be technically complex and require years of challenging work, operational studies must focus on conditions as much as 10 years in the future. This means that the system owner/user must continually extrapolate the conditions in which the system operates and reevaluate system operational effectiveness. In this sense, some form of needs analysis is being conducted throughout the life of the system.

The above process is most effective when it combines accumulated test data with analysis, often using existing system simulations. This approach provides two major benefits: a consistent and accurate evaluation of system operational performance and a documented history of results, which can be used to support the formal process of needs analysis if a new development program becomes necessary.

Obsolescence. The most prevalent single driving force for new systems is obsolescence of existing systems. System obsolescence can occur for a number of reasons; for example, the operating environment may change; the current system may become too expensive to maintain; the parts necessary for repair may be no longer available; competition may offer a much superior product; or technology may have advanced to the point where substantial improvements are available for the same or lower cost. These examples are not necessarily independent; combined elements of each can greatly accelerate system obsolescence. Belated recognition of obsolescence can be painful for all concerned. It can significantly delay the onset of the needs analysis phase until time becomes critical. Vigilant self-evaluation should be a standard procedure during the operational life of a system.

An essential factor in maintaining a viable system is keeping aware of advances in technology. Varied research and development (R & D) activities are carried out by many agencies and industry. They receive support from government or private funding or combinations of both. In the defense sector, contractors are authorized to use a percentage of their revenues on relevant research as allowable overhead. Such activity is called independent research and development (IRAD). There are also a number of wholly or partially government-funded exploratory development efforts. Most large producers of commercial products support extensive applied R & D organizations. In any case, the wise system sponsor, owner, or operator should continually keep abreast of these activities and should be ready to capitalize on them when the opportunity presents itself. Competition at all levels is a potent driver of these activities.

Operational Objectives

The principal outcome of operational studies is the definition of the objectives, in operational terms, that a new system must meet in order to justify its development. In a needs-driven development, these objectives must overcome such changes in the environment or deficiencies in the current system as have generated the pressure for an improved system. In a technology-driven development, the objectives must embody a concept of operations that can be related to an important need.

The term “objectives” is used in place of “requirements” because at this early stage of system definition, the latter term is inappropriate; it should be anticipated that many iterations (see Fig. 6.2) would take place before the balance between operational performance and technical risk, cost, and other developmental factors will be finally established.

To those inexperienced in needs analysis, the development of objectives can be a strange process. After all, engineers typically think in terms of requirements and specifications, not high-level objectives. Although objectives should be quantifiable and objective, the reality is that most are qualitative and subjective at this early stage. Some rules of thumb can be helpful:

- Objectives should address the end state of the operational environment or scenario—it focuses on what the system will accomplish in the large sense.
- Objectives should address the purpose of the system and what constitutes the satisfaction of the need.
- Taken together, objectives answer the “why” question—why is the system needed?
- Most objectives start with the infinitive word “provide,” but this is not mandatory.

Objectives Analysis. The term objectives analysis is the process of developing and refining a set of objectives for a system. Typically, the product of this effort is an objectives tree, where a single or small set of top-level objectives are decomposed into a set of primary and secondary objectives. Figure 6.3 illustrates this tree. Decomposition is appropriate until an objective becomes verifiable, or you begin to define functions of the system. When that occurs, stop at the objective. The figure illustrates functions by graying the boxes—they would not be part of your objectives tree. In our experience, most objectives trees span one or two levels deep; there is no need to identify extensive depth.

As an example of an objectives analysis, think about a new automobile. Suppose an auto company wants to design a new passenger vehicle, which it can market as “green” or environmentally friendly. Understanding the objectives of this new car establishes priorities for the eventual design. Thus, company management begins an objectives exercise. Objectives analysis forces the company, both management and the

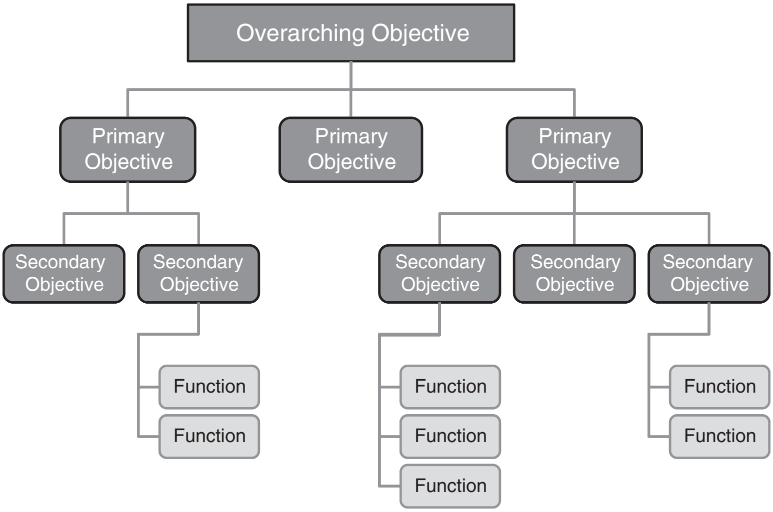

Figure 6.3. Objectives tree structure.

technical staff, to evaluate and decide what is important when developing a new system. Therefore, it is worth investing some time, energy, and capital in determining what the overall objectives of the system are. Moreover, agreeing to a concise single statement helps focus the development team to the job at hand.

In the automobile example, the company might soon realize that the overall objective of this new vehicle is to provide users with clean transportation. The top-level objective does not include performance, cargo capacity, off-road capability, and so on. In the overall objective are two key words: clean and transportation. Both imply various aspects or attributes of this new car. Since both words are not yet well defined, we need to decompose them further. But the overall goal is clear: this vehicle is going to be environmentally "clean" and will provide sufficient transportation.

The first decomposition focuses the thinking of the development team. Clearly, the two key words need to be "fleshed out." In this case, "clean" may mean "good gas mileage" as well as "comfortable." Transportation also implies a safe and enjoyable experience in the vehicle as it travels from one point to the next. There may also be another objective that is loosely tied to *clean* and *transportation*—cost.

Thus, in our example, the development team focuses on four primary objectives that flow from our overarching objective: comfort, mileage, safety, and cost. These four words need to be worded as an objective of course. Figure 6.4 presents one possibility of an objectives tree.

In determining whether an objective needs further decomposition, one should ask a couple of questions:

- Does the objective stand on its own in terms of clarity of understanding?
- Is the objective verifiable?

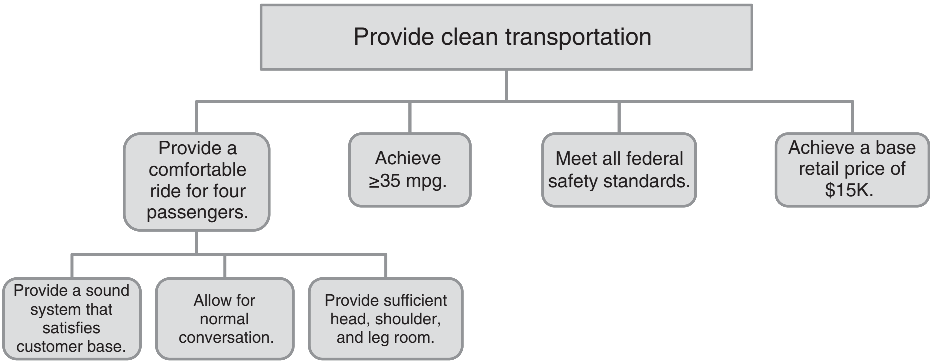

Figure 6.4. Example objectives tree for an automobile.

- Would decomposition lead to better understanding?
- Are requirements and functions readily implied by the objective?

In our example, one could argue that three of the primary objectives are sufficient as stated, and all three are verifiable. Only the subjective objective relating to comfort needs further decomposition. In this case, comfort can be divided into three components: a sound system, noise levels that allow conversation, and physical space. As worded in the figure, these three could all be verified by various methods (a satisfaction survey in the first, a definition of noise levels for normal conversation, and volume requirements). Having an objectives tree focuses the development effort on the priorities. In our example, the four primary objectives communicate what is important with this new automobile.

In many cases where objectives trees are used, an initial tree will be similar to our example, listing only those objectives that are the highest priorities. These trees would then be expanded to include other areas that will need to be addressed. For our automobile, these "other" areas would include maintenance considerations, human–system interaction expectations, and cargo space, to name a few. An objective of having an objectives tree is ultimately to identify the functions and their performance requirements. Therefore, the logical next step after objectives analysis is functional analysis.

6.3 FUNCTIONAL ANALYSIS

At this initial phase of the system development process, functional analysis is an extension of operational studies, directed to establishing whether there is a feasible technical approach to a system that could meet the operational objectives. At this stage, the term "feasible" is synonymous with "possible" and implies making a case that there is a good likelihood that such a system could be developed within the existing state of the art, without having to prove it beyond reasonable doubt.

Translation of Operational Objectives into System Functions

To make such a case, it is necessary to visualize the type of system that could carry out certain actions in response to its environment that would meet the projected operational objectives. This requires an analysis of the types of functional capabilities that the system would have to possess in order to perform the desired operational actions. In needs-driven systems, this analysis is focused on those functional characteristics needed to satisfy those operational objectives that are not adequately handled by current systems. In technology-driven systems, the advances in functional performances would presumably be associated with the technology in question. In any case, both the feasibility of these approaches and their capability to realize the desired operational gains must be adequately demonstrated.

The visualization of a feasible system concept is inherently an abstract process that relies on reasoning on the basis of analogy. This means that all the elements of the concept should be functionally related to elements of real systems. A helpful approach to the translation of operational objectives to functions is to consider the type of primary media (signals, data, material, or energy) that are most likely to be involved in accomplishing the various operational objectives. This association usually points to the class of subsystems that operate on the medium, as, for example, sensor or communication subsystems in the case of signals, computing subsystems for data, and so on. In the above process, it must be shown that all of the principal system functions, especially those that represent advances over previous systems, are similar to those already demonstrated in some practical context. An exception to this process of reasoning by analogy is when an entirely new type of technology or application is a principal part of a proposed system; in this case, it may be necessary to go beyond analysis and to demonstrate its feasibility by modeling and, ultimately, experimentation.

In identifying the top-level functions that the system needs to perform, it is important even at this early stage to visualize the entire system life cycle, including its nonoperational phases.

The above discussion is not meant to imply that all considerations at this stage are qualitative. On the contrary, when primarily quantitative issues are involved, as in the example of automobile pollution, it is necessary to perform as much quantitative analysis as available resources and existing knowledge permit.

Allocation of Functions to Subsystems

In cases where all operational objectives can be directly associated with system-level functions that are analogous to those presently exhibited by various real systems, it is still essential to visualize just how these might be allocated, combined, and implemented in the new system. For this purpose, it is not necessary to visualize some best system configuration. Rather, it need only be shown that the development and production of an appropriate system is, in fact, feasible. Toward this end, a top-level system concept that implements all the prescribed functions should be visualized in order to demonstrate that the desired capabilities can be obtained by a plausible combination of the prescribed functions and technical features. Here it is particularly important that all interactions and interfaces, both external and internal to the system, be identified and associated with the system functions, and that a trade-off process be employed to ensure that the consideration of the various system attributes is thorough and properly balanced. This is typically done in terms of an initial concept of operation.

6.4 FEASIBILITY DEFINITION

The feasibility of a system concept (and therefore of meeting the projected need) cannot be established solely on the basis of its functional design. The issue of feasibility must also address the physical implementation. In particular, system cost is always a dominant consideration, especially as it may compare to that of other alternatives, and this cannot be judged at the functional level. Accordingly, even at this initial phase of system development, it is necessary to visualize the physical makeup of the system as it is intended to be produced. It is also necessary to visualize all external constraints and interactions, including compatibility with other systems.

While it is necessary to consider the physical implementation of the projected system in the needs analysis phase, this does not imply that any design decisions are made at this time. In particular, no attempt should be made to seek optimum designs; those issues are dealt with much later in the development process. The focus at this point is to establish feasibility to meet a given set of operational objectives. It is the validation of these objectives that is the primary purpose of the needs analysis phase. The paragraphs that follow discuss some of the issues that need to be considered, but only in an exploratory way.

Visualization of Subsystem Implementation

Given the allocation of functions to subsystems, it is necessary to envision how these might be implemented. At this stage, it is only necessary to find examples of similar functional units in existing systems so that the feasibility of applying the same type of technology to the new system may be assessed. The identification of the principal media involved in each major function (signal, data, material, and energy), as discussed in the previous section, is also helpful in finding systems with similar functional elements and, hence, with physical implementations representative of those required in the new system.

Relation to the Current System. Where there exists a system that has been meeting the same general need for which the new system is intended, there are usually a number of subsystems that may be candidates for incorporation in modified form in the new system. Whether or not they will be utilized as such, they are useful in building a case for system feasibility and for estimating part of the development and production cost of the new system.

Existing models and simulations of the current system are especially useful tools in this type of analysis since they will usually have been verified against data gathered over the life of the system. They may be used to answer "What if?" questions and to find the driving parameters, which helps to focus the analysis process. Another important tool, used in conjunction with the system simulation, is an effectiveness model and the analytic techniques of effectiveness analysis, as described in the next section.

Other less tangible factors can also come into play, such as the existence of a support infrastructure. In the case of the automobile engine, many years of successful operation have established a very wide base of support for conventional reciprocating engines in terms of repair sites, parts suppliers, and public familiarity. Because of the prospective cost for changing this base, innovative changes, such as the Wankel rotary engine and designs based on the Stirling cycle, have been resisted. The point here is that beneficial technological innovations are often overridden by economic or psychological resistance to change.

Application of Advanced Technology. In technology-driven systems, it is more difficult to establish feasibility by reference to existing applications. Instead, it may be necessary to build the case on the basis of theoretical and experimental data available from such research and development work as has been done on the candidate technology. In case this proves to be insufficient, limited prototyping may be required to demonstrate the basic feasibility of the application. Consultation with outside experts may be helpful in adding credibility to the feasibility investigation.

Unfortunately, highly touted technical advances may also come with unproven claims and from unreliable sources. Sometimes, a particular technology may offer a very substantial gain but lacks maturity and an established knowledge base. In such situations, the case for incorporating the technology should be coupled with a comparably capable backup alternative. Systems engineers must be intimately involved in the above process to keep the overall system priorities foremost.

Cost. The assessment of cost is always an important concern in needs analysis. This task is particularly complicated when there is a mix of old, new, and modified subsystems, components, and parts. Here again, cost models and maintenance records of the current system, combined with inflation factors, can be helpful. By comparing similar components and development activities, cost estimation will at least have a credible base from which to work. In the case of new technology, cost estimates should contain provisions for substantial development and testing prior to commitment for its use.

Definition of a Feasible Concept

To satisfy the objectives of the needs analysis phase, the above considerations should culminate in the definition and description of a plausible system concept, and a well-documented substantiation of its technical feasibility and affordability. The system description should include a discussion of the development process, anticipated risks, general development strategy, design approach, evaluation methods, production issues, and concept of operations. It should also describe how the cost of system development and production had been assessed. It need not be highly detailed but should show that all major aspects of system feasibility have been addressed.

6.5 NEEDS VALIDATION

The final and most critical step in the application of the systems engineering method is the systematic examination of the validity of the results of the previous steps. In the case of the needs analysis phase, the validation step consists of determining the basic soundness of the case that has been made regarding the existence of a need for a new system and for the feasibility of meeting this need at an affordable cost and at an acceptable risk.

Operational Effectiveness Model

In the concept development stage the analyses that are designed to estimate the degree to which a given system concept may be expected to meet a postulated set of operational requirements is called *operational effectiveness analysis*. It is based on a mathematical model of the operational environment and of the candidate system concept being analyzed.

In effectiveness analysis, the operational environment is modeled in terms of a set of scenarios—postulated actions that represent a range of possible encounters to which the system must react. Usually, initial scenarios are selected to present the more likely situations, followed by more advanced cases for testing the limits of the operational requirements. For each scenario, the acceptable responses of the system in terms of operational outcomes are used as evaluation criteria. To animate the engagements between the system model and the scenarios, an effectiveness model is designed with the capability of accepting variable system performance parameters from the system model. A more extensive treatment of operational scenarios is contained in the next section.

Effectiveness analysis must include not only the operational modes of the system but also must represent its nonoperating modes, such as transport, storage, installation, maintenance, and logistics support. Collectively, all the significant operational requirements and constraints need to be embodied in operational scenarios and in the accompanying documentation of the system environment.

System Performance Parameters. The inputs from the system model to the effectiveness analysis are values of performance characteristics that define the system's response to its environment. For example, if a radar device needs to sense the presence of an object (e.g., an aircraft), its predicted sensing parameters are entered to determine the distance at which the object will be detected. If it needs to react to the presence of the object, its response processing time will be entered. The effectiveness model ensures that all of the significant operational functions are addressed in constructing the system model.

Measures of Effectiveness (MOE). To evaluate the results of effectiveness simulations, a set of criteria is established that identifies those characteristics of the system response to its environment that are critical to its operational utility. These are called "MOE." They should be directly associated with specific objectives and prioritized according to their relative operational importance. MOE and measures of performance (MOP) are described in more detail below.

While the effort required to develop an adequate effectiveness model for a major system is extensive, once developed, it will be valuable throughout the life of the system, including potential future updates. In the majority of cases where there is a current system, much of the new effectiveness model may be derived from its predecessor.

The Analysis Pyramid. When estimating or measuring the effectiveness of a system, the analyst needs to determine the perspective within which the system's effectiveness will be described. For example, the system effectiveness may be described within a larger context, or mission, where the system is one of many working loosely or tightly together to accomplish a result. On the other hand, effectiveness can be described in terms of an individual system's performance in a given situation in response to selected stimuli, where interaction with other systems is minimal.

Figure 6.5 depicts a common representation of what is known as the analysis pyramid. At the base of the pyramid is the foundational physics and physical phenomenology knowledge. Analysis at this end of the spectrum involves a detailed evaluation of environmental interactions, sometimes down to the molecular level.

As the analyst travels up the pyramid, details are abstracted and the perspective of the analyst broadens, until he reaches the apex. At this level, technical details have been completely abstracted and the analysis focuses on strategy and policy alternatives and implications.

The systems engineer will find that typically, analysis perspectives during the needs analysis phase tend to be near the top of the pyramid. Although strategy may not be in the domain of the system development effort, certainly the system's effectiveness within a multiple-mission or a single-mission context would need to be explored. The lower

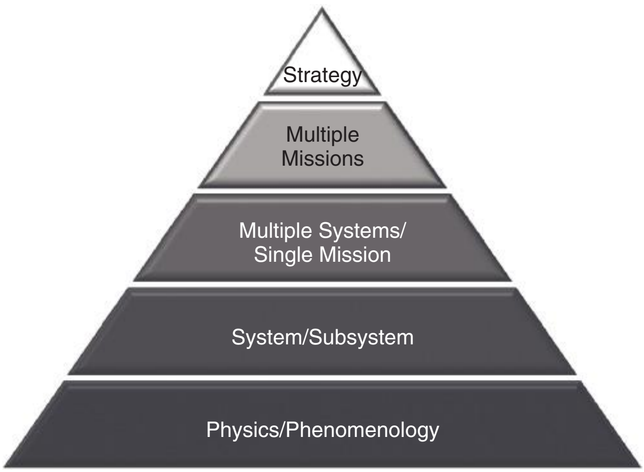

Figure 6.5. Analysis pyramid.

part of the pyramid is usually not analyzed due to lack of system definition. As the system becomes more defined, the analysis performed will tend to migrate down the pyramid. We will explore the analysis pyramid more as we continue our look at systems engineering within the development phases.

MOE and MOP

With the introduction of operational effectiveness analysis, we need to explore the concept and meaning of certain metrics. Metrics are key to ultimately defining the system, establishing meaningful and verifiable requirements, and testing the system. Therefore, defining these metrics appropriately and consistently through the development life cycle is essential.

Many terms exist to describe these effectiveness and performance metrics. Two commonly used terms (and ones we will use throughout this book) are MOEs and MOPs. Unfortunately, no universal definitions exist for these terms. But the basic concept behind them is crucial to understanding and communicating a system concept.

We propose the following definitions for this book:

MOE: a qualitative or quantitative metric of a system's overall performance that indicates the degree to which it achieves it objectives under specified conditions. An MOE always refers to the system as a whole.

MOP: a quantitative metric of a system's characteristics or performance of a particular attribute or subsystem. An MOP typically measures a level of physical performance below that of the system as a whole.

Regardless of the definition you use, it is a universal axiom that an MOE is superior to MOP. In other words, if the two are placed in a hierarchy, MOEs will always be above MOPs.

Typically, an MOE or MOP will have three parts: the metric, its units, and the conditions or context under which the metric applies. For example, an MOE of a new recreational aircraft (such as a new version of Piper Cub) would be maximum range, in nautical miles at sea level on a standard atmospheric day. The metric is "maximum range"; the units are "nautical miles"; and the conditions are "a standard atmospheric day (which is well defined) at sea level." This MOE relates to the aircraft as a whole and describes one aspect of its performance in achieving the objective of aerial flight.

MOEs can be of many forms, but we can define three general categories: measurement, likelihood, or binary. Measurement is an MOE that can be directly measured (either from an actual system, subsystem, or mathematical or physical model). It may be deterministic or random. Likelihood MOEs correspond to a probability of an event occurring and may include other MOEs. For example, a likelihood MOE could be the probability of an aircraft achieving a maximum altitude of 20,000 ft. In this case, the likelihood is defined in terms of another measurement MOE. Finally, a binary MOE is a logical variable of the occurrence of an event. Either the event occurs or not.

When an MOE is measured or determined, we call the resultant measurement the *value* of the MOE. Thus, in our aircraft example, if we measure the maximum range of a new aircraft as 1675 nm, then “1675” is the value. Of course, MOEs, as any metrics, can have multiple values under different conditions or they could be random values.

Finally, engineers use binary MOEs to determine whether a particular characteristic of a system exceeds a threshold. For example, we could define a threshold for the maximum range of an aircraft as 1500 nm at sea level on a standard day. A binary MOE could then be defined to determine whether a measured value of the MOE exceeds our threshold. For example, the binary MOE would be “yes”; our measured value of 1675 nm exceeds our threshold of 1500 nm.

MOEs and MOPs are difficult concepts to grasp! Unless one has worked with metrics before, they tend to be confusing. Many students of systems engineering will provide a requirement when asked for an MOE. Others provide values. Still others simply cannot identify MOEs for a new system. However, the concept of measures is utilized throughout the systems engineering discipline. We will revisit these concepts in the subsequent chapters.

Validation of Feasibility and Need

Finally, the effectiveness analysis described above is mainly directed to determining whether or not a system concept, derived in the functional and physical definition process, is (1) feasible and (2) satisfies the operational objectives required to meet a projected need. It assumes that the legitimacy of the need has been established previously. This assumption is not always a reliable one, especially in the case of technology-driven system developments, where the potential application is new and its acceptance depends on many intangible factors. A case in point, of which there are hundreds of examples, is the application of automation to a system previously operated mainly by people. (The airplane reservation and ticketing system is one of the larger successful ones.) The validation of the need for such a system requires technical, operational, and market analyses that seek to take into account the many complex factors likely to affect the acceptability of an automated system and its probable profitability.

In complex cases such as the above example, only a very preliminary validation can be expected before considerable exploratory development and experimentation should take place. However, even a preliminary validation analysis will bring out most of the critical issues and may occasionally reveal that the likelihood of meeting some postulated needs may be too problematical to warrant a major investment at the current state of the technology.

6.6 SYSTEM OPERATIONAL REQUIREMENTS

The primary product of needs analysis is a set of operational objectives, which are then translated into a set of operational requirements. The system operational requirements that result from the needs analysis phase will establish the reference against which the subsequent development of a system to meet the projected needs will be judged. Accordingly, it is essential that these requirements be clear, complete, consistent, and feasible of accomplishment. The feasibility has presumably been established by the identification of at least one system approach that is judged to be both feasible and capable of meeting the need. It remains to make certain that the operational requirements are adequate and consistent.

Operational Scenarios

A logical method of developing operational requirements is to postulate a range of scenarios that together are representative of the full gamut of expected operational situations. These scenarios must be based on an extensive study of the operational environment, discussions with experienced users of the predecessor and similar systems, and a detailed understanding of past experience and demonstrated deficiencies of current systems. It is especially important to establish the user priorities for the required improvements, in particular, those that appear most difficult to achieve.

While scenarios range widely in their content depending on their application, we are able to define five basic components of almost all scenarios.

1. *Mission Objectives.* The scenario should identify the overall objectives of the mission represented, and the purpose and role of the system(s) in focus in accomplishing those objectives. In some cases, this component is system independent, meaning that the role of any one system is not presented—only a general description of the mission at stake and the objectives sought. In a commercial example, the mission could be to capture market share. In a government example, the mission might be to provide a set of services to constituents. In a military example, the mission might be to take control of a particular physical installation.
2. *Architecture.* The scenario should identify the basic system architecture involved. This includes a list of systems, organizations, and basic structural information. If governance information is available, this would be included. This component could also include basic information on system interfaces or a description of the information technology infrastructure. In essence, a description of the resources available is provided. In a commercial scenario, the resources of the organization are described. If this is a government scenario, the organizations and agencies involved in the mission are described. If this is a military scenario, these resources could include the units involved, with their equipment.
3. *Physical Environment.* The scenario should identify the environment in which the scenario takes place. This would include the physical environment (e.g., terrain, weather, transportation grid, and energy grid) as well as the business environment (e.g., recession and growth period). "Neutral" entities are described in this section. For example, customers and their attributes would be defined, or neutral nations and their resources.
4. *Competition.* The scenario should identify competition to your efforts. This may be elements that are directly opposed to your mission success, such as a

software hacker or other type of "enemy." This may be your competition in the market or outside forces that influence your customers. This could also include natural disasters, such as a tsunami or hurricane.

5. *General Sequence of Events.* The scenario should describe a general sequence of events within the mission context. We are careful to use the term *general* though. The scenario should allow for freedom of action on the part of the players. Since we use scenarios to generate operational requirements and to estimate system effectiveness, we need the ability to alter various parameters and events within the overall scenario description. Scenarios should not "script" the system; they are analysis tools, not shackles to restrain the system development. Thus, scenarios typically provide a general sequence of events and leave the details to an analyst using the scenario. At times, a scenario may provide a detailed sequence of events leading up to a point in time, whereby the analysis starts and actions may be altered from that time forward.

A scenario could include much more, depending on its application and intended purpose. They come in all sizes, from a short, graphic description of a few pictures to hundreds of pages of text and data.

Even though the operational scenarios developed during this phase are frequently not considered a part of the formal operational requirements document, in complex systems, they should be an essential input to the concept exploration phase. Experience has shown that it is seldom possible to encompass all of the operational parameters into a requirements document. Further, the effectiveness analysis process requires operational inputs in scenario form. Accordingly, a set of operational scenarios should be appended to the requirements document, clearly stating that they are representative and not a comprehensive statement of requirements.

As noted above, the scenarios should include not only the active operational interactions of the system with its environment but also the requirements involved in its transport, storage, installation, maintenance, and logistics support. These phases often impose physical and environmental constraints and conditions that are more severe than normal operations. The only means for judging whether or not requirements are complete is to be sure that all situations are considered. For example, the range of temperature or humidity of the storage site may drastically affect system life.

Operational Requirements Statements

Operational requirements must initially be described in terms of operational outcomes rather than system performance. They must not be stated in terms of implementation nor biased toward a particular conceptual approach. All requirements should be expressed in measurable (testable) terms. In cases where the new system is required to use substantial portions of an existing system, this should be specifically stated.

The rationale for all requirements must be stated or referenced. It is essential for the systems engineers leading the system development to understand the requirements in terms of user needs so that inadvertent ambiguities do not result in undue risks or costs.

The time at which a new system needs to be available is not readily derived from purely operational factors but may be critical in certain instances due to financial factors, obsolescence of current systems, schedules of system platforms (e.g., airplanes and airports), and other considerations. This may place constraints on system development time and hence on the degree of departure from the existing system.

Since the initially stated operational requirements for a new system are seldom based on an exhaustive analysis, it should be understood by both the customer and potential developer that these requirements will be refined during the development process, as further knowledge is gained concerning the system needs and operating environment.

From the above considerations, it is seen that work carried out during the needs analysis phase must be regarded as preliminary. Subsequent phases will treat all system aspects in more detail. However, experience has shown that the basic conceptual approach identified during needs analysis often survives into subsequent phases. This is to be expected because considerable time and effort is usually devoted to this process, which may last for 2 or 3 years. Even though only limited funds are expended, many organizations are often involved.

Feasibility Validation

Effectiveness analysis is intrinsically concerned with the functional performance of a system and therefore cannot in itself validate the feasibility of its physical implementation. This is especially true in the case where unproven technology is invoked to achieve certain performance attributes.

An indirect approach to feasibility validation is to build a convincing case by analogy with already demonstrated applications of the projected technique. Such an approach may be adequate, provided that the application cited is truly representative of that proposed in a new system. It is important, however, that the comparison be quantitative rather than only qualitative so as to support the assumed performance resulting from the technology application.

A direct approach to validating the feasibility of a new physical implementation is to conduct experimental investigations of the techniques to be applied to demonstrate that the predicted performance characteristics can be achieved in practice. This approach is often referred to as "critical experiments," which are conducted early in the program to explore new implementation concepts.

The resources available for carrying out the validation process in the needs analysis phase are likely to be quite limited, since the commitment to initiate the actual development of the system has not yet been made. Accordingly, the quality of the validation process will depend critically on the experience and ingenuity of the systems engineering staff. The experience factor is especially important here because of the dependence of the work on knowledge of the operational environment, of the predecessor system, of analyses and studies previously performed, of the technological base, and of the methods of systems analysis and systems engineering.

Importance of Feasibility Demonstration. In defining a basis for developing a new system, the needs analysis phase not only demonstrates the existence of an important unfulfilled operational need but also provides evidence that satisfying the need is feasible. Such evidence is obtained by visualizing a realistic system concept that has the characteristics required to meet the operational objectives. This process illustrates a basic systems engineering principle that establishing realistic system requirements must include the simultaneous consideration of a system concept that could meet those requirements. This principle contradicts the widely held notion that requirements, derived from needs, should be established prior to consideration of any system concept that can fulfill those requirements.

6.7 SUMMARY

Originating a New System

Objectives of the needs analysis phase are to identify a valid operational need for a new system and to develop a feasible approach to meeting that need. This needs-driven system development approach is characteristic of most defense and other government programs and typically stems from a deficiency in current system capabilities. This type of development requires a feasible and affordable technical approach.

The other major type of approach is the technology-driven system development approach. This approach is characteristic of most commercial system development and stems from a major technological opportunity to better meet a need. This type of development requires demonstration of practicality and marketability.

Activities comprising the needs analysis phase are the following:

- *Operations Analysis*—understanding the needs for a new system;
- *Functional Analysis*—deriving functions required to accomplish operations;
- *Feasibility Definition*—visualizing a feasible implementation approach; and
- *Needs Validation*—demonstrating cost-effectiveness.

Operations Analysis

Studies and analyses are conducted to generate and understand the operational needs of the system. These studies feed the development of an objectives tree—describing the hierarchy of system expectations and outcomes.

Functional Analysis

Initial system functions are identified and organized that will achieve operational objectives. These functions are vetted through analysis and presentation to users and stakeholders.

Feasibility Definition

The system development approach is decided upon, articulated to stakeholders, and approximately costed. Moreover, an early feasible concept is articulated. Finally, developing operational requirements commences.

Needs Validation

The vetted set of operational needs is now validated by operational effectiveness analysis, usually at multiple levels within the analysis pyramid. System concepts that satisfy the operational needs are evaluated with agreed-upon MOE and reflect the entire system life cycle.

PROBLEMS

6.1 Describe and define the principal outputs (products) of the needs analysis phase. List and define the primary systems engineering activities that contribute to these products.

6.2 Identify the relationships between operational objectives and functional requirements for the case of a new commuter aircraft. Cite three operational objectives and the functional requirements that are needed to realize these objectives. (Use qualitative measures only.)

6.3 Referring to Figure 6.2, which illustrates the application of the systems engineering method to the needs analysis phase, select one of the four sections of the diagram and write a description of the processes pictured in the diagram. Explain the nature and significance of the two processes represented by circles and of each internal and external interaction depicted by arrows. The description should be several times more detailed than the definition of the step in the subsection describing the systems engineering method in needs analysis.

6.4 What is meant by "MOE"? For the effectiveness analysis of a sport utility vehicle (SUV), list what you think would be the 10 most important characteristics that should be exercised and measured in the analysis.

6.5 For six of the MOE of the SUV (see Problem 6.4), describe an operational scenario for obtaining a measure of its effectiveness.

6.6 Assume that you have a business in garden care equipment and are planning to develop one or two models of lawn tractors to serve suburban homeowners. Consider the needs of the majority of such potential customers and write at least six operational requirements that express these needs. Remember the qualities of good requirements as you do so. Draw a context diagram for a lawn tractor.

6.7 Given the results of Problem 6.6, describe how you would perform an analysis of alternatives to gain an understanding of the functional requirements and optional features that could fit the tractor to individual needs. Describe the

MOE you would use and the alternative architectures you would analyze. Describe the pros and cons for a single model as opposed to two models of different sizes and powers.

FURTHER READING

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