

1

Systems Engineering and the Sustainability Disciplines

1.1 PURPOSE OF THIS BOOK

1.1.1 Systems Engineers Create and Monitor Requirements

The textbook marketplace offers many high-quality books that provide the student, professional, and researcher with many points of view on the sustainability disciplines of reliability engineering, maintainability engineering, and supportability engineering. The point of view we advance here, though, is different from that of other books. This book focuses intently on the roles and responsibilities of the systems engineer in *creating* and *monitoring* the requirements for reliability, maintainability, and supportability that will guide development of products and services that are most likely to satisfy their customers and lead to success for their suppliers. Systems engineers play a pivotal role in this process. Get the requirements wrong and the likelihood of a successful product or service is almost nil. That, coupled with the importance of acting as early as possible in the development process to build in quality and reliability, compels a new emphasis on preparing systems engineers to understand how the sustainability disciplines contribute to product and service success and to enlarge their toolkit to incorporate generation and validation of sustainability requirements that promote greater product and service success. The first major purpose of this book is to provide systems engineers with the

Reliability, Maintainability, and Supportability: Best Practices for Systems Engineers,
First Edition. Michael Tortorella.

© 2015 John Wiley & Sons, Inc. Published 2015 by John Wiley & Sons, Inc.

knowledge they need to craft clear, concise, and effective sustainability requirements so that they may fulfill their role of key leader in successful product and service development.

Customers and suppliers also want to know whether requirements are being met by deployed products and services. For example, many telecommunications service providers offer service-level agreements (SLAs) to their larger customers (see Section 8.6). SLAs are usually based on certain service reliability criteria [11, 12]; when these criteria are violated, the customer is offered a full or partial refund for a stated period of service. In addition, many suppliers of commercial and consumer products offer warranties. The cost of servicing the warranty is borne by the supplier. The obvious financial consequences in these examples show why it is important to be able to determine in a systematic way whether and to what degree relevant requirements are likely to be met (in a planning phase) and are being met (in operation). Accordingly, the second major purpose of this book is to provide systems engineers with the concepts, tools, and techniques needed to carry out analyses for determining conformance to quantitative sustainability requirements.

1.1.2 Good Requirements are a Key to Success

Accepting, as we do, that a design faithfully realizing a set of complete and effective requirements will make a product or service that is no more or less than those requirements describe, it is clear that requirements are key contributors to a successful product or service. Accordingly, we need to understand what makes a good requirement. At least two important properties of a good requirement can be immediately discerned:

1. The requirement is written to promote an outcome (product or service property or behavior) that is desired by the customer.
2. The requirement is unambiguous: clear criteria are available to determine whether the requirement is met or not.

Every product or service property or behavior that is needed or desired by the customer for the product or service should be the subject of some requirement(s). There is no other reliable way to ensure that the product or service will have that property or behavior. This is nothing more than a restatement of the idea that if you want something, unless you ask for it specifically, you will only get it by some happy accident. Think of a customer, like a telecommunications service provider, who needs a reliable backup generator to ensure continuity of service during periods when utility power is unavailable. If the customer does not specify the length of time for which the backup generator is required to operate without failure, then the system designer has no guidance about how to specify which backup generator to use and what measures need to be taken to ensure that it operates for the needed period of time. Some backup generator will be chosen, but the reliability of that backup generator may or

may not be good enough to meet the customer's need. In this example, “you get what you get” without a clear plan to get, rather, what you need—the result is haphazard rather than systematic. Good requirements are complete (cover all properties and behaviors needed and desired by the customer).

The best way to promote unambiguous requirements is to state them in quantitative terms. Most requirements in the sustainability disciplines involve some quantitative variable. For example, we may wish to limit the amount of time it takes to complete a specified repair. To enforce such a limit, this duration will be the subject of a requirement. In practice, the time it takes to complete a repair is influenced by many factors, including control factors (those that the system designer and operator are able to control) and noise factors (factors that are thought of as “random” and not able to be readily adjusted by the designer or operator).¹ Consequently, it is customary to conceptualize the quantitative variables appearing in requirements as random variables in the sense used in probability theory. That is, the values taken by this variable over the different members of the population of products or service realizations may differ from one to another in unpredictable ways. For instance, the duration of the specified repair in the example will be influenced by factors like the location and ease of access of required spare parts, the location and ease of access of required documentation, how well-trained the repair technicians are, etc. The system designer can influence these factors by appropriate selection of requirements for them; see Part II of this book for maintainability considerations like these. However, the repair duration may also be influenced by factors that the designer cannot control, such as how fatigued the operator may be after having worked an entire shift before beginning the repair, whether the operator has to deal with inclement weather in an outdoor installation, etc. The designer cannot control these “noise factors.” For this reason, products or services should be designed to be “robust” against the effects of noise factors. This means that the product or service should be insensitive to variations in the values of the noise factors. The discipline of “robust design” [7, 14] has arisen to make this task systematic. A product or service that is robust in this sense is likely to experience fewer failures, making robust design a valuable tool for the systems engineer and design staff. We return to this idea in more detail in Section 6.8.

It is also important when assessing product or service performance against a set of requirements that statistical ideas be used—monitoring the performance of the product or service in operation generates data for each of the requirements. These data may be a census or only a sample from the population of

¹ This approach to conceptualizing operations in the real world was first introduced by Genichi Taguchi in the 1980s [10], in the context of statistically designed experiments. More broadly interpreted, it offers a useful conceptualization of how much of a given product or service realization may be controlled by requirements and how the design may be arranged, including considerations of how much margin may need to be built into the design, to mitigate the influence that “noise” factors have over the eventual outcome.

installed systems. Treating census data is straightforward; many examples are given in chapter 5 and elsewhere. Sampling data need to be analyzed in a consistent statistical manner that respects the sampling nature of the data collection so that an informative and fair picture of how well the product or service is performing may be obtained. The details of such analyses are discussed in various chapters of this book, so we are not going to dig deeper here, but we will point out, for the first time of many times, that comparisons between performance and requirements are expressed in statistical terms using probabilities, significance levels, and confidence intervals. The nature of real-world operation, especially when we are unable to collect data on anything but a sample of the population of systems in operation, brings with it these uncertainties. Whether it is possible to make absolute judgments about meeting requirements or not also depends on the form in which the requirements are written (see Chapters 3 and 5).

1.1.3 Sustainability Requirements are Important Too

At the most fundamental level, systems engineering exists to promote certain outcomes in product and service development and deployment. These outcomes include customer satisfaction and supplier profitability. The basic tool systems engineers use to carry out this function is to create and monitor requirements for specific product or service properties whose achievement promotes these outcomes. While there are many such properties that matter, this book focuses on those properties connected to reliability, maintainability, and supportability. Before narrowing to that focus, however, we need to discuss the broader context of the systems engineering role in these disciplines.

Promotion of certain key outcomes is a primary systems engineering function. In reliability, for example, understanding of customer needs may indicate that the customer is concerned primarily with the frequency of failures, perhaps because remediation of a failure requires dispatch of a repair crew to a remote or difficult-to-reach location, and the customer wishes to minimize the expense associated with these actions. Therefore the systems engineer creates a requirement for frequency of failures, perhaps something like “The equipment shall not experience failures requiring the dispatch of service personnel more often than once per decade per system.” Later in chapter 2, we will see why this requirement is incomplete (it lacks any statement about what conditions are to prevail for this failure frequency limit to be valid), but the key point here is that it is created based on a detailed understanding of the customers’ needs and the capabilities that need to be designed into the system to meet those needs.

As with any endeavor that undertakes to reach certain targets, an understanding of the process by which those targets are approached is necessary. This is a fundamental principle of quality engineering in which any effort to design and improve a product or service is based on an understanding of the process by which the product or service is created and used. Here, the

systems engineer acts to promote certain outcomes. In the sustainability disciplines, these outcomes represent what is needed of the product or service in reliability, maintainability, and supportability so that the product or service will satisfy its customers and produce a profit for the supplier. To do this effectively, he needs to understand the process used to achieve those outcomes. Then she can determine the key points in that process at which monitoring can be most effective in guiding the process toward its desired output.

1.1.4 Focused Action is Needed to Achieve the Goals Expressed by the Requirements

System or service development often begins with a “wish list” of desirable properties, or “features,” that will attract customers. From this list of features, a set of requirements is created. For purposes of this book, we categorize requirements as attribute requirements and sustainability requirements. Attribute requirements comprise functional, performance, physical, and safety requirements. Sustainability requirements are those pertaining to reliability, maintainability, and supportability that bear on whether a system or service can be developed not only to work satisfactorily when it is new but also to continue to operate satisfactorily for a significant period of time thereafter—enough time so that the system or service creates enough customer satisfaction and supplier profitability to be worthwhile.

Deliberate, focused action must be taken to create a design and realize the system or service that meets requirements. These actions are referred to as “design for x ” where x may refer to any of the requirements categories. While this is certainly true for attribute requirements, in this book we emphasize design for reliability, design for maintainability, and design for supportability as key enablers of goal achievement through systematic, repeatable, and science-based actions. Without deliberate attention to design for x , whatever requirement goals may be achieved are achieved only by chance, and the odds of meeting all requirements by chance are slim indeed. In particular, reliability, maintainability, and supportability are sometimes seen by those lacking training in these fields as arcane branches of knowledge whose implementation is beyond the capabilities of most engineers. Our position is emphatically that this is not so. We specifically discuss design for reliability, maintainability, and supportability in Chapters 6, 11, and 13, respectively, from the point of view that the actions constituting these fields are systematic, repeatable, and grounded in sound science, and are readily learned and readily applied by most engineers.

Finally, we point out that almost all, if not all, components of design for x are readily susceptible to quantitative modeling and optimization. For instance, the layout and process flow in a repair facility may be modeled as a stochastic network (see chapter 13) and optimized on that basis so that inefficiencies may be rooted out and speedier, more economical operation is promoted. The decision about whether to engage this greater degree of detail rests largely on

the organization's judgment about the balance between prevention costs and external failure costs. In this instance, an optimized repair facility promotes more rapid repair of failures, shorter system outages, and faster turnaround to the customer. This is worth something (even though it may be difficult to quantify); whether it is worth enough to justify the expenditure of scarce, skilled resources to carry out the optimization depends on the organization's quality management approach. In any case, the duration of the improvement is likely to be much longer than the time spent on carrying out the optimization, an argument in favor of the modeling approach. You will see many examples of this approach in the design for x chapters, but not every opportunity will be discussed in detail because to do so would require turning this into a book surveying all of operations research. Where an important technique of this kind may be useful but is not covered in this book, appropriate references are provided.

1.2 GOALS

For systems engineers to be able to do these things effectively, they need to reach certain goals. These goals determine the goals of this book.

1. Systems engineers need to know how success is defined for the product or service in development. Two primary indicators of success are profitability for the organization supplying the product or service, and satisfaction on the part of their customers. Throughout, we emphasize the relationships between sustainability requirements, product/service success, and the technical content of sustainability models in helping systems engineers look forward and see how the profitability and customer satisfaction results may play out.
2. Systems engineers rarely will be required to carry out detailed reliability, maintainability, or supportability modeling, but they will almost always receive advice from specialists in these disciplines. They may also
 - subcontract the creation of reliability, maintainability, and/or supportability to teams of experts in those disciplines and
 - be part of a team negotiating sustainability requirements with customers or suppliers.

Therefore, systems engineers need to know how to be good customers of specialist engineering suppliers and be effective negotiators of sustainability requirements. This requires a minimum level of understanding of some details of reliability, maintainability, and supportability engineering. This book will present this kind of information not with a goal of creating reliability, maintainability, or supportability specialists, but rather with an amount of detail necessary to acquire the understanding needed to be good consumers of specialist information and good negotiators. We aim to give systems engineers the skills needed to ask good questions and

understand the answers, particularly with regard to the systems engineer's primary responsibility concerning the creation of suitable requirements for reliability, maintainability, and supportability—those that promote successful product and service development and deployment, satisfied customers, and a profitable business. Experienced sustainability engineers may find that some of the explanations needed to support this goal are already familiar to them and do not bear repeating, but they are included—indeed, emphasized—here to provide systems engineers with the background and understanding they need so that they can be good customers and suppliers in this context.

3. A third goal that is at least as important as others mentioned so far is to promote clarity of language and communication across the community of systems engineering stakeholders: customer representatives, specialist engineers, the product or service development team, management, and executives. The sustainability disciplines are loaded with special terms and the temptation to lapse into jargon is sometimes overwhelming. Nonetheless, we firmly believe that the best ideas are the simple ones, or at least those that can be explained simply and clearly, and this book is written with the promotion of clear, unambiguous, and consistent communication as a primary goal. I once worked for a manager who claimed that at times it was necessary to “vague it up,” but my experience has been that “vaguening it up” is more often than not a means for disguising a lack of understanding or playing political games, and rarely does it have its claimed benefits. This book intends to help you express yourself clearly and concisely. You may choose not to do so at times, but at least you will be prepared to do so successfully when needed.
4. In addition to providing a modest introduction to sustainability modeling skills, this book aims to enable systems engineers to employ a systematic and repeatable procedure to determine whether the sustainability requirements they have created are being met by systems and services, both during development and after deployment. This key step in the product or service development process enables management to undertake quality improvement programs based on reliable data and sound analyses. In other words, these requirement verifications are part of the Deming cycle's [9] “check” phase. Preventive action—to maintain good performance—and corrective action—to improve performance—should only be undertaken after a solid understanding of the success or failure of relevant requirements is achieved. This book aims to provide readers with the concepts, frameworks, tools, and techniques needed to efficiently determine the degree to which requirements are being met or not met and form the foundation for management by fact.
5. Sustainability engineering is sometimes practiced by engineers who are not specifically trained in these disciplines. Those fulfilling such a role are expected to make good use of the resources available to them while those resources may be written in language that may be unfamiliar and that may leave a lot of gaps in reasoning because they are intended for experts.

Systems engineers who have a broader background and education may need help filling those gaps. One of the purposes of this book is to present material on the sustainability disciplines carefully and with the needs of the systems engineer in mind. Readers will find discussions intended to fill in these gaps, especially as regards clear use of the language, so that confusion and ambiguity may be avoided. In some cases, experts may find these discussions tedious and/or repetitive, but the detailed, step-by-step discussions are deliberately prepared to help the non-expert rapidly be able to make substantive contributions.

1.3 SCOPE

The sustainability disciplines are reliability engineering, maintainability engineering, and supportability engineering. These disciplines are linked in important ways (see chapter 2) and are important factors in product or service success. To enhance learning about these engineering disciplines, this book emphasizes certain points of view and covers certain topics while omitting others.

The primary point of view expressed in this book is that requirements are a key driver of product or service success. As systems engineers are the developers of requirements, they must be skilled in developing requirements that lead in the right directions. Accordingly, they need enough knowledge about each of the three sustainability disciplines to be able to develop sensible and effective requirements. The scope of this book is dictated primarily by this need.

1.3.1 Reliability Engineering

To be able to accomplish reliability engineering tasks effectively requires two key skills: first (and foremost), understanding how actions taken during product or service design and manufacturing promote (or inhibit) reliability, and second, ability to work with the quantitative aspects of reliability modeling and statistical analysis. Accordingly, the two goals of the reliability engineering part of this book (Part I) are

1. to introduce the reader to design for reliability through learning about failure modes and failure mechanisms, failure causes, and preventive actions, in a variety of electronic and mechanical contexts and
2. to provide enough material on quantitative reliability modeling and statistical analysis so that the reader can understand the implications of writing requirements in various ways and be able to determine when the performance of the product or service conforms to the requirements.

This is not a textbook in reliability physics, software design patterns, or general hardware or software development best practices, so the first goal is approached in rather more general terms. From the examples of failure modes and failure

mechanisms given, the reader will be expected to inductively transfer this knowledge to new situations. Neither is this a textbook in the mathematical theory of reliability; many such books of high quality are already available to interested readers and are cited in the references herein. Rather, there is given here enough of quantitative reliability modeling and statistical analysis that readers will see how to speak and write about these correctly, understand the results specialists in this discipline will supply as part of the systems engineering and development process, and create procedures to determine to what degree reliability requirements are being met when the product or service is finally deployed. Reliability engineering specialists may find that the material on reliability modeling for systems engineers presented in chapter 4 may be simultaneously too basic and not complete. It is deliberately presented in basic terms so that it may be accessible to a non-specialist audience. It is not complete in the sense that no proofs of mathematical assertions are given (though plenty of references are provided), but it is comprehensive in the sense that the reliability modeling topics of greatest importance are all covered. Specialists may find some of the foundational discussions useful for refreshing their basic understanding of commonly used techniques.

1.3.2 Maintainability Engineering

As with reliability engineering, and as we will point out again with supportability engineering, systems engineers need to understand how actions taken during product or service design and manufacturing promote (or inhibit) maintainability, and they also need the ability to work with the quantitative aspects of maintainability modeling and statistical analysis. Accordingly, the two goals of the maintainability engineering part of this book (Part II) are

1. to introduce the reader to design for maintainability through learning about the key factors that influence maintainability and
2. to provide enough material on quantitative maintainability modeling and statistical analysis so that the reader can understand the implications of writing maintainability requirements in various ways and be able to determine when the performance of the system conforms to the maintainability requirements.

It is important to realize that maintainability and reliability are not independent. As we will see in detail in chapter 2, decisions about maintainability also have consequences for system reliability. For instance, the architecture you choose for the field-replaceable parts of the system influences the duration of the out-of-service period incident on the failure of such a part. This in turn influences the system availability, a key measure² of system reliability. Design for maintainability will consider these implications and help guide the systems

² In chapter 3 and thereafter, we will refer to availability as a *reliability figure of merit*.

engineer toward effective maintainability requirements when considering system reliability, maintainability, and cost together. And of course, it is still necessary to assess after deployment the degree to which the maintainability requirements are being met, not only to provide the facts necessary to adjudicate customer claims, but also to provide a factual foundation for management and improvement of system maintainability and of the process by which maintainability requirements are created.

1.3.3 Supportability Engineering

By now, you know what's coming. Like maintainability, supportability is not necessarily an end in itself: because system unavailability is directly proportional to the duration of outages, and poorer supportability increases outage duration, supportability plays a direct role in improving system reliability. Therefore, the importance of proper supportability is not only in its opportunity for decreased system cost but also in its implications for system reliability. The supportability part of this book, Part III, emphasizes the optimal allocation of supportability resources to improve reliability while paying attention to supportability cost. Accordingly, the two goals of the supportability engineering part of this book are

1. to introduce the reader to design for supportability through study of the key factors influencing supportability and
2. to provide enough material on supportability optimization and statistical analysis of supportability data so that the reader can understand the implications of writing requirements in various ways and be able to determine when the performance of the product or service conforms to the supportability requirements.

As noted before about maintainability, it is important to realize that supportability and reliability are not independent. It is possible to create a set of system requirements for reliability and supportability independently of each other, but doing so ignores the synergies that are possible from considering these together. Supportability engineering and design for supportability provide a clear application of optimization techniques that we will introduce in this part of the book.

1.4 AUDIENCE

1.4.1 Who Should Read This Book?

While practicing systems engineers and students of systems engineering are the primary audience for this book, others in the technological systems community too may benefit from it. Customer representatives, who may

have yet-unformed ideas about reliability as part of a desired features list, may benefit from understanding how the systems engineering process takes informal, imprecise ideas for desired reliability and makes specific requirements from them and maps these requirements to each desired reliability feature. Reliability, maintainability, and supportability engineering specialists may find new material of interest to them, particularly in the chapters concerning data analysis techniques for comparing field results with requirements. These chapters may also be useful to risk management teams and management in general. Design and development engineers will find organized, systematic treatment of design for reliability, design for maintainability, and design for supportability—key disciplines needed to ensure that sustainability requirements become fulfilled.

1.4.2 Prerequisites

No resource of this kind can hope to be completely self-contained. Readers will need to bring some background in certain subjects to gain the greatest benefit from this book. Foremost among these is a facility with statistical thinking. Almost all the language used in the areas of reliability, maintainability, and supportability engineering is based on a probabilistic and statistical approach. The quantities treated in these disciplines are almost never deterministic and require the language of probability and statistics to deal with properly. While this book does not expect you to be an expert probabilist, some maturity with probability concepts, stochastic processes, and statistical inference is assumed. For probability and stochastic processes, familiarity at about the level of [3] is helpful. For statistics, consider Refs. 2 or 6. To help with concepts or models of this kind that may be unfamiliar, other references are provided with the relevant chapters so that additional explanation may be readily obtained.

In addition, this book assumes a certain familiarity with, and maturity in, quality engineering. Systems engineers are vital contributors to the success of a product or service by crafting the requirements that are needed to drive development of a product or service that will fulfill customers' needs and that customers will find attractive and compelling. We will not dwell on the development of quality engineering methods in this book, but rather will use these concepts and methods when needed. A good introduction may be found in Ref. 13.

1.4.3 Postrequisites

Continuing the thought that no resource of this kind can hope to be completely self-contained, readers also should be aware that there are many places in the book where we discuss things that systems engineers are advised to consider doing (or contracting to have done) but that the details of those things are not given. For instance, in chapter 12, we discuss determining the proper size of an inventory of spare parts as an important

part of the systems engineering responsibility in system support. Two approaches to solving this problem are mentioned, one based on minimizing the stockout probability and another based on maximizing the system availability, within budget constraints. However, we do not discuss the details of either of these approaches in the book because they are adequately covered elsewhere, either in other textbooks or in papers in the literature. In either case, references are provided so you can acquire these techniques if you so desire, but they will normally be the province of specialists on the design team. The systems engineer's responsibility is to see that these tasks are attended to, though, in most cases, she will not carry out the tasks herself. The structure of this book largely follows this division of labor. This book emphasizes sustainability engineering tasks that need to be carried out in order to develop a successful system or service without necessarily delving deeply into the operational details of the tasks. Carrying out the tasks will usually be the responsibility of some specialist engineers on the development team, and they will use other resources for their needs.

There are a few exceptions to this rule in this book. These were chosen mainly for pedagogical value or are new approaches to sustainability engineering tasks recommended by the author. For example, in chapter 13, we discuss design optimization of a repair facility as part of design for supportability. While the use of stochastic network flow models for this task is certainly not unheard of, it is unusual enough that a brief introduction to the technique is offered in chapter 13. As always, references are provided for further exploration if needed.

Postrequisites *is* a neologism. We hope it will help you remember our emphasis on the sustainability engineering tasks systems engineers need to make sure are done while in many cases referring to other resources for the details of tasks which are mostly the province of specialist engineers on the development team.

1.5 GETTING STARTED

If you are a working systems engineer, collect a bundle of sustainability requirements that you may be familiar with. As you read through the book, or carry on with a course based on the book, examine the requirements you have collected and see if they conform to the recommendations presented. Understand the similarities and differences using the material presented in the text. Experiment with possible alternatives and improvements. Send feedback to the author.

If you are new to systems engineering, it is our hope that by following the precepts given in this book, you will rapidly mature in the sustainability disciplines to the point where you can be counted on to always create clear and effective sustainability requirements.

1.6 KEY SUCCESS FACTORS FOR SYSTEMS ENGINEERS IN RELIABILITY, MAINTAINABILITY, AND SUPPORTABILITY ENGINEERING

1.6.1 Customer–Supplier Relationships

Setting requirements does not happen in a vacuum. To set requirements effectively, it is important to understand the customer–supplier relationships that are at play in this process.

- The primary customer–supplier relationship to consider is, of course, the customer for the system (or service) purchased from its supplier. This customer is an external customer who has a lot to say about whether the system or service will prove profitable to the vendor. Requirements must flow from a deep understanding of this customer’s needs. Systematic procedures are available to elicit these needs and to ensure that any requirements developed can be traced directly to them. These procedures include
 - quality function deployment [1],
 - the “House of Quality” [4], [8], and
 - Kano analysis [5], among others.

A detailed discussion of these techniques is outside the scope of this book. Our intention is to help you develop effective requirements that truly promote the design and development of a product or service that fully and profitably meets the customer needs once they have been determined by these (or other) techniques. Of course, these procedures can also help in the development of sustainability requirements, and it is recommended that they be used in this development to the extent possible.

- The systems engineer is a supplier to the rest of the design and development team. The product supplied by the systems engineer is the set of requirements for the system (or service). The design and development team, an internal customer, needs clear direction from systems engineering, and the techniques we discuss in this book promote that clarity. A good customer–supplier relationship here includes process management for the requirements development process incorporating a robust feedback mechanism for improvement not only of individual requirements but also of the process by which they are generated.
- The systems engineer is also a supplier to management of information about timeliness of requirements development, appropriateness of requirements as related to customer needs and product or service profitability, scope creep, etc. Management needs in this relationship include clarity and forthrightness. Communication skills form the basis for being able to fulfill these needs well. This book will help you become a more skillful communicator in the sustainability disciplines. We provide many

“language tips” at various places in the text that help clarify communication points so that you can clarify them for your customers.

- The systems engineer is a customer for sustainability engineering specialists on the product or service design and development team. Systems engineers as a rule do not carry out all the modeling and analyses needed to support requirements development, and most often time pressures prevent their doing so except in extraordinary situations. Therefore, the systems engineer needs to learn how to be a good customer for this specialized information. That means having at his/her command at least enough knowledge about reliability, maintainability, and supportability engineering to be able to tell when the results submitted by specialists in these disciplines are reasonable, are products of appropriate modeling and analysis, and form a suitable basis for downstream verification of requirements from data collected during deployment. Accordingly, this book covers some of the basic ideas of quantitative modeling for each of the three disciplines. The intent is not to create specialists in reliability, maintainability, or supportability engineering, but rather to enable systems engineers to be good communicators and good customers of the suppliers of this specialty information.

1.6.2 Language and Clarity of Communication

In any technical discipline, the words we use come from ordinary English but usually carry more precise, restricted meanings. This can be a source of confusion because technical discourse uses the same ordinary English words without necessarily indicating that the precise, restricted meaning is being used. For example, in everyday speech, the word “reliable” usually means something like “able to be depended on to perform duties without fail.” From this, the noun “reliability” stems and carries a corresponding meaning. But in reliability engineering, “reliability” has precise technical meanings that are narrower than its meaning in ordinary discourse. The specific definitions of “reliability” used in systems engineering are covered in Chapters 2, 3, and 4. When we talk about reliability with nonspecialists, including managers, we usually intend a wider meaning, something akin to “absence of failure.” Leaving aside that “failure” is so far an undefined term (see chapter 2), nonspecialists will almost certainly not intend to use “reliability” as, for example, the probability definition in Section 2.2.5 or the survivor function definition in Section 3.3.2.3, and specialists may sometimes so use it and sometimes not, usually without warning. Finally, the word “reliability” is used as a portmanteau word for a system property that contains within it many possible specific criteria, such as availability, times between failures, repair times, etc., *besides* the probability definition. We refer to these as reliability effectiveness criteria (see chapter 2). Keeping this all straight is an important function of systems engineering and promotes clear and effective communication.

The position taken in this book is that it is the systems engineer who is best positioned to discern language problems of this kind and to sort them out so that all constituencies are clear on what is being said. This is a large and important responsibility. Accordingly, we emphasize learning the technical language of the sustainability disciplines and, while so learning, thinking about ways terms may be misunderstood by important constituencies: executives, managers, team members, and customers. Being conscious of possible misunderstandings helps the systems engineer anticipate and overcome the difficulties his/her various audiences are likely to have and become a great communicator as well as a great engineer.

The value of being able to keep everyone on the same page cannot be overstated. Therefore, we urge systems engineers to learn the different languages spoken by specialists and nonspecialists in the sustainability disciplines. You will find “language tips” in many places in this book where some help may be needed in sorting these out.

1.6.3 Statistical Thinking

The relevant quantities in reliability, maintainability, and supportability are not physical constants. They all come from measurements on populations of the systems to which these disciplines are applied. Consequently, they need to be understood in a statistical context, and it helps to have some familiarity with the basic concepts of statistics. In particular, we place a lot of emphasis on the notion of determining when two statistical quantities are “truly” different, that is, is the difference we observe (between a requirement for some quantity and an estimate of that quantity from operational data) explainable, with high probability, by chance fluctuations in the mechanism generating the data? Or is the difference “real” when we account for the sampling errors involved? Such reasoning is important when comparing the performance of a system against its quantitative requirements: while it is appropriate to respond to a difference that is determined to be significant, it is equally important to know when not to expend resources to make corrections when none may be warranted by the quality of our knowledge about the operational performance involved. These are basic principles of management by fact that apply whenever the quantities involved are statistical in nature, and systems engineers should be able to deal confidently with these matters, and to explain them to other stakeholders who are affected by decisions one way or another.

1.7 ORGANIZING A COURSE USING THIS BOOK

The book is organized so that Parts I, II, and III are mostly self-contained, so a course whose primary emphasis is on either reliability, or maintainability, or supportability can be constructed based on the appropriate part separately. In this case, a one-semester course can be constructed with most of the modeling chapters (3, 4, 8, 11,13) covered in depth. But it would be a mistake

to study only the modeling aspects of these disciplines. The real benefit of studying sustainability engineering comes from application of the design for (reliability, maintainability, supportability) principles that are the subject of Chapters 6, 11, and 13. Consistent with the principles of quality engineering, we advocate for application of these principles early in the development process so that prevention costs may be managed and controlled while increasing the chance that the product, system, or service will be successful. As a consequence, a more valuable course could be constructed using the “design-for” chapters as a foundation and using the modeling chapters as supporting material. If a more general overview is desired, this can be done using chapter 2, and parts of Chapters 6, 10, 11, 12, and 13. In the services industry, Chapters 6, 8, and 9 are helpful. For “high-consequence” systems in which the consequences of failure are very serious, perhaps even life-threatening, consider using chapter 7 as a basis with supplementary material from Chapters 3, 4, 5, 8, 11, and 13. An overview course aimed at introducing systems engineers to the sustainability disciplines would draw from all three parts of the book, and to be able to fit this into one semester the modeling chapters can be touched on more lightly.

1.7.1 Examples

This book contains many examples, but not every concept or technique discussed has an example given. For example, the discussion of reliability budgeting in Section 4.7.3 proceeds at a fairly abstract level and does not contain a complete worked-out example. You will find other instances of this in most chapters. This is deliberate: the variety of possible applications is very large, and the author makes no pretense to being familiar with all of them. More importantly, these situations offer the instructor an opportunity to fill in with examples from her own experience and particular field of expertise. Instructors are encouraged to make the most of this opportunity by planning ahead for class discussion of an ample number of applications, drawn from their own experience, of the concepts and techniques presented.

1.7.2 Exercises

Each chapter contains exercises. These are an integral part of the presentation. Some exercises amplify or complete examples introduced in the text. Others give the reader an opportunity to try out some of the ideas and procedures presented in the chapter. Still others are of an advanced nature that may be suitable as research projects. These are marked with an asterisk.

1.7.3 References

Each chapter contains references to supplementary or source material for the ideas in the chapter. Some of the references are to the author’s own work which has ranged widely over theoretical and practical aspects of reliability engineering. This field has grown so extensively that citation of all potentially

relevant references is an impossible task. The ones chosen aim to provide historical context as well as foundational material and additional amplification for the material in the chapter.

1.8 CHAPTER SUMMARY

This chapter prepares readers to extract maximum value from this book. It tells the aims and scope of the book, but more importantly it tells who may benefit from it and how that benefit may be gained. The book does not aim to turn systems engineers into specialists in the sustainability disciplines, but rather aims to enable systems engineers, who usually do not receive specific training in the sustainability disciplines, to become successful and productive when dealing with that portion of their responsibilities that include reliability, maintainability, and supportability. We emphasize key success factors in this endeavor. These include understanding the customer–supplier relationships at play in systems engineering, clear and proper use of language, and a facility with statistical thinking.

REFERENCES

1. Akao Y. *Quality Function Deployment—Integrating Customer Requirements into Product Design*. New York: Productivity Press (a division of CRC Press); 2004.
2. Berry DA, Lindgren BW. *Statistics: Theory and Methods*. 2nd ed. Belmont: Duxbury Press (Wadsworth); 1996.
3. Chung KL, AitSahia F. *Elementary Probability Theory: With Stochastic Processes and an Introduction to Mathematical Finance*. New York: Springer-Verlag; 2006.
4. Clausing D, Houser J. The house of quality. *Harv Bus Rev* 1988;66 (3):63–73.
5. Kano N, Seraku N, Takahashi F, Tsuji S. Attractive quality and must-be quality (in Japanese). *J Jpn Soc Qual Control* 1984;14 (2):39–48.
6. Moore DS, McCabe GP. *Introduction to the Practice of Statistics*. New York: Freeman and Co.; 1993.
7. Park SH, Antony J. *Robust Design for Quality Engineering and Six Sigma*. Singapore: World Scientific; 2008.
8. Park T, Kim K-J. Determination of an optimal set of design requirements using house of quality. *J Oper Manage* 1998;16 (5):569–581.
9. Scherkenbach WW. *The Deming Route to Quality and Productivity*. Washington: CEE Press Books; 1988.
10. Taguchi G. Quality engineering in Japan. *Commun Statist Theory Methods* 1985; 14 (11):2785–2801.
11. Tortorella M. Service reliability theory and engineering, I: foundations. *Qual Technol Quant Manage* 2005;2 (1):1–16.
12. Tortorella M. Service reliability theory and engineering, II: models and examples. *Qual Technol Quant Manage* 2005;2 (1):17–37.
13. Wadsworth HM, Stephens KS, Godfrey AB. *Modern Methods for Quality Control and Improvement*. New York: John Wiley & Sons, Inc; 2002.
14. Wu Y, Wu A. *Taguchi Methods for Robust Design*. New York: ASME Press; 2000.