Chapter **10**

Problem Definition

TIMOTHY TRAINOR, Ph.D.
GREGORY S. PARNELL, Ph.D.

A great solution to the wrong problem is . . . wrong.

—Anonymous

10.1 INTRODUCTION

History is rife with examples of solutions developed to a problem incorrectly or incompletely defined by hard-working, well-intentioned individuals. For example:

- General Robert E. Lee (United States Military Academy Class of 1829) of the Army of Northern Virginia believed that the Confederacy's problem was to decisively defeat the Union Army in the Civil War to achieve the goals of the Confederate states. Lee's strategy to solve this problem was to invade the Union States to draw their Army into a decisive engagement. Ultimately this led to a disaster at the Battle of Gettysburg when Lee attacked the larger and better-equipped Union Army, which held ground favorable to the defense. Others in the Confederacy, including Lieutenant General James "Pete" Longstreet (United States Military Academy Class of 1842), believed the problem was to destroy the Union's will to continue the conflict by threatening the seat of government in Washington, DC. Through superior leadership and maneuvering, some felt the Confederate Army could capture Washington, DC and

Decision Making in Systems Engineering and Management, Second Edition
Edited by Gregory S. Parnell, Patrick J. Driscoll, Dale L. Henderson

sue for a favorable peace to achieve their goals [1]. We will never know who correctly defined the Confederacy's problem, but it is evident from history that destruction of the Union Army was not necessarily the complete problem facing the Confederacy in achieving their goals.

- The late 1970s and 1980s saw Japanese automakers gain a significant share of the U.S. auto market. U.S. auto manufacturers believed the problem was how to compete on cost against the smaller, more fuel-efficient Japanese cars that were cheaper to purchase and operate. While true, this problem definition proved to be incomplete. Japanese auto manufacturers were successful then due to both the lower costs and higher quality of their cars. U.S. auto manufacturers were slow to recognize that they could realize a positive return on investment in improved quality control measures in producing cars [2]. As history has shown, Japanese automakers gained significant market share of the U.S. auto market during this period.
- In 1983, IBM introduced the IBM PC Junior to compete in the home computer market against the then-dominant Commodore 64 and Apple II [3]. Apparently IBM's plan to meet consumer needs in the home computer market was to build a scaled-down version of its popular IBM PC, which was then very successful for business consumers. Unfortunately the changes to the business IBM PC did not make the Junior easy to use at home and did not make it affordable. The IBM PC Junior suffered from an incomplete definition of the problem for IBM to successfully compete against Apple and Commodore in the home computer market.

These examples from history show that a thorough, complete definition of a problem is crucial in forming effective solutions. This chapter provides a process for defining a problem and articulating what decision maker(s) value from a solution to his/her problem. Included in this process are the other stakeholder values that the decision maker(s) need to consider as well.

10.1.1 The Problem Definition Phase

In Chapter 9 we saw that defining the problem was the first phase in our systems decision process. We gather and process information in this phase. As with any good problem solving process, this phase requires thorough research. Performing a literature review of appropriate laws, organizational policies, applicable studies previously performed, and pertinent discipline-specific principles is necessary to effectively define a problem.

The concept diagram in Figure 10.1 shows the tasks involved in the Problem Definition phase and the relationships between them. Systems engineers define a system and determine its objectives. They also define a problem statement for a system or decision problem by analyzing the stakeholders involved, analyzing the functions of the system, and modeling what decision makers value in an effective solution. The key tasks in this phase are *research* and *stakeholder analysis*, *functional* and *requirements analyses*, and *value modeling*. While research into a systems decision problem continues throughout the SDP, it is particularly helpful early on to help the systems team gain a more comprehensive understanding of the challenge and to identify specific disciplines related to the problem. Moreover, research helps to identify those stakeholders who have a vested interest in any resulting solution.

Stakeholder analysis enables systems engineers to identify the objectives, functions, and constraints of a system or decision problem and the values of decision makers. Systems interact in an environment that affects the stakeholders of this system. As we saw in Chapter 2, systems engineers use systems thinking to understand the environmental factors affecting a system in order to identify the relevant stakeholders. These stakeholders include consumers of the products and services provided by the system. An analysis of the stakeholders and their needs helps us identify the correct and complete problem requiring a solution. This analysis also leads us to new areas to research in order to understand the problem domain. A problem is not correctly defined unless we have received input from all stakeholders. We will discuss several techniques for completing a thorough stakeholder analysis.

A system is developed to perform certain functions. These functions should be designed to meet the objectives of the system. Systems must also meet certain requirements in order to be feasible and effective. Systems engineers need to understand the functions a system is intended to perform and the requirements it must meet in order to develop effective solutions. We will describe the techniques involved in performing both functional and requirements analyses of a system.

What determines an effective solution to a problem? An effective solution is one that meets the values articulated by the key stakeholders. To determine if a potential solution meets these values, systems engineers follow a process that qualitatively and quantitatively models the stakeholder values by identifying objectives for each function and value measures for each objective. This chapter describes this process of value modeling.

10.1.2 Comparison with Other Systems Engineering Processes

Beginning our systems decision process with a deliberate, focused process for the problem definition is not unique. No matter what form of systems engineering process or life cycle is packaged, it will involve a *formulation of the problem* step in which an initial problem statement is assessed and the needs of decision makers are determined [4].

Several systems engineering and problem solving processes naturally start with some form of problem definition [5]. Wymore defines a system life cycle in seven phases, the first of which is the development of requirements. During this phase, systems engineers work on tasks such as understanding the problem situation and the customer needs [6]. The SIMILAR process for the systems design starts with a "state the problem" function [7]. The International Council on Systems Engineering includes Plowman's model of the systems engineering process in their systems engineering body of knowledge. This process includes a function for understanding what a customer wants and how a system must perform [8]. This identifies just a few of the systems engineering processes and/or life cycles that incorporate a deliberate process for defining the problem.

10.1.3 Purpose of the Problem Definition Phase

The Problem Definition phase can and should be done to support systems decision making in each stage in the life cycle. This phase provides a process for helping stakeholders define their problem before attempting to develop solutions. The initial problem defined is never the real problem that needs to be addressed. In the auto market example described at the opening of this chapter, the U.S. auto manufacturers spent considerable resources and time in attempting to get trade legislation passed that would increase the cost of Japanese cars to American consumers. While this attempted to address the cost part of the problem, it ignored the quality issues underlying the problem. The tasks and techniques described in this chapter can hopefully help prevent wasting resources by chasing potential solutions to the incorrect problem.

The initial problem is never the real problem.

The goal for the end of this phase is to have a clearly defined problem statement that meets the approval of the key stakeholders, a set of systems requirements or constraints that alternative solutions must meet before alternatives are fully designed, modeled, and analyzed, and an initial quantitative methodology for evaluating how well alternatives meet the values of stakeholders in solving the correct problem.

10.1.4 Chapter Example

To illustrate the key points in this chapter, we will use the following systems decision problem: An aeronautics manufacturer wants to develop a new small, mobile rocket that can be used for multiple applications—for example, military or research uses. We will use this initial problem statement to demonstrate some of the tasks and techniques useful in the problem definition phase of our systems decision process.

10.2 RESEARCH AND STAKEHOLDER ANALYSIS

Given the multi- and interdisciplinary nature of systems engineering, a systems engineer will need to be an aggressive and inquisitive researcher in order to learn about a variety of topics. The research and stakeholder analysis task is an important and iterative process. When introduced to a new problem, systems engineers conduct research in order to understand the nature and domain of disciplines involved. This research leads to identifying the stakeholders impacted by the problem. Stakeholders identify additional research sources for the systems engineering team to investigate. Thorough research is critical in performing a complete definition of the problem.

Stakeholders comprise the set of individuals and organizations that have a vested interest in the problem and its solution [9]. Besides decision makers, stakeholders

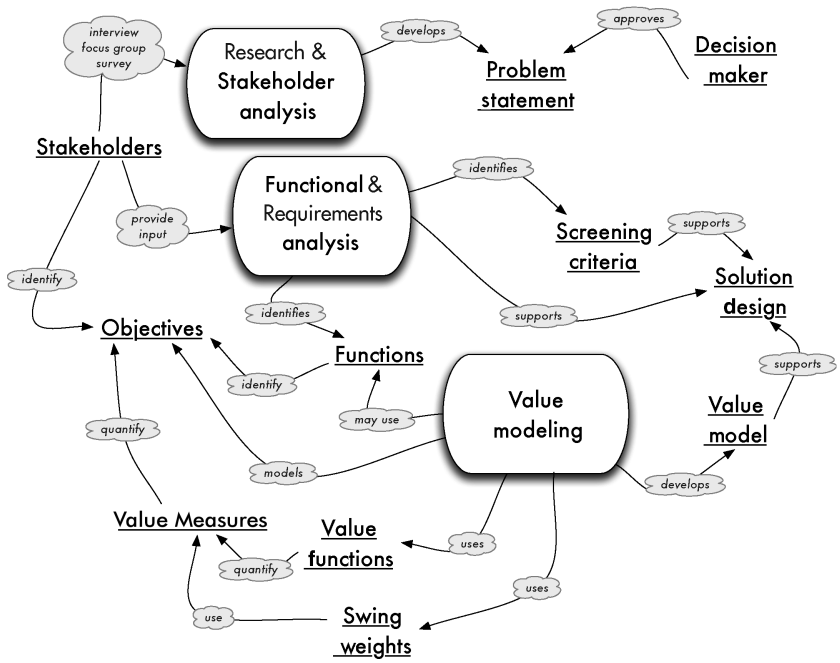

Figure 10.1 Concept diagram for problem definition.

can include the customers of the products and services output by the system, system operators, system maintainers, bill payers, owners, regulatory agencies, sponsors, manufacturers and marketers, among others. Understanding who is affected by a system or solution to a decision problem provides the foundation for developing a complete definition of the problem.

Systems engineers use research and stakeholder analysis to understand the problem they face, identify the people and organizations relevant to the problem at hand, and determine their needs, wants, and desires with respect to the problem. Through this task, stakeholders identify the functions, objectives, value measures, and constraints of the systems decision problem. It is also important in this task to understand the decision space for the problem. Systems engineers need to clearly understand up front what decisions have to be made by stakeholders in addressing the problem. Stakeholder analysis also includes a thorough research into the environmental factors impacting the systems decision problem. By considering such relevant issues as the political, economic, social, ethical, and technological factors affecting the problem, we can identify all the active and passive stakeholders within the scope of the problem. Systems engineers need to identify the requirements and constraints that all candidate solutions must meet. This task also helps identify the values that stakeholders deem important in any solution to the systems decision problem. These values help the systems engineer evaluate the quality of potential solutions.

The initial problem statement is seldom the full statement of the problem from the perspective of all stakeholders. The primary purpose of stakeholder analysis is to obtain diverse stakeholder perspectives on the problem that will provide a broader definition of the problem that captures the stakeholder perspectives. In addition, stakeholder analysis provides important insights for the systems decision process. Performing an analysis of these stakeholders will provide insight useful for developing and evaluating potential solutions for the problem.

For our rocket systems decision problem example, the list of relevant stakeholders can be very large. Stakeholders include the potential users of the rocket—for example, research organizations (like NASA) and military commanders. Senior and mid-level leaders of the manufacturer are also stakeholders, including the financial decision makers and production operations personnel. Stakeholders can also include subcontractors that may contribute to the design and production of the rocket system. Performing an analysis of these stakeholders will provide insights useful for developing and evaluating candidate solutions for the problem.

Several familiar techniques exist for soliciting input from diverse stakeholders. The three techniques we will describe are interviews, surveys, and focus groups.

10.2.1 Techniques for Stakeholder Analysis

Three general techniques are commonly used for stakeholder analysis: interviews, focus group meetings, and surveys. Each technique has different characteristics. We consider five characteristics: the time commitment of the participants, ideal stakeholder group, the preparation activities, the execution activities, and the analysis activities. Table 10.1 provides a description and a comparison of the three techniques for each of the five characteristics. The number of interviews, the number and size of focus groups, and the number of surveys required depend on the problem and the diversity of the stakeholders. Statistical tests can be used to determine the required sample sizes.

Interviews Interviews are one of the best techniques for stakeholder analysis if we want to obtain information from each individual separately. Interviews are especially appropriate for senior leaders who do not have the time to attend a longer focus group session or the interest in completing a survey. However, interviews are time-consuming for the interviewer due to the preparation, execution, and analysis time.

Since interviews take time, it is important to get the best information possible. The following are best practices for each phase of the interview process: planning, scheduling, conducting, documenting, and analyzing interviews.

Before the Interview For interviews with senior leaders and key stakeholder representatives, it is important to prepare a questionnaire to guide the interview discussion. The following are the best practices for interview preparation:

- Unless the team has significant problem domain experience, research is essential to understand the problem domain and the key terminology.

TABLE 10.1 Stakeholder Analysis Techniques

	Time Commitment of Participants	Ideal Stakeholder Group	Preparation	Execution	Analysis
Interviews	30–60 minutes	Senior leaders and key stakeholder representatives	Develop interview questionnaire(s) and schedule or reschedule interviews.	Interviewer has conversation with senior leader using questionnaire as a guide. Separate note taker.	Note taker types interview notes. Interviewer reviews typed notes. Team analyzes notes to determine findings, conclusions, and recommendations.
Focus groups	Shortest: 60 minutes Typical: 4–8 hours	Mid-level to senior stakeholder representatives	Develop meeting plan, obtain facility, plan for recording inputs. May use Group Systems software to record.	At least one facilitator and one recorder. Larger groups may require breakout groups and multiple facilitators.	Observations must be documented. Analysis determines findings, conclusions, and recommendations.
Surveys	5–20 minutes	Junior to mid-level stakeholder representatives	Develop survey questions, identify survey software, and develop analysis plan. Online surveys are useful.	Complete survey questionnaire, solicit surveys, and monitor completion status.	Depends on number of questions and capability of statistical analysis package. Conclusions must be developed from the data.

- Develop as broad a list of interviewees as possible. Identify one or more interviewees for each stakeholder group. Review the interview list with the project client to ensure that all key stakeholders are on the list of potential interviewees.
- Begin the questionnaire with a short explanatory statement that describes the reason for the interview, the preliminary statement of the problem, and the stakeholders being interviewed.
- It is usually useful to begin the interview with an unfreezing question that encourages the interviewee to think about the future and how that will impact the problem that is the subject of the interview.
- Tailor the questionnaire to help you define the problem and obtain information that will be needed in the future.
- Tailor the questionnaire to each category of interviewee. Make the questions as simple as possible.
- Do not use leading questions that imply you know the answer and want the interviewee to agree with your answer.
- Do not ask a senior leader a detailed question the answer to which can be looked up on the Internet or obtained by research.
- End the questionnaire with a closing question, for example, "Is there any other question we should have asked you?"
- Arrange to have an experienced interviewer and a recorder for each interview.
- Decide if the interviews will be for attribution or not for attribution. Usually, the information obtained during interviews is not attributed to individuals.

Schedule/Reschedule the Interview Interviews with senior leaders require scheduling and, frequently, rescheduling. The following are best practices for interview scheduling:

- It is usually best to conduct interviews individually to obtain each interviewee's thoughts and ideas on the problem and the potential solutions. Additional attendees change the interview dynamics. The senior leader may be reluctant to express ideas in front of a large audience or may defer to staffers to let them participate.
- Provide the brief problem statement to the interviewees when the interview is scheduled.
- Provide the interviewee with a short read-ahead document that clearly communicates the purpose of the interview and enables the interviewee to adequately prepare for the session. A typical read-ahead applicable for all meetings with stakeholders includes:
    1. A short summary of the background of the problem/issue being discussed. This could take the form of an abstract or executive summary. The individual(s) or organization(s) sponsoring the study that motivated the interview should be clearly identified.

2. A statement of the purpose of the interview (e.g., "... to identify all system linkages to outside agencies...", "... to identify key stakeholders related to the system design, their vested interests, and point-of-contact to schedule future interviews in support of the project ...", etc.).
3. The proposed duration of the interview.
4. A short list of desired outcomes if not clear from the purpose statement.
5. Attachments that contain pertinent, *focused* materials supporting the interview.
6. If slides are going to be forwarded as part of the read-ahead, then:
   a. Use no more than two slides per page; less is inefficient, more challenges the eyesight of the interviewee.
   b. Use the Storyline format (see Chapter 12) for slides to limit the interviewee's likelihood of misinterpreting the intended message on each slide. Remember: these slides will be present at the interviewee's location before you get a chance to conduct the interview in-person.
7. A list of the key project personnel and their contact information, identifying a primary point-of-contact for the team among those listed. Once interviewees become connected with a project via an interview, the systems team should anticipate additional information and follow-on questions to ensue. Designating a single team member to have responsibility as the centralized contact keeps this information flow (both in-and-out of the team) controlled and organized while simultaneously creating a "familiar face" on the team for the interviewees.

- Many times it is best to have the stakeholder representatives assigned to your team schedule the interview since they may have better access.
- Depending on the importance of the problem and the difficulty of scheduling, we usually request 30–60 minutes for the interview.
- The interviews can be done in person or over the phone. In-person interviews are the most effective since interaction is easier, but sometimes they are not possible and the only practical choice is a phone interview.
- The more senior the leader, the more likely scheduling will be a challenge.

One cautionary note is in order regarding advanced materials sent to the interviewee. It is usually *not* a best practice to provide detailed questions ahead of the interview for two reasons. First, remember that the purpose of the interview is to obtain information directly from the stakeholder and not an intermediary representative. If the interview questions are provided in a read-ahead packet, there is a likelihood that the stakeholder's staff will prepare responses to the questions, thereby defeating the purpose of the interview. Second, the systems team conducting the interview should have the flexibility to add questions and/or follow-up on valuable information leads should they arise. If the stakeholder is preconditioned into knowing the questions (and responses) in advance, the team might not be able to "stray from the script" without providing written questions to the stakeholder or staff.

During the Interview The interview teams' execution of the interview creates an important first impression with the senior leader about the team that will develop a solution to the problem. The goal of the interview is to obtain the stakeholder insights in a way that is interesting to the interviewee. Some thoughts for conducting interviews are as follows:

- The best number of people to conduct the interview is one interviewer and one notetaker. An alternative to the notetaker is a recorder. Some interviewees may be reluctant to be recorded. If you wish to use a tape recorder, request permission first.
- Conduct the interview as a conversation with the interviewee. Use the interview questionnaire as a guideline. Take the questions in the order the interviewee wants to discuss them.
- Make the interview interesting to the interviewee.
- Use an unfreezing question for the first question. An unfreezing question helps the interviewer focus on the problem in the future.
- Be flexible, following up on an interesting observation even if it was not on your questionnaire. Many times an interviewee will make an interesting observation you did not anticipate in your questionnaire. It is critical to make sure you understand the observation and the implications.
- Ask simple open-ended questions that require the interviewee to think and respond. Avoid complex, convoluted questions that confuse the interviewee.
- Respect the interviewee's time. Stay within the interview time limit unless the interviewee wants to extend the interview period.
- When the interviewee's body language signals that they have finished the interview (e.g., fold up paper, look at their watch), go quickly to your closing question, and end the interview.

After the Interview Documentation of the interview is the key to providing the results of the interview to the problem definition team. The best practice for documenting the interviews is the following:

- As soon as possible after the interview, the recorder should type the interview notes.
- The questions and the answers should be aligned to provide proper context for the answers.
- It is best to record direct quotes as much as possible.
- The interviewer should review the recorder's typed notes and make revisions as required.
- Once the interview notes are complete, they should be provided to the interview team.
- The documentation should be consistent with the decision to use the notes with or without attribution.

Analysis of the Interview Notes The interview notes are a great source of data for the entire systems engineering team. The key to interview analysis is binning (i.e., categorizing) the comments, summarizing observations, and identifying unique "nuggets" of information that only one or two interviewees provide. The best practice for analysis of interview notes is the following:

- The most common analysis approach is to bin the interviewee responses by the questions.
- The most challenging task is to identify unique "nuggets" of information that only one or two interviewees provide.
- The best way to summarize interviews is by findings, conclusions, and recommendations. Findings are facts stated by the stakeholders. Conclusions are a summary of several findings. Recommendations are what we recommend we do about the conclusion.
- It is important to integrate research findings with the interview findings. Many times an interviewee will identify an issue that we must research to complete our data collection.
- Identifying the findings for a large number of interviews is challenging. One approach is the preliminary findings approach. Here is one way to do the approach:
  - Read several of the interview notes.
  - Form preliminary findings.
  - Bin quotes for the interviews that relate to the preliminary findings.
  - Add research information to the quotes.
  - Revise the preliminary findings to findings that are fully supported by the interview and research data.

Table 10.2 is an illustrative example of a set of findings and conclusions that lead to a recommendation.

As the findings are being identified, it is important not to get distracted by focusing on potential findings that are interesting but unrelated to the purpose of the stakeholder analysis. If appropriate, these findings should be presented separately to the decision makers.

Follow up with Interviewees Many times the interviewee will request follow-up information. The following are examples of appropriate follow-up:

- Thank you note or e-mail to the interviewee and/or the stakeholder representative that scheduled the meeting.
- A revised statement of the problem after the problem definition is complete.
- A copy of the findings, conclusions, and recommendations from the interviews.
- A briefing or copy of the report at the end of the project.

TABLE 10.2 Illustrative Example of Findings, Conclusions, and Recommendations

Findings	Conclusions	Recommendations
20 of the 30 interviewees were concerned about the cost of the solution.	Many of the stakeholders believe that cost will be an important criteria in our study.	The system analysis team should consider cost and should use the System Life Cycle Cost Model for the cost analysis.
Policy directive 10.123 recommends the consideration of life cycle costs for all acquisition decisions [research].	Policy directives recommend the consideration of life cycle costs.	
The cost expert stated that the most appropriate cost model for solution evaluation is the System Life Cycle Cost Model		

Examples of Studies Using Interviews The following are a selection of studies conducted by the authors that have used interviews as a key technique in the stakeholder analysis task:

- Ewing, P, Tarantino, W, Parnell, G. Use of decision analysis in the army base realignment and closure (BRAC) 2005 military value analysis. *Decision Analysis Journal*, 2006;(1)l3:33–49 [about 40 interviews with senior Army leaders].
- Powell, R, Parnell, G, Driscoll, PJ, Evans, D, Boylan, G, Underwood, T, Moten, M. Residential communities initiative (RCI) portfolio and asset management program (PAM) assessment study, Presentation to Assistant Secretary of the Army for Installations and Environment, 15 December 2005 [72 interviews with Army senior leaders, installation leaders, and RCI personnel].
- Parnell, G, Burk, R, Schulman, A, Westphal, D, Kwan, L, Blackhurst, J, Verret, P, Karasopoulos, H. Air Force Research Laboratory space technology value model: Creating capabilities for future customers, *Military Operations Research*, 2004, 9(1):5–17 [about 50 interviews with senior Air Force leaders].
- Parnell, G, Engelbrecht, J, Szafranski, R, Bennett, E. Improving customer support resource allocation within the National Reconnaissance Office. *Interfaces*, 2002;32(3):77–90, [about 25 interviews with senior leaders and key stakeholders].
- Trainor, T, Parnell, G, Kwinn, B, Brence, J, Tollefson, E, Downes, P. Decision analysis aids regional organization design. *Interfaces*, 2007;37(3):253–264 [about 50 interviews with senior Army leaders and key stakeholders].

Focus Groups Focus groups are another technique for stakeholder analysis. Focus groups are often used for product market research; however, they can also be useful for determining relatively quickly how groups of stakeholders feel about a specific systems decision problem. While interviews typically generate a one-way flow of information, focus groups create information through a discussion between the group members who typically have a common background related to the problem being studied. For example, if the problem involved designing an efficient production plant, the team would form separate focus groups for plant management and for plant laborers. As a general rule, focus groups should comprise 6–12 individuals. Too few may lead to too narrow a perspective, while too many will lead to some individuals not able to provide meaningful input. As with interviews, the focus group facilitation team needs to devote time to the preparation of, execution of, and analyzing data from focus groups [10].

Preparing for the Focus Group Session As with any stakeholder analysis technique, developing the goals and objectives of the focus group session is critical to success. A few best practices for preparing for a focus group session [11] include the following:

- Develop a clear statement of the purpose of the focus group and what you hope to achieve from the session. This should be coordinated with the project client and provided to the focus group participants.
- Develop a profile of the type of participant that should be part of the session and communicate that to the project client.
- Select a participant pool with the project client.
- Select and prepare moderators that can facilitate a discussion without imposing their own biases on the group. If resources permit, hire a professional moderator.
- Schedule a time and location during which this group can provide 60–90 minutes of uninterrupted discussion.
- Develop a set of questions that are open-ended and will generate discussion. Do not use "Yes/No" questions that will yield little discussion. The most important information may come out of discussion about an issue ancillary to a question posed to the group.

Conducting the Focus Group Session The most important components of conducting the session are the moderator and the recording plan. Here are some thoughts for the execution of a focus group session [12]:

- The moderator should review the session goals and objectives, provide an agenda, and discuss the plan for recording the session.
- Ask a question and allow participants a few minutes to discuss their ideas. The moderator should ensure even participation from the group to prevent a few individuals from dominating the group.

- A good technology solution for facilitating focus groups is the GroupSystems software [13]. This technology facilitates groups in brainstorming activities and generating ideas. It helps mitigate the impacts from individuals who tend to dominate discussions because participants type their ideas on a computer in response to questions generated by the moderator. It also significantly helps the team in recording the information from the session and sets them up for analysis of the data.
- Do a video and audio recording of the session if possible. If not, use multiple notetakers.
- The moderator may steer the discussion to follow a particular issue brought up that impacts the problem being studied.
- On closing, tell the participants they will receive a record of the session to verify their statements and ideas.
- Follow up the session with an individual thank you note for each participant.

Analyzing the Information Focus groups can provide a great source of qualitative data for the systems analysis team to analyze and create useful information. The recorders should first verify the raw data that was generated during the session. These data should then be processed into findings, conclusions, and recommendations using the methods discussed in the interview section of this chapter. If you run more than one focus group, realize that you cannot necessarily correlate the data between the groups since they represent different subgroups of the stakeholders.

Surveys Surveys are a good technique for collecting information from large groups of stakeholders particularly when they are geographically dispersed. Surveys are appropriate for junior to mid-level stakeholders. If the problem warrants, surveys can be used to gather quantitative data that can be analyzed statistically in order to support conclusions and recommendations. A great deal of research exists on techniques and best practices for designing effective surveys. Systems engineers can distribute and collect survey data via mail, electronic mail, or the World Wide Web for many of the problems they face. This section provides an overview of survey design and methods for conducting surveys. As with any stakeholder analysis technique, surveys require detailed planning to accomplish the team's goals. These steps can be followed to plan, execute, and analyze surveys [14]:

- Establish the goals of the survey.
- Determine who and how many people you will ask to complete the survey, that is, determine the sample of stakeholders you will target with the survey.
- Determine how you will distribute the survey and collect the survey data.
- Develop the survey questions.
- Test the survey.
- Distribute the survey to the stakeholders and collect data from them.
- Analyze the survey data.

Preparing an Effective Survey Determine your goals, survey respondents, and means of distributing and collecting survey data. The stakeholder analysis team needs to clearly articulate the goals of the survey and the target sample of stakeholders whom they want to answer the survey. Often surveys for systems engineering decision problems will be used to collect textual answers to a standard set of questions. However, if the team plans to collect and analyze data from questions with standard answer scales (e.g., "Yes/No" or multiple choice answer scales), it is important to determine the appropriate sample size needed to draw valid statistical conclusions from the survey data. Sample size calculations are described in basic statistics books, and online tools are available to do these calculations [15]. The team needs to work with the project client in determining the appropriate stakeholders to survey. The method for implementing a survey needs to be selected before the survey is designed. Popular methods for systems engineers are mail, electronic mail, and web surveys. Table 10.3 provides a listing of some of the advantages and disadvantages of these survey methods [14].

The ability to collect survey responses in a database when using a web survey instrument can be extremely beneficial to the stakeholder analysis process. Several online programs now exist to help teams design web surveys, collect responses, and analyze the results. Some popular programs include surveymonkey.com [16], InsitefulSurveys.com [17], and the SurveySystem.com [18].

Executing a Survey Instrument Developing the survey questions, testing, and distributing the survey. Surveys should be designed to obtain the information that will help the stakeholder analysis team meet the goals of the survey. To maximize response, the survey should be short with clearly worded questions that are not ambiguous from the respondent's perspective. Start the survey with an overview of the purpose of the survey and the goals that the team hopes to achieve from the information provided by the respondents. Here are some general principles that can be followed in developing effective survey questions [19]:

- Ask survey respondents about their first-hand experiences, that is, ask about what they have done and their current environment so that they can provide informed answers. Respondents should not be asked hypothetical questions, nor should they be asked to comment on things outside their working environment.
- Ask only one question at a time.
- In wording questions, make sure that respondents answer the same question. If the question includes terms that could be interpreted differently by respondents, provide a list of definitions to clarify any possible ambiguities. This list of definitions should precede the questions.
- Articulate to respondents the kind of acceptable answers to a question. For objective questions, the answer scales can be set up as multiple choice answers from a rating scale or level-of-agreement scale. For certain questions and stakeholders, it may be appropriate to provide benchmark examples for the

answer scales. For example, the responses to a question regarding the respondent's level of effort on a project may include a benchmark statement like "full time effort equates to 40 hours of work per week." For open-ended text response questions, the question should be worded so that respondents provide information germane to the question. Close the survey with a statement allowing respondents to provide any additional information they believe is pertinent to the goals of the survey.

- Format the survey so that it is easy for respondents to read the questions, follow instructions, and provide their answers. For example, answer scales should follow a similar pattern in terms of the order in which they are presented (e.g., the least desirable answer is the first choice ascending to the most desirable answer).
- Orient the respondents to the survey in a consistent way. This can be accomplished with a set of instructions that describe the goals of the survey, the

TABLE 10.3 Advantages and Disadvantages of Popular Survey Methods

Survey Method	Advantages	Disadvantages
Mail	• Can include extensive supporting graphics • Respondents have flexibility in completing the survey	• Takes a great deal of time • Hard to check compliance and conduct follow-up with respondents • Response data will have to be transformed by the analysis team into a format for analysis
Electronic mail	• Fast to distribute and get responses • Low cost • Easy to check compliance and do follow-up	• Need to obtain e-mail addresses for the survey sample • Cannot program automatic logic into the survey (e.g., "skip over the next set of questions if your answer is No to this question") • Respondent e-mail programs may limit the type of information that can be sent in the survey • Response data will have to be transformed by the analysis team into a format for analysis
Internet Web survey	• Extremely fast • Can include special graphics and formatting • Can collect responses in a database to facilitate analysis	• May be hard to control who responds to the survey due to worldwide Internet access • Respondents can easily provide only a partial response to the survey

method for completing their responses, and the means for submitting the completed survey.

Once the survey questions are written, test the survey instrument with a few individuals outside the team. Ask them to complete the survey using the same medium that respondents will use (e.g., by e-mail, mail, or on the web). Ask for input from the test sample regarding the instructions and wording of the questions and answer scales. If a web survey is used, test the method for collecting responses, for example, in a database. Use the input from the test sample to improve the survey. Once improvements are made, distribute the survey to respondents using the method chosen. Develop a plan for monitoring the response rate and establish when reminders will be sent to respondents who have not completed the survey. The team should also have a standard way to thank respondents for their time and efforts, for example, a thank you note or e-mail.

Analyzing Survey Data A key part of the analysis effort will be in formatting the survey data that is received. If a web survey is used, the team can program the survey instrument to put responses directly into a database file. This will allow the team to perform statistical analysis on objective-type questions relatively quickly. For text answer questions, a database file provides a means to bin the responses quickly. The goals of the analysis are the same as for interviews and focus group sessions. Similar to the process discussed earlier in this section, the team should bin the responses by survey question and analyze these responses to develop findings. These findings will lead to forming conclusions, which then will lead the team to form recommendations.

10.2.2 Stakeholder Analysis for the Rocket System Decision Problem

The systems engineering team primarily relied on the interview technique for the stakeholder analysis for the rocket system. They also conducted focus groups with potential military and research stakeholders. Table 10.4 provides a partial (notional) example of the analysis of the information obtained from stakeholders using the binning process described in Section 10.2. Through research and stakeholder analysis we also discover any "must meet" requirements affecting the problem. For our rocket example, the stakeholders identified that the rocket system must meet the following constraints:

- The rocket must have a minimum effective range of 5 km.
- The rocket must be launched from a four-wheeled drive vehicle.
- The rocket must be able to move through a variety of terrain conditions, from open fields to forested areas.

These requirements become screening criteria that candidate solutions must meet. These are discussed in greater detail in Chapter 11.

TABLE 10.4 Partial Stakeholder Analysis Results for the Rocket System Decision Problem

Findings	Conclusions	Recommendations
15 of the 20 interviewees said the current need of potential users was for a smaller mobile rocket system.	Stakeholders believe that mobility of the rocket system will be a key design criterion.	The systems engineering team should consider mobility and the ability to operate at short-range key design criteria for the new rocket system.
The military has a call for proposals out to manufacturers to build a rocket system that can be easily moved around the battlefield [from research and interviews].		
Current rocket systems are only useful at ranges of greater than 10 kilometers [research].	Stakeholders think the rocket system should be designed to operate at short ranges.	
Most interviewees said that a market exists for rockets that can deploy an object (e.g., a warhead or sensor) between 5 and 10 km.		

10.2.3 At Completion

When research and stakeholder analyses are completed, the systems engineering team should have a thorough understanding of the stakeholder objectives and decisions needed in arriving at a solution to the systems decision problem. The team will also understand the facts and assumptions that are needed in further analysis of the problem. The team should also understand what stakeholders value from solutions to the problem. This is discussed further in Section 10.4. Stakeholder analysis should help the team identify the key life-cycle cost and risk factors that should be considered in any solution to the problem along with any screening criteria.

While stakeholder analysis helps identify initial requirements, objectives, and values for developing candidate solutions to the systems decision problem, we use functional analysis and requirements analysis to identify the key functions and requirements that the solution must be designed to perform.

10.3 FUNCTIONAL AND REQUIREMENTS ANALYSES

In Chapter 2 we introduced functional hierarchies as a technique for describing the functions a system will be designed to perform. In Section 6.5 we concluded that defining the system functions and requirements was one of the three fundamental tasks of systems engineers. In Section 10.2 we described the systems engineering activities involving systems requirements analysis and functional analysis. In this section we describe the central role of functional and requirements analyses in the SDP. We focus first on functional analysis in some depth and then provide an overview of requirements analysis.

10.3.1 Terminology

We begin by introducing some key terminology used in functional analysis.

Function. "A characteristic task, action, or activity that must be performed to achieve a desired outcome. For a product it is the desired system behavior. A function may be accomplished by one or more system elements comprised of equipment (hardware), software, firmware, facilities, personnel, and procedural data" [19].

Functional Analysis. A systematic process to identify the system functions and interfaces required to achieve the system objectives.

Functional Hierarchy. A hierarchical display of the functions and subfunctions that are necessary and sufficient to achieve the system objectives.

Functional Flow Diagram. A flow diagram that depicts the interrelationships of the functions.

IDEF0. IDEF0 stands for Integrated Definition for Function Modeling and is a modeling language (semantics and syntax) with associated rules and techniques for developing structured graphical representations of a system or enterprise [20].

Functional Architecture. "The hierarchical arrangement of functions, their internal and external functional interfaces and external physical interfaces, their respective functional and performance requirements, and the design constraints" [19].

Models and Simulations. See Chapter 4 for definitions.

Requirements Analysis. "The determination of system specific characteristics based on analysis of customer needs, requirements and objectives; missions; projected utilization environments for people, products and processes; and measures of effectiveness" [21].

10.3.2 Importance of Functional Analysis

Systems accomplish functions with system elements. Functional analysis is the process to identify the system functions and interfaces required to meet the system performance objectives. Functional analysis of the system design is performed in the first several stages of the system life cycle. If we do not identify all the system functions and interfaces, the system will not be designed to perform all the functions and will not work with its environment. The functional architecture is the allocation of the functions and interfaces to systems elements. If we do not allocate the functions to system elements, the functions will not be performed. If we do not identify the external and internal system interfaces, the system elements will not be able to perform the functions. If we do validate the system design using models and simulations, we may have to make costly changes to meet system performance objectives. Functional analysis can also be performed later in the system life cycle.

Since functional analysis plays such a critical systems engineering role in the system life cycle, we have included functional analysis in the SDP. We believe that systems engineers should use the most appropriate functional analysis information for the stage of the system life cycle that the SDP is being used.

10.3.3 Functional Analysis Techniques

There are many functional analysis techniques. The INCOSE Systems Engineering Handbook lists 13 functional analysis techniques [19]. In this section we introduce, in the order of increasing detail, four of the most useful techniques. Table 10.5 summarizes the purposes, uses, and limitations of the four techniques. Each of these will be discussed in the following sections.

Functional Hierarchy Functional hierarchies can be developed using affinity diagrams. An affinity diagram is a collection of ideas binned into logical groupings for a specific purpose (Figure 10.2) [22]. Affinity diagramming is a simple creative technique that has many valuable uses. Affinity diagramming is usually a group process used to generate ideas and provide new groupings of the ideas for a specific purpose. The affinity diagram is similar to the KJ Method originally developed by Kawakita Jiro [23]. The affinity diagram was made popular as a quality management technique. It is one of the most widely used Japanese management and planning tools.

Affinity diagramming can be done on any vertical or horizontal surface with Post-It™ notes (hence the nickname "the yellow-stickee" drill) or it can be done with specialized collaborative decision support software—for example, GroupSystems [13].

Affinity diagramming can be used for many systems engineering activities that require working with a group to generate new ideas and grouping the ideas into logical categories. Affinity diagramming can be combined with other techniques to determine priorities or actions for each group of ideas. Our interest in using affinity diagramming in functional analysis is to develop a functional hierarchy.

Steps for Affinity Diagramming for Functional Analysis We describe each of the steps for developing a functional hierarchy in what follows.

1. *Invite Required Stakeholders or Their Representatives to Attend.* For the affinity diagramming exercise to be successful, stakeholders must participate in the process either directly or through a representative who can clearly articulate the viewpoint of the stakeholder. All key stakeholder groups should

TABLE 10.5 Selected Functional Analysis Techniques

Functional analysis techniques	Purpose	Uses	Limitations
Functional hierarchy	Identify the system functions and subfunctions.	Provides functional hierarchy to guide concept development, design, and help identify performance measures.	Does not define functional relationships and interfaces, nor does it validate the system design.
Functional flowdiagram	Identify and show the relationships of system functions and subfunctions.	Defines the relationship of functions and subfunctions to guide concept development, design and help identify performance measures.	Does not define or validate system interfaces, nor does it validate the system design.
IDEF0	Model the decisions, actions, and activities of an organization or system.	Provides detailed information on the functions including inputs, outputs, mechanism, and controls to support the system design and development. Helps refine performance measures.	Does not validate system design.
Models and simulations	Model the system and/or its operation	Understand and support system design and evaluation. Helps refine performance measures.	Will not validate all aspects of system design.

be represented. If key stakeholders are not represented, important functions may not be identified.

2. *Define the System.* The scope of the system is critical for obtaining the appropriate functions. The following systems will have very different functions: the U.S. transportation system, an urban transportation system, an automobile, or a car engine. We recommend using a system boundary diagram (Figure 2.3) or an input–output diagram.
3. *Generate System Functions.* Each function should be specified with a verb and an object. The verb defines the activity of the function. The object provides the context. Both are required! The function should be specified without specifying the system element that will perform the function. For a vehicle, some appropriate functions might be transport passengers, store luggage, avoid collision with an object, and so on. An inappropriate function would

Figure 10.2 Affinity diagramming in action.

be "step on the brakes" since this function assumes that brakes will be an element and that the foot will be used to activate the brakes. The brainstorming can be done by individuals in the groups on the basis of their knowledge and experience. In some settings, it is appropriate (if not essential) to have the individual use organizational documents that provide required capabilities, functions, or requirements for the system. It is usually a good idea to get 10–20 functions from each individual.

4. *Rapidly Group (Affinitize) Similar Functions.* Once the functions have been recorded they should be displayed. Next, a few individuals should bin the functions into logical groups. Usually the verbs are the most helpful for binning the functions. For example, the following functions might be binned together: relocate passengers, take family to the store, seat passengers, and transport kids to soccer practice. As the affinitizing process is being performed, participants should continue to add new functions as ideas come to their mind or the discussion keys an idea. These function groups will become the lowest tier in the functional hierarchy. At this point each function group should be named. The name should be the most general name that captures the activity of all the functions in the group. The functional group should be named with a verb and an object. You can use one of the function names or develop a new name. In our example, "transport passengers" might be a good function group name.
5. *Develop Preliminary Functional Hierarchy.* The next step is to affinitize the function groups into the next higher level. Again, similar function groups will be binned together. The higher level function groups will need to be named with a verb and object that capture the meaning of the function groups below

it in the hierarchy. For example, transport passengers and move material, might binned into transport people and objects. For some systems, two levels may be sufficient. For complex systems, many levels may be required. This step would be repeated until the first tier of the hierarchy has about three to five functions. Three to five is a useful guideline since it is relatively easy to remember this number of functions. At each level of the hierarchy, the functions should be presented in the most logical order. For example, time sequencing may be appropriate. At this point the group activity is complete.

6. *Refine the Functional Hierarchy.* The lead systems engineer will need to refine the hierarchy and vet it with stakeholders who could not attend the affinity diagramming workshop and with system decision makers. During the process the function names on each tier may change as reviewers provide insights on a clearer or more acceptable way to name the functions.

Uses of Functional Hierarchy Once the functional hierarchy is complete, it has several uses. First, the functional hierarchy can (should!) be used to provide a clear understanding of the functions the system is being designed to perform. This makes it useful for presentations to participants in the systems engineering process, including decision makers and stakeholders. Second, the functional hierarchy is an important first step for more detailed functional analysis, which is required to identify and define interfaces and requirements. These systems engineering activities are described in Chapter 7. Third, the functional hierarchy can serve as the foundation for the assessment of the candidate solution designs (see Section 10.4). Fourth, the functional hierarchy can be used to help develop models and simulations. The functional hierarchy should be updated throughout the system life cycle and especially at every application of the systems decision process. Fifth, the functional hierarchy can be used to support system architecting and system design. Both of these processes involve the allocation of system elements to system functions.

USING THE AFFINITY DIAGRAMMING TECHNIQUE TO DEVELOP A FUNCTIONAL HIERARCHY FOR THE ROCKET SYSTEM EXAMPLE

To continue our notional example, the systems engineering team assembled a group of stakeholders representing users of the rocket (military, commercial, and research organizations) and manufacturers. After providing the system description, the group used the affinity diagramming process to develop a list of functions. The team grouped the resulting list into these top level functions:

Function 1.0: Launch rocket.
Function 2.0: Transport payloads.
Function 3.0: Achieve desired effect.

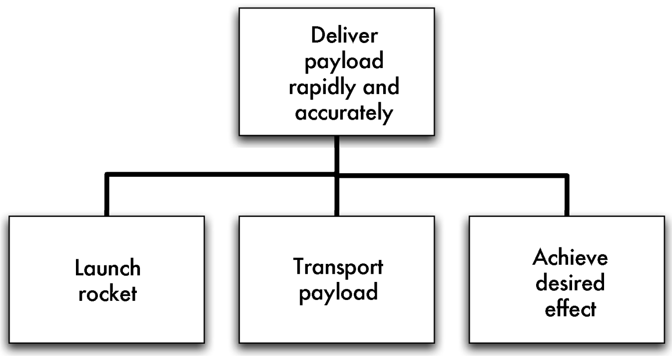

Figure 10.3 Functional hierarchy for the rocket example.

While this is a short list, it is useful to illustrate the affinity diagramming process. At the most basic level, the functions of a rocket are to launch, carry an object in flight, and put that object when and where needed to achieve some desired effect. Figure 10.3 provides a basic functional hierarchy for this example. We will continue to develop the example further.

Limitations of Functional Hierarchy Hierarchy is a first step to identify and structure the system functions; however, additional information is required to identify the interrelationships of functions and interfaces. The functional hierarchy can also identify the functions that may need to be modeled and/or simulated, but additional information will be required to develop the models and simulations for the development and evaluation of the system design.

Functional Flow Diagram Once the top-level functions have been identified their relationships can be depicted in a functional flow diagram. As the functions are decomposed their interfaces become more specific and more complex. The functional decomposition can be continued until discrete tasks have been defined that can be allocated to system elements. Trade studies are performed to allocate tasks to system elements. Figure 10.4 illustrates the functional decomposition for the top level of the National Aeronautical and Space Agency's Space Transportation System (STS) Flight Mission [19]. The flight mission is composed of eight tasks.

Each of the top-level functions in Figure 10.4 can be decomposed into the functions that are required to perform the top level functions. Figure 10.5 [19] shows the functional decomposition for the Perform Mission Operations 4.0 function into 10 functions and provides more information about their interfaces. The functional decomposition of each of the functions could continue to the next level.

Functional flow diagrams are the most useful in the system concept, design, and development stages of the systems life cycle. The functional flow diagram defines the relationships of the functions but does not define the interfaces needed to complete the design. The next technique provides additional functional analysis data.

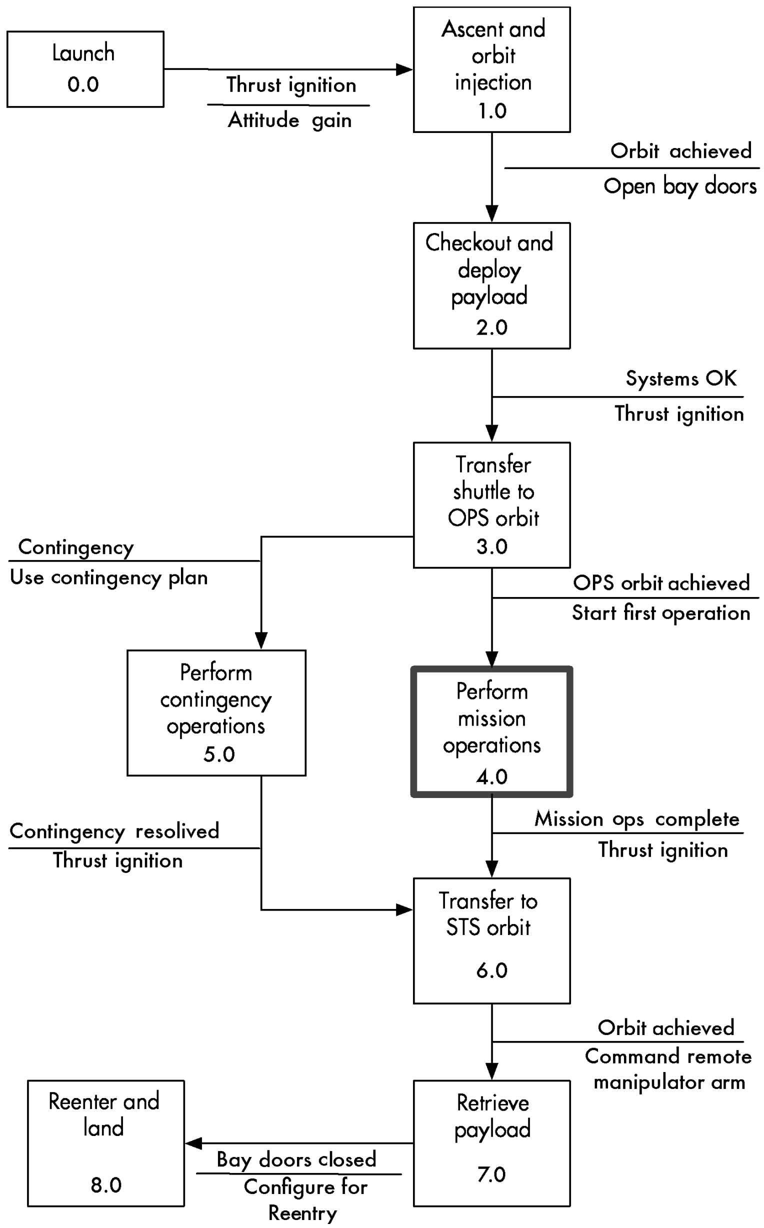

Figure 10.4 Functional decomposition for the top level of the STS flight mission.

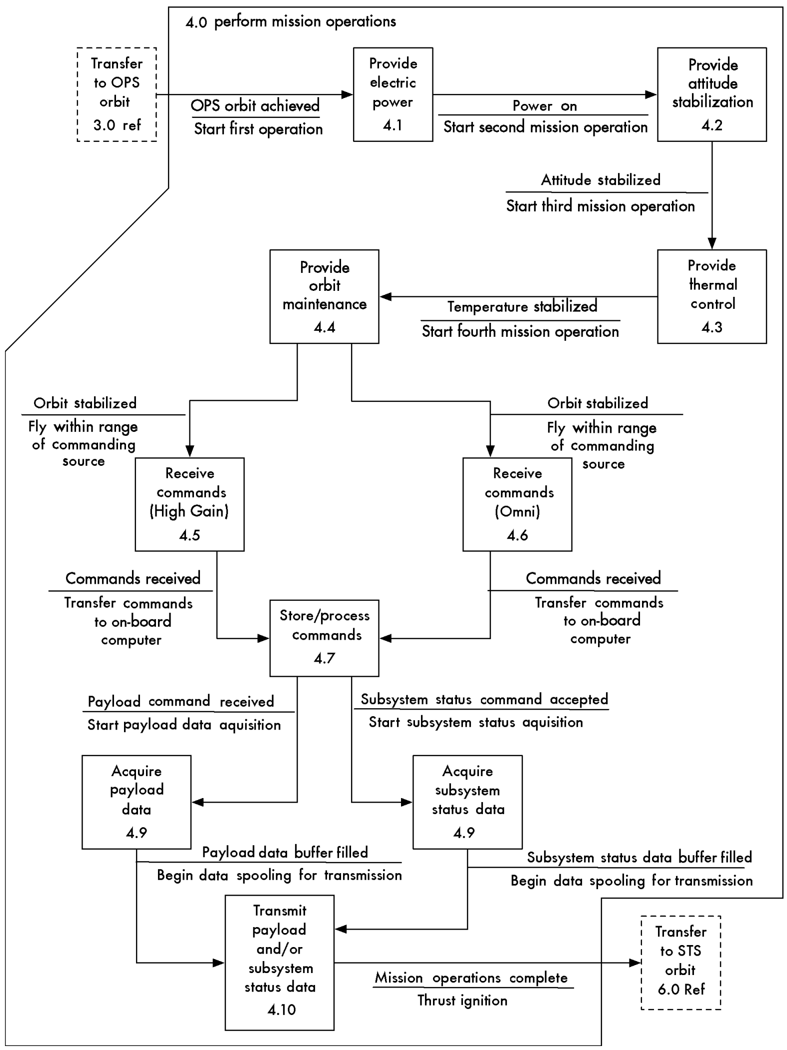

Figure 10.5 Functional decomposition—level 4.0 perform mission operations [19].

Uses of the Functional Flow Diagram Once the functional flow diagram is complete it has several uses. First, the diagram provides a better understanding of the relationships of the functions and tools to support the identification of the requirements. The top-level functions are useful for presentations to participants in the systems engineering process, including decision makers and stakeholders. Second, the functions in the diagram can serve as a foundation for the assessment of the alternative solution designs (see Section 10.4). Third, the functional flow diagram

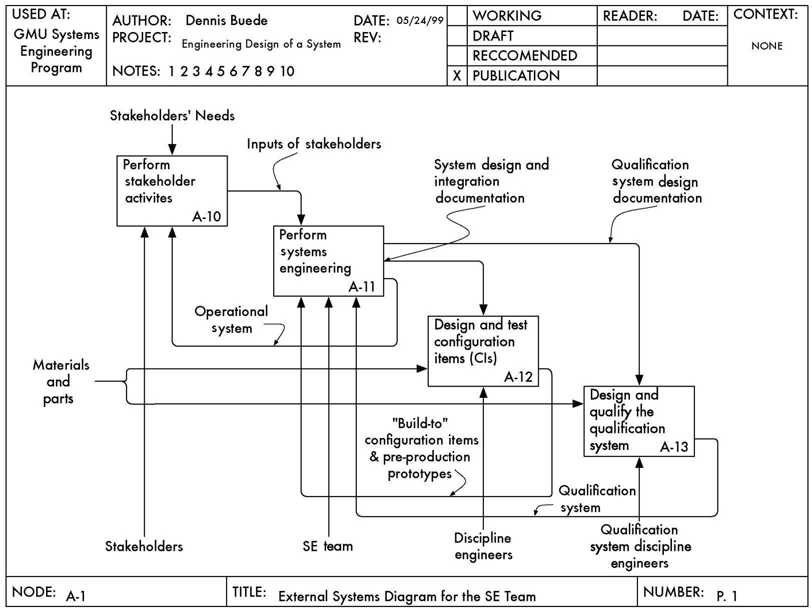

Figure 10.6 IDEF0 Level 1 functional analysis example.

can be used to support system architecting and system design. Fourth, the functional flow diagram can be used to help develop models and simulations to design and evaluate systems.

Limitations of the Functional Flow Diagrams The diagrams identify the functions and the interrelationships of the functions. This information is useful in identifying the models required. However, the diagrams do not identify all the inputs, outputs, controls, and mechanisms that are required for system design or the detailed development of models and simulations.

IDEF0 Functional Modeling Method IDEF0 models were discussed in detail in Chapter 2. These models can help the systems engineer communicate with key stakeholders to identify the functions, inputs, outputs, mechanisms, and controls of the system. IDEF0 is a useful method for functional analysis. The simple graphical approach helps involve subject matter experts early in the system development process. IDEF0 can be implemented with widely available tools (e.g., Microsoft® Visio [24]) or can be implemented with specialized software. Figure 10.6 provides an example from Buede's book of a high-level IDEF0 functional analysis for performing an engineering design of a system [25].

Uses of IDEF0 The model has several uses. First, the model can support the system design. IDEF0 helps identify and structure the system functions. IDEF0 models can be used to define 'As-Is' and 'To-Be' architectures. As-Is models are usually developed bottom-up, whereas To-Be models are developed top-down. For each function the inputs, outputs, controls, and mechanisms (ICOMs) are specified using a standard modeling language. The model is developed as a hierarchy of functions. The modeler can stop when functions are specified at the level of detail required to allocate components to functions. Second, the functions in the diagram can serve as a foundation for the assessment of the alternative solution designs (see Section 10.4). Third, the models can be used to help develop models and simulations to design and evaluate systems.

Limitations of IDEF0 These models provide detailed information to support system design and qualitative evaluation of candidate solutions. However, the models do not validate that the design will work in the environment or that the design has the capacity to provide the inputs and outputs of each function to meet the quantitative system performance parameters. Models, simulations, development tests, and operational tests are needed to overcome these limitations.

Models and Simulations Models and simulations have been described in Chapter 4. Models and simulations play an important role in system design and evaluation. We believe developing models will save time and money in system design and evaluation. If you cannot develop a model, you probably do not have enough information to design the system. In Chapter 4, we also described the uses and limitations of models and simulations. While simulation can replace some of the testing and evaluation, we believe that in almost all cases[1] some live testing is required to ensure that the system design meets the system performance objectives.

10.3.4 Requirements Analysis

Requirements analysis involves determining the specific characteristics of a system and is critical in designing an effective and cost efficient solution to a problem. This topic can be the subject of whole courses in universities however we will provide only a cursory introduction to the subject. For a more complete discussion see Martin [21], Wasson [26], or Kossiakoff [27].

Requirements, which are also called specifications or specification requirements, describe the technical capabilities and levels of performance desired in a system. These requirements can be binned into several types such as stakeholder, operational, capability, interface, verification, and validation requirements, to name a few. Requirements are not established randomly and the systems engineering team should maintain auditable records that trace requirements to objective information defining and describing the requirement. Similar to functional hierarchies, requirements can be derived from top down so the lowest level of requirements can be mapped back to some higher level operational requirement [26]. Software products,

[1] Nuclear weapons systems are an obvious example of systems that cannot be fully tested in an operational environment.

such as CORE® exist to create and trace requirements hierarchies [28]. A good way to categorize requirements is to describe them as constraints or capabilities. A constraint is a requirement that must be met while a capability is a desired feature, trait or performance characteristic [21]. Constraints will be used in a screening matrix in the Solution Design phase in order to weed out alternative solutions that do not meet requirements categorized as constraints. A key objective of requirements analysis is to transform operational requirements, or required outcomes of a system, into performance requirements that can be defined as engineering characteristics of the system [27].

Wasson [26] provides a helpful list of questions that systems engineers can think about while performing requirements analysis:

1. Do the list of requirements appear to be generated as a feature-based "wish list" or do they reflect a structured analysis?
2. Do the requirements appear to have been written by a seasoned subject matter expert?
3. Do the requirements adequately capture user operational needs? Are they necessary and sufficient?
4. Do the requirements unnecessarily constrain the range of viable alternative solutions?
5. Are all the system interface requirements identified?
6. Are there any critical operational or technical issues that require resolution or clarification?

Systems engineers need to follow a process to elicit, understand, document and trace the requirements of a system throughout the system life cycle. At this point in the Problem Definition phase, critical stakeholder and operational requirements should be defined and constraints identified so that alternative solutions can be screened for feasibility.

10.3.5 At Completion

A key output from functional and requirements analyses is a thorough understanding of the functions required from the solution to the systems decision problem. This task also provides an understanding of the interrelationships between the system functions. The system requirements are also defined and classified into constraints (must be met) and desired capabilities.

At this point, research, stakeholder, functional, and requirements analyses have enabled us to identify the objectives, functions, and constraints of the system being designed. The requirements identified as constraints become the screening criteria, which all candidate solutions must satisfy. However, how do we evaluate the goodness of candidate solutions to our problem? We create evaluation criteria based on what stakeholders value from the solution. These evaluation criteria become the value model that we use to evaluate candidate solutions. We use a process called value modeling to develop the candidate solution evaluation criteria.

10.4 VALUE MODELING

Value modeling provides the systems engineering team an initial methodology for evaluating candidate solutions. This task employs the concepts of value-focused thinking discussed in Chapter 9. This methodology will continue to be refined in the solution design and decision-making phases of the systems decision process. We use the information developed from the research and stakeholder analysis and the functional and requirements analysis tasks to create the evaluation methodology. These tasks enable us to develop a qualitative value model that captures the most important functions and objectives for the system. We use the qualitative value model to build a quantitative value model, which provides a measurable method to evaluate how well candidate solutions meet the fundamental objective of our systems decision problem. In essence, we are evaluating the future value of the implemented solution to our problem. We use the concepts of multiple objective decision analysis to build the mathematical framework for the value model.

The key question is, whose values are in the value model? Three important stakeholder groups must be considered: consumers, users, and customers. The consumers use the systems products and services. The users operate the system to provide products and services. The customers acquire the systems and provide them to users. For individual investing financial Web sites, the consumer is the investor, the user is the Web site manager, and the customer is the IT department that manages the design and development of the Web site. One individual or organization can perform multiple roles. For example, for an automobile system, the user (driver) is one of the consumers. Passengers are also consumers.

10.4.1 Definitions Used In Value Modeling

Constructing a value model requires a good deal of attention to detail in research and sensitivity to what stakeholder groups are expressing during stakeholder analysis. It is important to clearly define some of the key terminology used in value modeling [29].

Fundamental Objective. The most basic high level objective the stakeholders are trying to achieve.

Value Measure. Scale to assess how well we attain an objective. Alternate terms include the following: evaluation measures, measures of effectiveness, performance measures, and metrics.

Qualitative Value Model. The complete description of the stakeholder qualitative values, including the fundamental objective, functions (if used), objectives, and value measures.

Value Hierarchy/Value Tree. Pictorial representation of the qualitative value model.

Tier. Levels in the value hierarchy.

Weights. The weight assigned to a value measure reflects the measure's importance and the range of its measurement scale. We assess swing weights by assessing the impact of "swinging" the value measure from its worst to its best level.

Score. A number in the range of the value measure that reflects the estimated future performance of a candidate solution.

Value Function. A function that assigns value to a value measure's score. A value function measures returns to scale over the range of the value measure.

Quantitative Value Model. The value functions, weights, and mathematical equation used to evaluate candidate solutions.

Global (Measure) Weights. The measure weights for each value measure. Global (measure) weights sum to 1.

Local Weights. The weights at each node in the value hierarchy. Local weights below each node sum to 1.

10.4.2 Qualitative Value Modeling

In value modeling, we create both qualitative and quantitative value models. Of these the qualitative value model is the most important because it reflects the key stakeholder values regarding the systems decision problem. If the qualitative model does not accurately capture these values, the quantitative value model will not be useful in evaluating candidate solutions. In this section we describe how to develop a qualitative value model and then demonstrate it using our rocket example.

Criteria for a Value Model Kirkwood describes the criteria for a good value hierarchy as "completeness, nonredundancy, decomposability, operability, and small size" [30]. The concept of completeness basically means that the value model, represented by all its objectives and value measures, must be sufficient in scope to evaluate the fundamental objective in the systems decision problem. Nonredundancy means that functions or value measures on the same tier in the hierarchy should not overlap. The criteria of completeness and nonredundancy are often referred to as the value model being "collectively exhaustive and mutually exclusive." Value independence means that value of the scores on one value measure to not depend on the scores on any of the other value measures. Operability means that the value hierarchy is easily understood by all who use it. Finally, a value hierarchy should contain as few measures as possible while still meeting the requirement to be mutually exclusive and collectively exhaustive. This will help the team focus their analysis on the most important value measures.

Developing a Qualitative Value Model We use the information developed in the research and stakeholder analysis and functional and requirements tasks to determine the functions, objectives, and value measures that comprise the value model. These are the basic steps in developing the qualitative value model [29]:

1. *Identify the Fundamental Objective.* This is a clear, concise statement of the primary reason we are undertaking the decision problem. For example, the authors worked on a decision problem for the U.S. Army concerning the organizational structure of a key subordinate element of the army. The fundamental objective of this decision problem was “develop the most effective and efficient organizational structure to support the Army’s mission” [32].
2. *Identify Functions that Provide Value.* We did this in developing the functional hierarchy in Section 10.3. For many systems, the functional hierarchy provides a basis for the value hierarchy.
3. *Identify the Objectives that Define Value.* An objective provides a statement of preference, for example, we may want to “maximize efficiency” or “minimize time.”
4. *Identify the Value Measures.* Chapter 4 provides a detailed discussion on measures of effectiveness (MOE), including the characteristics of a good MOE. Value measures are the same as MOEs. Value measures tell us how well a candidate solution attains an objective. Value measures are developed based on their alignment with the objective and their scale of measurement. Kirkwood [30] describes value measures as either direct (can directly measure attainment of an objective) or proxy (measures attainment of an associated objective). For example, profit would be a direct measure of an objective for maximizing profit. For “maximize safety,” a reasonable proxy measure might be the estimated number of fatalities. Value measure scales can be either natural or constructed scales. A natural scale for “maximize profit” would be dollars. A constructed scale for “maximize profit” would be thousands, millions, tens of millions, hundred of millions, and billions of dollars. Parnell [29] provides a good synopsis of preferences in developing value measures. Table 10.6 shows that value measures with natural scales that directly measure attainment of an objective are the most preferred while proxy measures with constructed scales that measure attainment of an associated objective are least preferred, but may be necessary given the problem. At this point, we can build a value hierarchy using the structure depicted in Figure 10.7.
5. *Discuss the Value Model with the Key Stakeholders.* At this point it is very important to get approval of the value model from the key stakeholders. This will ensure that future system development efforts are on track.

TABLE 10.6 Preferences for Types of Value Measures

Type of Measure	Direct	Proxy
Natural	1	3
Constructed	2	4

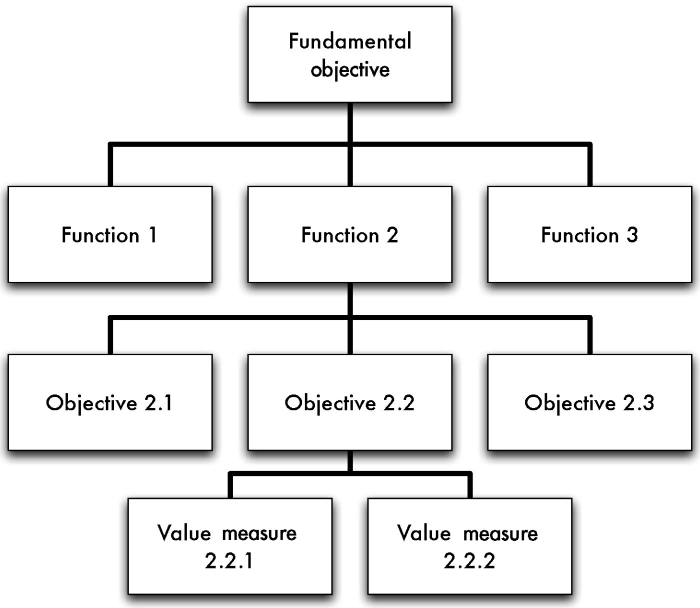

Figure 10.7 Structure of a value hierarchy.

QUALITATIVE VALUE MODEL FOR THE ROCKET EXAMPLE

Recall that our initial systems decision problem was "to develop a new small, mobile rocket that can be used for multiple applications." Our stakeholder and functional analysis yielded the screening criteria listed in Section 10.2.2, and the functions that provide value depicted in the functional hierarchy in Figure 10.3. Throughout stakeholder analysis we also sought to identify stakeholder values in this decision problem. Here is a list of the values identified by the systems engineering team:

1. Mobility of the launch platform through a variety of terrain is important.
2. The support requirements for launch platform should be as small as possible.
3. The rocket should be able to carry heavy payloads.
4. The rocket needs to be flexible enough to carry different types of payloads.
5. The rocket needs to be as accurate as possible.
6. The rocket should be able to carry payloads as far as possible.

These values can be translated into objectives, the attainment of which can be evaluated using the value measures depicted in our value

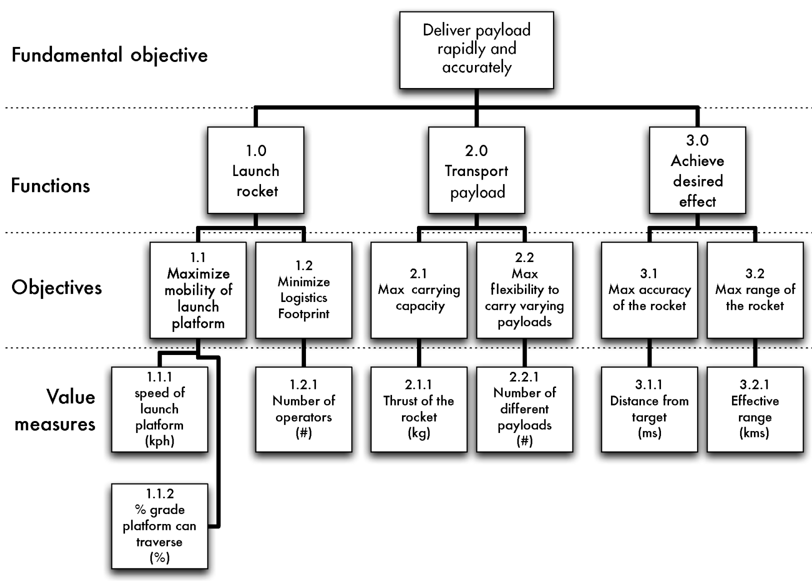

Figure 10.8 Value hierarchy for the rocket example.

hierarchy in Figure 10.8. Our fundamental objective in this problem is to develop a small, mobile rocket that delivers payloads rapidly and accurately to the intended destination. The functions are the functions from the functional hierarchy. The objectives provide a statement of preference regarding the values articulated by the stakeholders. The seven value measures provide a quantitative means to evaluate how well a candidate rocket system attains the stated objectives. The objectives and associated value measures are further defined as follows:

Objective 1.1 Maximize mobility of the launch platform. Mobility is difficult to directly measure, so it is broken down into two components here: speed and the ability to move up/down hills.

Measure 1.1.1 Speed of the launch platform in kilometers per hour (kph). Speed of candidate solution platforms in kph is a natural measure for attainment of an associated objective (proxy) to maximize the mobility of the launch platform.

Measure 1.1.2 Percent grade of hill the launch platform can traverse (% grade). This is a proxy measure. Again since attainment of the mobility objective is not directly measured, this measure is classified as a "natural-proxy" measure. Modeling, simulation, and testing can provide the percent of hill grade (natural measure) candidate solution platforms can traverse.

Objective 1.2 Minimize the logistical footprint of the launch platform. The size of the total support requirement for the system will be difficult to directly measure, so it will be measured in terms of the number of people needed to put the rocket into operation.

Measure 1.2.1 Number of people required to operate the rocket system. Since attainment of the logistics footprint objective is not directly measured, this measure is also classified as a "natural-proxy" measure.

To illustrate a different type of value measure, here is the classification for objective 3.2:

Objective 3.2 Maximize range of the rocket. The range of the candidate solutions can be directly evaluated through testing.

Measure 3.2.1 Effective range of the rocket (kilometers). Kilometers that candidate rockets travel in testing is a natural measure that can be used to directly evaluate attainment of this objective; so this is an example of a "natural-direct" measure.

The classifications of the remaining value measures are left as chapter exercises.

10.4.3 Quantitative Value Model

Quantitative value modeling allows us to determine how well candidate solutions to our systems decision problem attain the stakeholder values. We introduce here the basics of forming a mathematical model to assess the values of candidate solutions. The emphasis for our quantitative value model is at the bottom tier of the value hierarchy. We build functions for each value measure to convert a candidate solution's score on the measure to a standard unit called "value." We also weight the value measures to reflect their importance to the overall problem and the impact of the variability in their measurement scales on the decision.

The Multiple Objective Decision Analysis Mathematical Model In our rocket example, the objective to maximize mobility of the launch platform would guide designers to make the rocket as small as possible so that it can be moved around easily. However, the objective to maximize the carrying capacity of the rocket would steer designers to build a large rocket that can generate a high level of thrust. These are conflicting objectives in our decision problem that need to be resolved.

Multiple objective decision analysis (MODA) provides a quantitative method for trading off conflicting objectives [30]. MODA has many different mathematical relationships to do this. We will focus on the most common method called the additive value model to calculate how well candidate solutions satisfy stakeholder values for the problem.

The mathematical expression for the additive value model used to compute the total value for competing solution is given by

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i) \qquad (10.1)$$

where $v(x)$ is the total value of a candidate solution, $i = 1$ to n for the number of value measures, x_i is the score of the candidate solution on the ith value measure, $v_i(x_i)$ is the single-dimensional value of the candidate solution on the ith value measure, w_i is the measure weight (normalized swing weight) of the ith value measure and $\sum_{i=1}^{n} w_i = 1$.

The additive value model makes some assumptions about the structure of the problem to which it is applied. Kirkwood [30] provides an excellent discussion of the concepts of mutual preferential independence, measurable value, and utility for the reader who wishes to gain a deeper understanding of this topic. If two value measures are preferentially dependent, we can combine the measures into one measure and then use the additive value model [31]. We will continue to develop the quantitative value model assuming that the additive value model is applicable to most systems decision problems.

Developing Value Functions Value measures have varying units in their measurement scales. In our rocket example, the effective range of the rocket is measured in kilometers while the thrust is measured in pounds force (lbf). We use value functions to convert candidate solution scores on the value measures to a standard unit. For a single-dimensional value function, the x-axis is the scale of the value measure (e.g., kilometers) while the y-axis is a standard unit of value scaled from 0 to 1. Other scales for value can be used—for example, 0–10 or 0–100 depending on what stakeholders are comfortable with; however, the scale needs to be consistent for all value measures.

Value functions measure returns to scale on the value measure. Value functions can be discrete or continuous. Continuous functions typically follow four basic shapes shown in Figure 10.9. The curves on the left of the figure are monotonically increasing from a minimum to a maximum level of the value measures. The curves on the right are monotonically decreasing. Kirkwood [30] provides several techniques to develop the shape of value curves using input from subject matter experts. One technique starts with having an expert identify the general shape of the curve. Then proceed to have the expert identify their increase (or decrease depending on the shape of the curve) in value from a specific incremental increase in the measure scale. Doing this for multiple increments up to the maximum on the measure scale will lead to the shape of the value function. This could produce a piecewise linear function.

As an example we will use value measure 1.2.1, the number of people to operate the system, from our rocket example. Since the objective is to minimize the logistic footprint, less people are better. We first set the limits of the x-axis of our function for the number of people. These limits are set based on what we expect

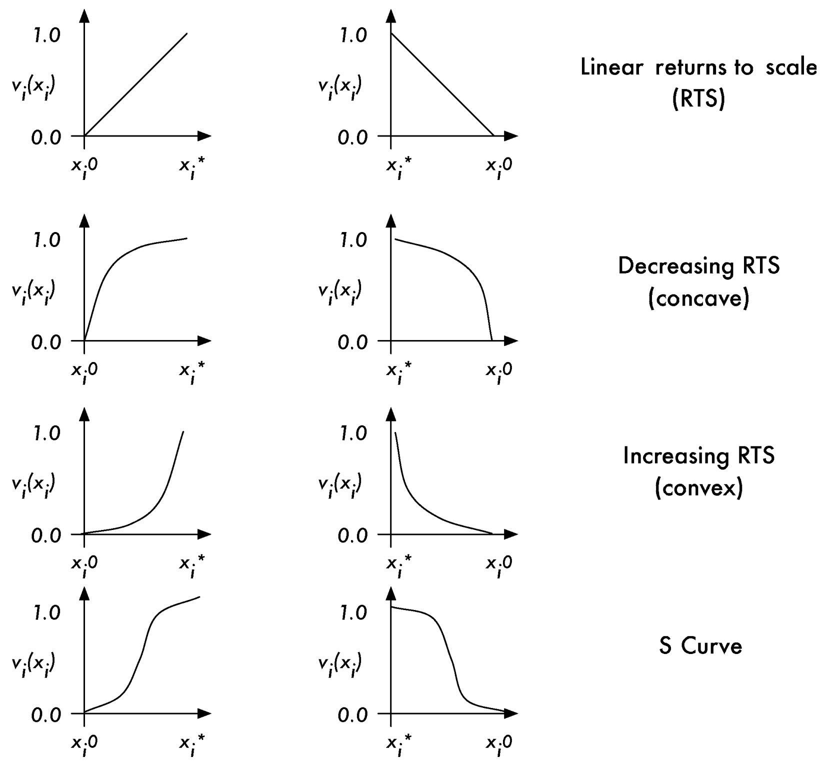

Figure 10.9 Typical shapes of value function.

an ideal solution and worst feasible solution would have for the number of people required. The best we can achieve is to both drive the platform and fire the rocket with no people (total remote control). The maximum number of people for a candidate solution would be seven since more people than that would require either an additional four-wheel drive vehicle, or require larger than a four-wheel drive vehicle. Seven is therefore a screening criterion.

Experts say the general shape of the value curve is an S-curve. With two or less people, the candidate solution has high value, but the value decreases rapidly beyond two people. Figure 10.11 demonstrates the process of building this value function. Using a scale of 0 to 100 for value, subject matter experts said that the incremental decrease in value from 0 to 1 person was only 3 units, while the incremental decrease in value from 2 to 3 people was 30 units of value. The table in Figure 10.10 shows the remaining increments of value. The resulting value function is piecewise linear, generally following the S-curve shape depicted in Figure 10.10. Once this process is complete, a candidate solution's value for a measure can be derived from the value function using the candidate solution score.

Weighting the Value Model Typically, not all value measures are equal in the view of stakeholders. The measures are weighted in the additive value model

Personnel	Value
0	100
1	97
2	90
3	60
4	40
5	15
6	5
7	0

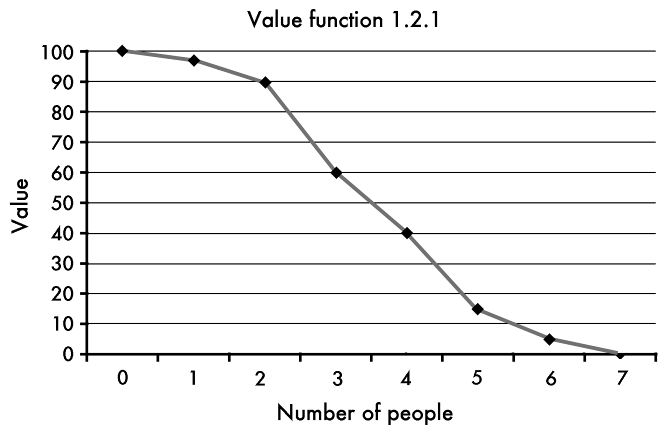

Figure 10.10 Value function for minimizing the logistical footprint value measure for the rocket example.

to arrive at an overall value for candidate solutions. These weights enable us to quantify the tradeoffs between conflicting objectives. The weights depend on both the importance of the value measure and the impact of changing the value of the score within the range on the x-axis scale of value measures [30]. Therefore, we assess measure weights using swing weights by “swinging” the value measure score from its worst to its best level.

The concept of swing weights is one of the most important concepts in MODA and, for many, the most difficult to understand. Kirkword [30] provides a mathematical proof for the definition of swing weights and Parnell and Trainor [36] provide summary of the issue and several examples of the swing weight matrix. Weights should be generated bottom up to ensure that the importance and variation are considered. Weights must sum to one at each tier of the hierarchy. Kirkwood [30] and Clemen and Reilly [33] provide multiple methods to elicit weights from stakeholders. We will describe a swing weight matrix method developed by Parnell [29] that can be used to generate weights relatively quickly from the bottom up.

To develop weights, first create a matrix in which the top scale defines the value measure importance and the left side represents the impact of changing the value measure range on the decision. A measure that is very important in arriving at a solution to the decision problem and is one in which changes across its range of values has a large impact on the decision would be placed in the upper left of the matrix. A value measure that is deemed not important and whose changes across its range have little impact on the decision would be placed in the lower right of the matrix. Figure 10.11 illustrates an example 3×3 matrix. While this is a fairly standard size used in applications, the dimensions of the matrix could expand if a higher level of discrimination between value measures (e.g., 5×5) is required. Once all the value measures are arrayed in the matrix, we could use any swing weight technique to obtain the weights. The levels of importance and variability (high, medium, low) should be defined in terms appropriate for the systems decision.

		Level of importance of the value measure		
		High	Medium	Low
Variation in measure ranges	High	measure X $f_1 = 100$		
	Medium			
	Low			measure Y $f_9 = 1$

Figure 10.11 Example of swing weighting matrix for determining measure weights.

Using the method introduced by Parnell [29], we begin by assigning measure x (the upper left-hand corner cell) an arbitrary non-normalized swing weight, for example, 100. Using the value increment approach [30] we assign the weight of the lowest weighted measure, measure y (the lower right-hand corner) the appropriate swing weight, for example, 1. This means the weight of measure x is 100 times more than that of measure y. Non-normalized swing weights are assigned to all the other value measures relative to the weight of 100 by descending through the very important factors, then through the important factors, then through the less important factors. We then normalize the resulting swing weights to obtain measure weights on a scale of 0.0–1.0 using Equation (10.2). This converts the swing weights into *measure weights*, which are also referred to as *global weights*. We use the terms interchangeably in what follows.

The mathematical expression for obtaining measure weights by normalizing swing weights in order to express the relative weighting of value measures in the quantitative value model is given by

$$\text{Measure weights for value measures}(w_i): \qquad w_i = \frac{f_i}{\sum_{i=1}^{n} f_i} \tag{10.2}$$

where f_i is the non-normalized swing weight assigned to the ith value measure, $i = 1$ to n for the number of value measures, and w_i are the corresponding measure weights.

The basic concept of this method in determining weights is relatively straightforward. A measure that is very important to the decision problem should be weighted higher than a measure that is less important. A measure that differentiates between candidate solutions—that is, a measure in which the changes in candidate solution scores have a high impact on the decision—is weighted more than a measure that does not differentiate between candidate solutions.

Since the swing weights may be provided by different individuals, it is important to check for the consistency of the weights assigned. It is easy to understand that a very important measure with a high impact for changes in its range will be weighted more than a very important measure with a medium impact for changes in its range. It is harder to trade off the weights between a very important measure

		Level of importance of the value measure		
		Very important	Important	Less important
Variation in measure range	High	A	B_2	C_3
	Medium	B_1	C_2	D_2
	Low	C_1	D_1	E

Figure 10.12 Value measure placement in swing weight matrix: consistency example.

with a low impact on the decision for range changes and an important measure with a high impact on the decision for changes in its range. Weights should descend in magnitude as we move in a diagonal direction from the top left to the bottom right of the swing weight matrix. For clarity, consider the matrix in Figure 10.12. For the weights to be consistent, they need to meet the following relationships:

- A measure placed in cell A has to be weighted greater than measures in all other cells.
- A measure in cell B_1 has to be weighted greater than measures in cells C_1, C_2, D_1, D_2, and E.
- A measure in cell B_2 has to be weighted greater than measures in cells C_2, C_3, D_1, D_2, and E.
- A measure in cell C_1 has to be weighted greater than measures in cells D_1 and E.
- A measure in cell C_2 has to be weighted greater than measures in cells D_1, D_2, and E.
- A measure in cell C_3 has to be weighted greater than measures in cells D_2 and E.
- A measure in cell D_1 has to be weighted greater than a measure in cell E.
- A measure in cell D_2 has to be weighted greater than a measure in cell E.

No other strict relationships hold. The stakeholders will need to express their tradeoffs between level of importance and the impact of range changes in value measure as weights are assigned. More concisely, the strict relationships in inequalities 10.3 through 10.10 must hold:

$$A > \text{ all other cells} \tag{10.3}$$

$$B_1 > C_1, C_2, D_1, D_2, E \tag{10.4}$$

$$B_2 > C_2, C_3, D_1, D_2, E \tag{10.5}$$

$$C_1 > D_1, E \tag{10.6}$$

$$C_2 > D_1, D_2, E \tag{10.7}$$

$$C_3 > D_2, E \tag{10.8}$$

$$D_1 > E \tag{10.9}$$

$$D_2 > E \tag{10.10}$$

No other specific relationships hold.

Quantitative Value Model for the Rocket Example The quantitative value model consists of the objectives and weighted value measures with definitions, scales, and functions. This model is passed to the Solution Design phase of the systems decision process as an initial means of evaluating alternatives to identify the candidate solutions. Figure 10.13 provides the functions for the value measures, minus measure 1.2.1 that is depicted in Figure 10.10. Of course, Figures 1.2.1 and 2.2.1 could also be plotted as bar charts since their scores are discrete. The systems engineering team used the swing weight matrix method to elicit

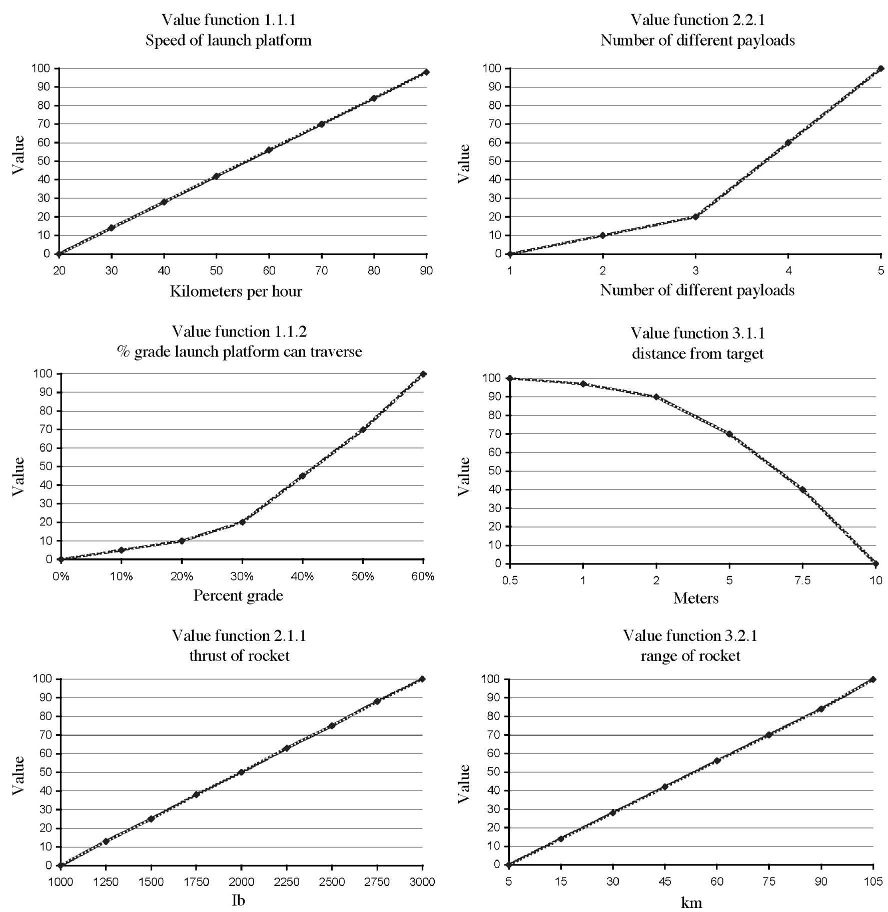

Figure 10.13 Value functions for the rocket example.

Variation in measure ranges	Level of importance of the value measure: Mission critical	Mission enabling	Mission enhancing
Large capability gap	3.1.1 Accuracy 100	3.2.1 Range 50	
Significant capability gap	1.1.1 Speed of platform 85	2.1.1 Thrust 45	1.1.2 % Grade 5
Small capability gap	2.2.1 Number of payloads 60	1.2.1 Number of people 20	

Figure 10.14 Completed swing weight matrix for the rocket example.

global weights for the value measures from the key stakeholders. Figure 10.14 provides the completed matrix. Importance was defined as the importance of that value measure to accomplishing the mission. Variation was defined as the impact of the capability gap between the lowest value score and the ideal score for each value measure. The numbers appearing under each measure represent the swing weight assigned by the key stakeholders. The value measures are indexed by numbers assigned during the creation of the value hierarchy shown in Figure 10.8.

The measure, or global, weights for value measures are then calculated from the data in the swing weight matrix by using Equation (10.2). Figure 10.15 shows both the stakeholder assigned swing weights and their corresponding measure, or global, weights. The key information about the quantitative value model can be concisely summarized as in Table 10.7. The systems engineering team uses this value model to evaluate alternatives and candidate solutions developed during the Solution Design and Decision Making phases of the systems decision process. Candidate solutions receive a value for each of the value measures using the value functions. These values combined with their corresponding measure global are used to calculate a candidate solution's total value using the additive value model given in Equation (10.1).

Value measures	Swing weight	Measure global weight
1.1.1 Speed of platform	85	0.23
1.1.2 % Grade	5	0.01
1.2.1 Number of people	20	0.06
2.1.1 Thrust	45	0.12
2.2.1 Number of payloads	60	0.17
3.1.1 Accuracy	100	0.27
3.2.1 Range	50	0.14
Total =	365	1.00

Figure 10.15 Global weights of the value measures rocket example.

TABLE 10.7 Quantitative Value Model for the Rocket Example

Function	Objective	Value Measure	Definition of Value Measure	Measure Type	Global Weight	Shape of Value Curve
1.0 Launch rocket	1.1 Maximize mobility of launch platform	1.1.1 Speed of platform	Speed of launch platform in kph (more is better)	Proxy, natural	0.23	Linear
		1.1.2 % Grade	% Grade platform can traverse (more is better)	Proxy, natural	0.01	Convex
	1.2 Minimize logistics footprint	1.2.1 Number of people	of people to operate system (less is better)	Proxy, natural	0.06	S-curve
2.0 Transport payloads	2.1 Max carrying capacity of the rocket	2.1.1 Thrust	Thrust of the rocket in pounds force (more is better)	Proxy, natural	0.12	Linear
	2.2 Max flexibility to carry varying payloads	2.2.1 Number of payloads	Number of different payloads rocket can carry (more is better)	Direct, natural	0.17	Convex
3.0 Achieve desired effects	3.1 Max accuracy of the rocket	3.1.1 Accuracy	Average distance from target in testing in meters (less is better)	Direct, natural	0.27	Concave
	3.2 Max range of the rocket	3.2.1 Range	Effective range of the rocket in kilometers (more is better)	Direct, natural	0.14	Linear

10.4.4 At Completion of Value Modeling

The value modeling process provides the framework for evaluating how well candidate solutions attain the objectives articulated by the stakeholders for the decision problem. We want to develop this model before developing candidate solutions so that we can focus on developing solutions that meet stakeholder values. We create a value hierarchy using information developed during the research and stakeholder, requirements, and functional analysis tasks. The value hierarchy depicts the fundamental objective in solving the problem, the key functions, the stakeholder objectives the solution should attain, and the measures the team can use to quantify stakeholder values. We develop value functions as the means for evaluating how well candidate solutions meet these values. We weight these value measures based on their relative importance and impact of the variation in the measurement scale. This value modeling process can be refined as the systems engineering team continues their work in the Solution Design and Decision Making phases of the SDP.

10.5 OUTPUT OF THE PROBLEM DEFINITION PHASE

The Problem Definition phase of the systems decision process prepares the systems engineer to develop effective candidate solutions to a problem. The tasks of performing research and conducting stakeholder analysis, functional analysis, and requirements analysis focus the effort on defining the right problem that needs to be solved. The output from these tasks is used in value modeling to provide an initial evaluation methodology for solutions. At this point, the systems engineering team should have a refined problem statement, constraints that will serve as screening criteria, and a value model. We cannot overstate the need for the team to provide these to the key stakeholders for review before getting deeply involved in the Solution Design phase.

10.5.1 Discussion

Screening criteria are simply requirements that any potential solution to the problem must meet in order to be a feasible solution. These requirements constrain solutions by establishing characteristics, along with upper or lower bounds on value measures that must be met. We developed the value model in great detail in Section 10.4 to map stakeholder values for a solution to a methodology for evaluating how well candidate solutions attain these values. The problem statement also flows from the Problem Definition phase.

Problem statements can come in several forms. In the military, problem statements are usually expressed as a mission statement. A mission statement has as its basic elements who, what, when, where, and why. The military groups these elements into two basic components: the purpose of the mission and the key tasks to accomplish. The who, what, when, and where elements form the key task(s) component while the why element becomes the purpose. The purpose is the most important part of the mission statement. There may be several ways to complete the stated mission task(s); however, all ways must lead to accomplishing the overall purpose of the mission.

The problem statement is similar to the military mission statement. The problem statement contains functions that must be accomplished in order to achieve some purpose. INCOSE provides this discussion of a problem statement:

> The problem statement starts with a description of the top-level functions that the system must perform, the operational environment in which the functions must be performed, and the key items (physical, informational, and energy entities) that the system must output. This problem statement might be in the form of a vision, mission statement and mission requirements, a set of scenarios for how the system will be used and interact with other systems, and a set of contexts in which the system will be used. Acceptable systems must satisfy all mandatory requirements. The problem statement should be in terms of *needs* or what must be done (e.g., the key characteristics of the items to be produced by the system), not how to do it (e.g., what resources the system should have) [34].

This problem statement captures the needs of the stakeholders and the key objectives that must be attained by its solution. For our rocket example, the problem statement could be stated as follows:

> Develop a small, mobile rocket system that can accurately deliver a variety of payloads rapidly in order to meet a market niche that is currently not met.

This problem statement addresses both the broad functions of the system and the needs and values of the stakeholders. It also provides a purpose for the rocket system, which we had not discussed in previous sections. For another example of a problem statement, see the problem statement for the illustrative example at the end of Section 10.6.

10.5.2 Conclusion

Through research, stakeholder analysis, functional analysis, requirements analysis, and value modeling, we now have a refined problem statement, screening criteria that candidate solutions must meet, and a quantitative value model that can be used to evaluate any candidate solutions. In the Solution Design phase that follows, we develop candidate solutions that meet stakeholder objectives to solve this refined problem.

10.6 ILLUSTRATIVE EXAMPLE: SYSTEMS ENGINEERING CURRICULUM MANAGEMENT SYSTEM (CMS)—PROBLEM DEFINITION

In this section we use techniques for the three tasks in the Problem Definition phase of the systems decision process: research and stakeholder analysis, functional and requirements analyses, and value modeling.

RESEARCH AND STAKEHOLDER ANALYSIS

Robert Kewley, Ph.D. U.S. Military Academy

To determine the proper functions and performance measures for the system, the development team had to first identify the system's stakeholders.

- Cadets (consumers) receive the entire curriculum from the department and must apply what they learned upon graduation in a dynamic world with proliferating technology.
- Instructors (users) prepare and deliver that curriculum to cadets.
- Program directors (users) synchronize that curriculum across courses to support a major. They are also responsible for program accreditation and assessment.
- The department's accreditation officer (user) works with ABET, Inc. and various Academy committees to ensure their programs meet accreditation requirements.
- The department operations officer (user) synchronizes execution of the department's entire curriculum from semester to semester.
- The department leadership (decision authority, owner) sets and enforces standards, allocates resources to the academic programs, ensures alignment with the Academy's overall academic program goals, and ensures that programs achieve and maintain accreditation.

The department employed all three stakeholder analysis techniques to elicit needs, wants, and desires from the stakeholders listed above.

Cadet Survey

The development team issued a Web survey to cadets. This method was selected based on the considerations in Tables 9.1 and 9.3. This was a large group of very important stakeholders. They selected cadets enrolled in a junior year Computer Aided Systems Engineering course as our sample. The sample of 70 cadets represented about 35% of the total population. However, because one cannot control respondents in a web survey, only 48 cadets completed it. The primary focus of the cadet survey was to determine their needs for curriculum delivery. Questions asked them to compare and rank the various delivery methods used by the department. They were also asked for suggestions to improve content delivery. Analysis of survey data produced the findings shown in Tables 10.8 and 10.9.

One survey question described a structured web-based portal to cadets and asked them to rank it with respect to the other methods currently used.

Free text questions asked cadets to describe the reasoning for their rankings and to provide suggestions as to how the department can improve content

TABLE 10.8 Percentage of Cadets Who Prefer Different Methods of Electronic Content Delivery

Content Delivery Method	Percentage of Cadets Who Ranked This Method 1st	95% Confidence Interval
Course Web site	56%	± 12.3%
Course network folder	33%	± 11.6%
Academy wide portal	10%	± 7.4%

TABLE 10.9 Percentage of Cadets Who Would Rank a Newly Developed Portal Against the Current Methods

Ranking against Current Methods	Percentage of Cadets Who Ranked This Ranking	95% Confidence Interval
1st	58%	± 12.2%
2nd	27%	± 10.1%
No preference	15%	± 8.8%

delivery. There were a few trends in their responses. Several cadets mentioned availability as a reason for ranking criteria. The Academy-wide portal failed frequently. They also did not like having to do a separate logon to get content. One thing they liked about course folders was the ability for them to deposit files there while in class and access them later from their rooms. Finally, they wanted consistency across courses.

From these findings, we can conclude with strong confidence that most cadets prefer Web-based content delivery. However, they do not like the current academy-wide implementation of that delivery. They show a strong preference for a proposed redesigned portal. However, they are concerned about system availability, extra logon steps, ability to post content, and consistency.

These conclusions yield a recommendation to consider redesigning the department's content delivery system as a web-based portal that is reliable, easy to use, allows two-way communication, and is used consistently across the department.

Faculty Focus Groups

The primary users of the system are the Department of Systems Engineering faculty. To elicit needs, wants, and desires from this group, the design team brought them together as a focus group in the department's Systems Methodology and Design Lab. This lab is specially configured for the use of GroupSystems collaboration software. GroupSystems enables much more productive focus groups because it allows anonymous parallel input from many people. One person cannot dominate the session, so the group is less susceptible to "groupthink". Finally, the system automatically records all input and generates a report for future reference. Before the focus group meeting, the lead engineer developed an agenda:

1. Brainstorm functions in the Topic Commenter. This allows faculty to list functions in a brainstorming fashion. Other faculty can comment on the ideas.
2. Bin functions in the Categorizer. This develops related groups of functions.
3. Brainstorm values for this system in the Topic Commenter.
4. Bin values in the Categorizer.

The entire focus group took about 90 minutes and resulted in the following categories of functions and values:

• Functions	→ Lesson management
	→ Compatibility with other Academy and department IT systems
	→ Scheduling
	→ Resources
	→ Course administration
	→ Course project management
	→ Interface
	→ Accreditation
• Values	→ Easy to use interface
	→ Automatic administrative report generation
	→ Compatibility and non-redundancy with other systems
	→ Accessibility
	→ Security and stability
	→ Usability
	→ Ad hoc query capability
	→ Ease of maintenance

Note that there is some overlap between the above lists of functions and values. As is usually the case, the focus group output cannot be directly translated into a functional hierarchy and values hierarchy. However, the GroupSystems report is a valuable resource to ensure that the needs, wants, and desires of the faculty are reflected in the follow-on steps.

Stakeholder Interviews

Because of their unique positions and critical relationship with this system, the following people were interviewed to elicit their needs, wants, and desires:

- Department leadership—establishes department vision, mission, and objectives, allocates department resources. The results of this interview contributed to development of top-level values in the values hierarchy and approval of top-level functions for the functional hierarchy.
- Department operations officer—responsible for scheduling and execution of department courses. The results of this interview contributed to the development of the Integrate Department Academic Operations function.
- Department accreditation officer—responsible for coordinating accreditation for department programs. The results of this interview contributed to development of the Assess Program function.

FUNCTIONAL AND REQUIREMENTS ANALYSES

Once complete with research and stakeholder analysis, the design team was able to develop a functional hierarchy for this system. Using the general trends from the surveys, focus group, and interviews, they developed the high-level functions for the system. They then used the detailed information from these components of the stakeholder analysis to break these high-level functions into subfunctions. Many of the subfunctions were broken down as well. Once complete, the design team presented the functional hierarchy to the department leadership for approval.

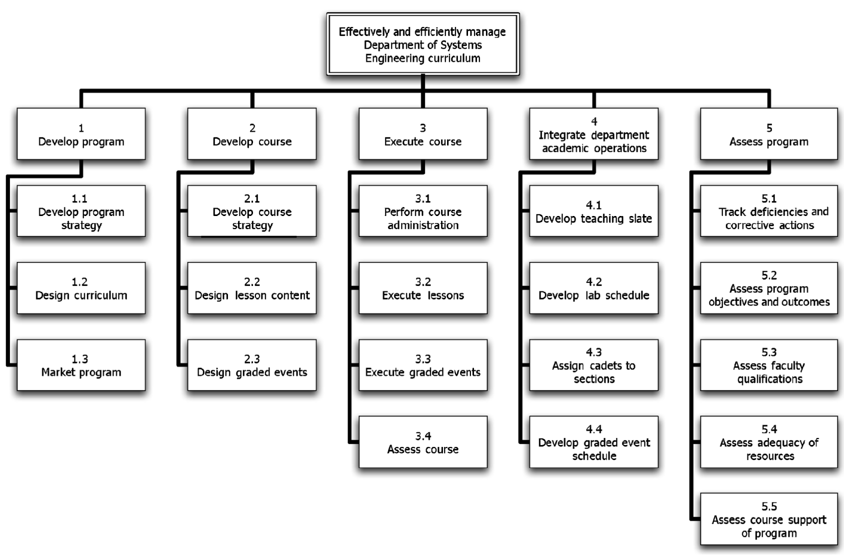

Figure 10.16 Partial functional hierarchy for curriculum management system.

Figure 10.16 shows the first two levels of the functional hierarchy for the CMS system. It is important to note that the functions depicted in this hierarchy are not simply the functions of the CMS information system. They are all of the functions that the department faculty has to perform in order to manage the curriculum. A subset of these functions will be supported by the CMS information system. This design technique ensures that we are developing an information system that helps us perform our core functions and not simply designing an information system to pass data around hoping someone will use it for something.

VALUE MODELING

Upon completion of functional analysis, the design team was able to align curriculum management functions with top-level department values solicited from the department head. Once they had this alignment, they developed supporting objectives that would enable execution of the CMS functions. Figure 10.17 illustrates this alignment. The team assigned weights to each of the objectives based on the degree to which that capability supports the critical CMS functions in the diagram. These objectives will distinguish the different alternatives for the system concept decision.

The development team used swing weighting to calculate the global weights assigned to each value measure for the supporting IT objectives. These swing weights were based on importance values determined

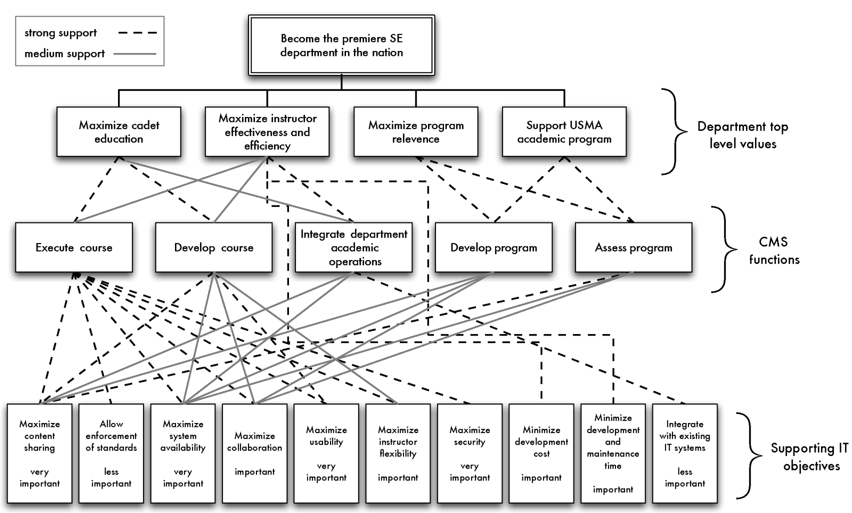

Figure 10.17 Crosswalk of value functions to objectives.

Variation in measure ranges		Level of importance of the value measure		
		Very important	Important	Less important
	High	Usability 100	Collaboration 75 Development time 75 Development cost 50	
	Medium	Content sharing 90 Availability 75	Instructor flexibility 40	Enforce standards 10 Integrate 5
	Low	Security 45		

Figure 10.18 Swing weight matrix for system concept decision.

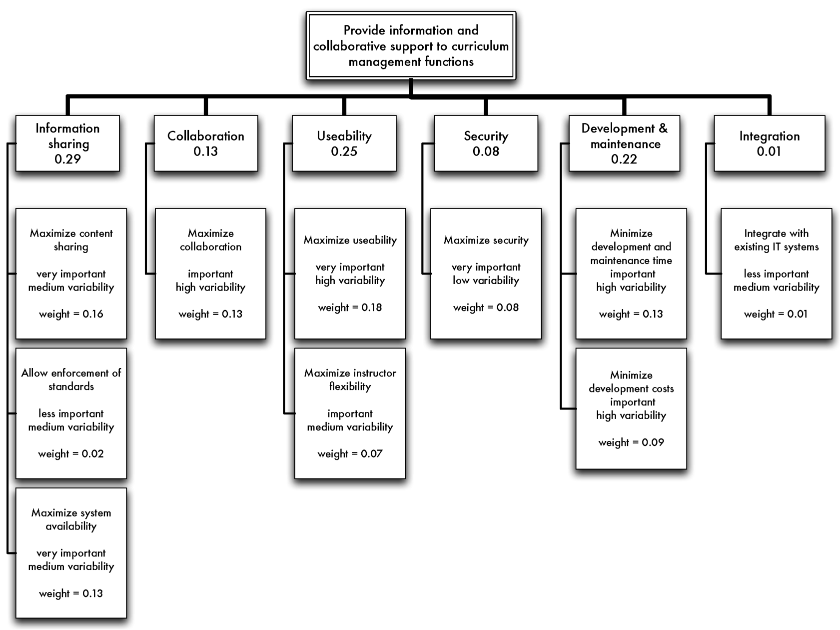

Figure 10.19 Curriculum management system's value hierarchy.

by the values to functions to objectives crosswalk and the degree to which the alternatives varied with respect to these measures. Figure 10.18 shows the swing weight matrix for this decision.

The development team organized the objectives into categories shown in the hierarchy of the values in Figure 10.19.

For each of the supporting objectives, the design team developed a value measure by which they would assess the degree to which each alternative achieved that objective. In most cases, they used a constructive scale to compare the alternative to the current system for an objective. The constructive scale had the following values:

−1 Worse than current system
0 Same as current system
+1 Marginal improvement to current system
+2 Some improvement to current system
+3 Significant improvement to current system

For two of the objectives, development cost and development time, the design team used the available data. They had total cost estimates for each alternative. They also had estimates of the time required (in months) to achieve course-level functionality for each system.

For each value measure, the design team developed a value function to convert the individual scores (raw scores) to a value between 0 and 10. These value functions are shown in Figure 10.20. Some of the criteria, such as content sharing, enforcement, and collaboration, have increasing returns-to-scale. This reflects the exponential increase in collaborative interactions as more and more people join the collaboration network. Some criteria, such as availability and security, have decreasing returns-to-scale. This reflects the negative consequences of not achieving at least a baseline performance. Others, such as development cost and development time, have a linear return-to-scale.

The requirements analysis also exposed several constraints for the system. The total development budget, including software and development effort is \$250,000. The system has to operate on the United States Military Academy IT network. To support an upcoming ABET accreditation visit, the system must achieve course-level functionality by December 2006 and program assessment functionality by June 2007.

The revised problem statement is as follows:

> The United States Military Academy Department of Systems Engineering will develop an integrated curriculum management system to support the following core functions: develop programs, develop courses, execute courses, integrate department academic operations, and assess programs. In order to support these functions, the system requires capabilities for information sharing, collaboration, usability, security, efficient development and maintenance, and integration with other IT systems. In order to meet accreditation time lines, the system must fully support course-level functionality by December 2006 and assessment functionality by June 2007. The department Chief Information Officer will lead development using a combination of internal IT support, capstone students, and contractor support as required. The total cost of system development shall not exceed \$250,000.

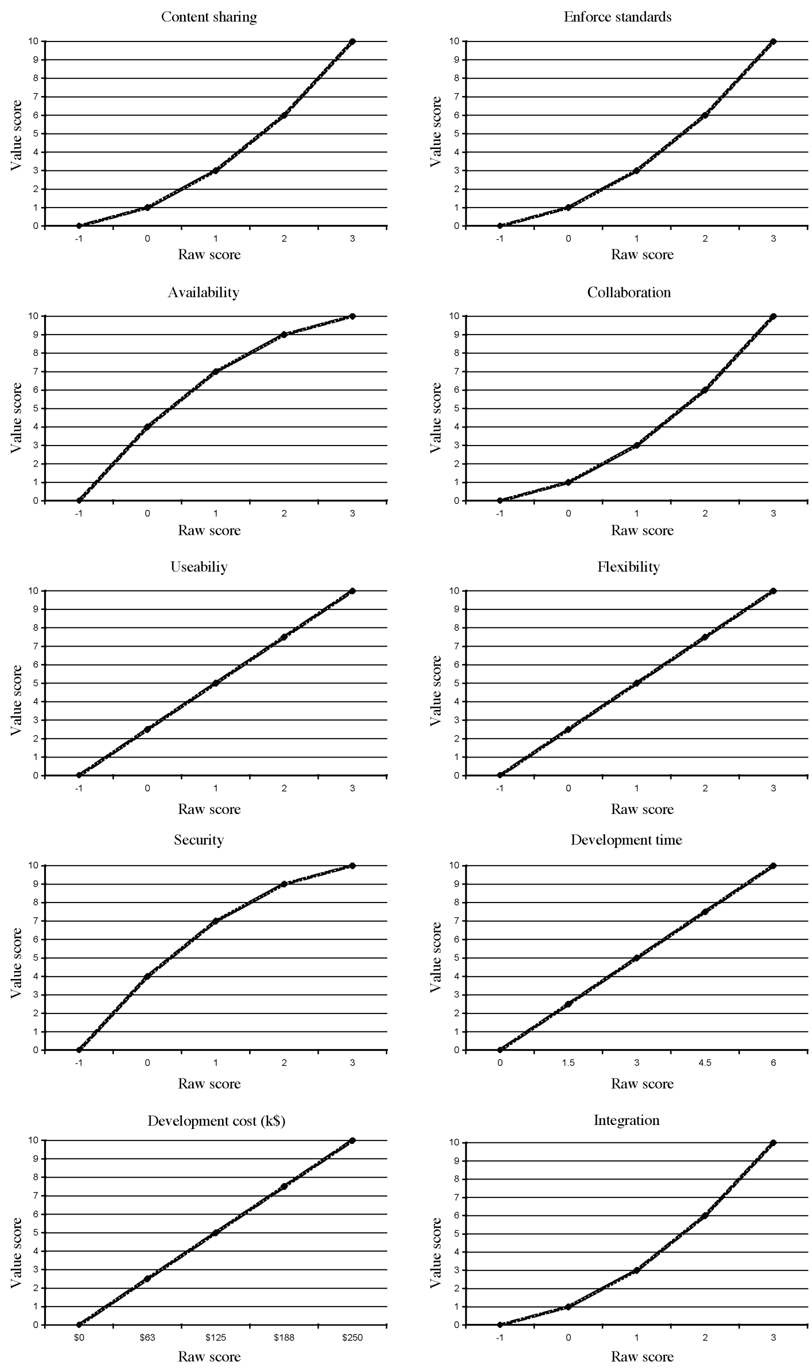

Figure 10.20 Value functions for value measures used for the system concept decision.

10.7 EXERCISES

10.1. Define the three main tasks of the problem definition phase of the systems decision process.

10.2. Compare and contrast the three main techniques for stakeholder analysis. Which technique would you use primarily in designing a new cell phone?

10.3. In Chapter 7 you developed a list of functions for a clock. Build a functional hierarchy for this clock.

10.4. Compare and contrast the four main techniques presented for functional analysis.

10.5. Use Microsoft® Visio to draw an input–output diagram using the IDEF0 framework from Figure 10.6 for the function "launch rocket" from our rocket example.

10.6. Classify value measures 2.1.1, 2.2.1, and 3.1.1 from our rocket example (Figure 10.8). Discuss your rationale for each classification.

10.7. Develop one additional value measure for the rocket example. Define the measure, classify it, and develop a value function for this new measure. Create your function and curve in Microsoft® Excel.

10.8. Create a new swing weight matrix for the rocket example incorporating your additional value measure created for Exercise 9.7. Develop new weights for all the value measures using this matrix.

10.9. Generate a creative candidate solution to the rocket example problem that meets the screening criteria listed in Section 10.2.2. Create quantitative parameters of this candidate solution that can be evaluated with the seven value measures developed in Section 10.4.

10.10. Generate a total value (Equation 10.1) for your candidate solution from Exercise 10.9 using the quantitative value model developed in Section 10.3.

10.11. Write a problem statement that describes your decision problem of whether to pursue graduate education or not in the future. Define the stakeholders for your decision.

10.12. Perform all three tasks of the Problem Definition phase for the purchase decision for your next car.

REFERENCES

1. Shaara, M. *The Killer Angels*. New York: Ballantine Books, 1974.
2. Reid, RD, Sanders NR. *Operations Management: An Integrated Approach*, 2nd ed. New York: John Wiley & Sons, 2005.
3. Old Computers.com. IBM PC Junior. Available at http://www.old-computers.com.
4. Sage, AP, Rouse, WB. *Handbook of Systems Engineering and Management*. New York: John Wiley & Sons, 1999.

5. Information & Design. What is Affinity Diagramming? Available at http://www.infodesign.com.au/usabilityresources/general/affinitydiagramming.asp. Accessed June 16, 2006.
6. Wymore, AW. *Model-Based Systems Engineering*. New York: CRC Press, 1993.
7. Bahill, AT, Gissing, B. Re-evaluating systems engineering concepts using systems thinking. *IEEE Transactions on Systems, Man, and Cybernetics—Part C: Applications and Reviews*, 1998; 28(4): 516–527.
8. International Council on Systems Engineering (INCOSE). Plowman's Model of the Systems Engineering Process. INCOSE Guide to the Systems Engineering Body of Knowledge, G2SEBoK. Available at http://g2sebok.incose.org/.
9. Sage, AP, Armstrong, JE, Jr. *Introduction to Systems Engineering*. New York: John Wiley & Sons, 2000.
10. Proctor, C. What are Focus Groups? Section on Survey Research Methods, American Statistical Association, 1998. Available at http://www.surveyguy.com/docs/surveyfocus.pdf.
11. Greenbaum, TL. Focus Groups: A help or a waste of time ? *Product Management Today*, 1997; 8(7): 00–00 Available at http://www.groupsplus.com/pages/pmt0797.htm.
12. McNamara, C. Basics of Conducting Focus Groups. Free Management Library, 1999. Available at http://www.managementhelp.org/evaluatn/focusgrp.htm.
13. Group Systems Corporation. Collaborative Thinking and Virtual Meetings: The New Way to Work! Available at http://www.groupsystems.com/page.php?pname=home.
14. Creative Research Systems. The Survey System—Survey Design, 2005. Available at http://www.Surveysystem.com/sdesign.htm.
15. Creative Research Systems. The Survey System—Sample Size Calculator, 2005. Available at http://www.Surveysystem.com.
16. SurveyMonkey.com. Available at http://surveymonkey.com/home.asp?Rnd=0.5588495.
17. Insiteful Surveys. Available at http://insitefulsurveys.com/.
18. Creative Research Systems. The Survey System. Available at http://www.Surveysystem.com.
19. INCOSE-TP-2003-016-02. 2004. *INCOSE SE Handbook*, Version 2a.
20. Draft Federal Information Processing Standards Publication 183, December, 21, 1993, Standard for Integration Definition For Function Modeling (IDEF0). Available at http://www.itl.nist.gov/fipspubs/idef02.doc. Accessed June 2, 2006.
21. Martin, JN. *Systems Engineering Guidebook: A Process for Developing Systems and Products*. Boca Raton, FL: CRC Press, 1997.
22. Affinity Diagrams, Basic Tools for Process Improvement. Available at http://www.saferpak.com/affinity_articles/howto_affinity.pdf. Accessed June 1, 2006.
23. SkyMark Corporation. Available at http://www.skymark.com/resources/tools/affinity_diagram.asp. Accessed June 1, 2006.
24. Lempke, J. *Microsoft Visio 2003, Step-by-step*. Redmond, Washington: Microsoft Press, 2003. Available at http://office.microsoft.com/visio. Accessed June 2, 2006.
25. Buede, DM. *The Engineering Design of Systems: Models and Methods*. Wiley Series in Systems Engineering. New York: Wiley-Interscience, 2000.
26. Wasson, CS. *System Analysis, Design, and Development: Concepts, Principles, and Practices*. Hoboken, NJ: John Wiley & Sons, 2006.

27. Kossiakoff, A, Sweet, NS. *Systems Engineering: Principles and Practice*. Hoboken, NJ: John Wiley & Sons, 2003.
28. CORE Software, Vitech Inc. http:\\www.vitechcorp.com Information about the CORE® Software from Vitech, Incorporated is available online.
29. Parnell, GS. Value-focused thinking. In: Loerch, AG, and Rainey, LB, editors. *Methods for Conducting Military Operational Analysis* Military Operations Research Society, 2007. pp. 619–656.
30. Kirkwood, CW. *Strategic Decision Making: Multiple Objective Decision Analysis with Spreadsheets*. Pacific Grove, CA: Duxbury Press, 1997.
31. Ewing, P, Tarantino, W, Parnell, G. *Use of decision analysis in the army base realignment and closure (BRAC) 2005 military value analysis. Decision Analysis Journal* 2006; (1)13): 33–49.
32. Trainor, T, Parnell, G, Kwinn, B, Brence, J, and Tollefson, E, Downes, P. The US Army uses decision analysis in designing its installation regions. *Interfaces*, 2007; 37(3): 253–264.
33. Clemen, RT, Reilly, T. *Making Hard Decisions with Decision Tools Suite*. Pacific Grove, CA: Duxbury Press, 2004.
34. International Council on Systems Engineering (INCOSE), State the problem. INCOSE Guide to the Systems Engineering Body of Knowledge, G2SEBoK. Available at http://g2sebok.incose.org/. Accessed June 16, 2006.
35. Fowler, FJ, Jr. *Improving Survey Questions—Design and Evaluation*. Applied Social Research Methods Series, Volume 38. Thousand Oaks, CA: Sage Publications, 1995.
36. Parnell, G. and Trainor, T., *"Using the Swing Weight Matrix to Weight Multiple Objectives."*. *Proceedings of the INCOSE International Symposium*, Singapore, July 19–23, 2009