Preface

At the end of the last century, corporations and government entities in the United States showed increasing concern for the loss of competitive advantage previously enjoyed by products designed and manufactured in the United States. The loss of competitive advantage experienced by manufacturers of these products was attributed to a variety of causes that both threatened the country's standard of living as well as its position within the larger world economy (Dertouzos et al. 1989). A report by the National Research Council reported that:

> *Engineering design is a crucial component of the industrial product realization process. It is estimated that 70 percent or more of the life cycle cost of a product is determined during design.* (NRC 1991, p. 1)

The engineering community agreed with this assessment, stating that "market loss by U.S. companies is due to design deficiencies more than manufacturing deficiencies" (Dixon and Duffey 1990, p. 13). A variety of studies on both manufacturing and engineering design were undertaken in order to improve the situation in both the industrial sector and in academia (NRC 1985, 1986, 1991). The engineering community found that in order to improve both the cost and efficacy of products produced for the global economy and "To regain world manufacturing leadership, we need to take a more strategic approach by also improving our engineering design practices" (Dixon and Duffey 1990, p. 9).

"Market loss by U.S. companies is due to design deficiencies more than manufacturing deficiencies" (Dixon and Duffey 1990, p. 13). The engineering design process in use in the industrial sector required improvement, but more importantly, the theory of design and implementing design methodologies advocated by the academic community were stagnant. A renewed emphasis on design and a new subdiscipline in engineering design were adopted by the engineering community. New requirements for design activities in the academic curricula were mandated, and the national engineering accreditation organization included additional design criteria as part of the accreditation assessment process. Major efforts to reinvigorate design in both undergraduate and graduate engineering programs in the United States have reemphasized the role of design in the engineering curricula. This text

has been developed to address a unique topic in engineering design, thereby filling a void in the existing engineering literature.

The topic of this text—*Nonfunctional Requirements in Systems Analysis and Design*—supports endeavors in the engineering of systems. To date, nonfunctional requirements have only been addressed within highly focused subdisciplines of engineering (e.g., reliability, maintainability, availability; traceability; testability; survivability; etc.). The wider engineering community has not had access to materials that permit them to develop a holistic, systemic perspective for nonfunctional requirements that regularly affect the entire system. Having a basic understanding of how the principal nonfunctional requirements affect the sustainment, design, adaptability, and viability concerns of a system at a high level, should help fill a void in the existing engineering literature.

To support this approach to understanding nonfunctional requirements during engineering design endeavors, the book is divided into six major parts: (1) Systems Design and Nonfunctional Requirements; (2) Sustainment Concerns; (3) Design Concerns; (4) Adaptation Concerns; (5) Viability Concerns; and (6) Conclusion.

Part I focuses on the purposeful design of systems and how nonfunctional requirements fit into the design approach. Chapter 1 provides an introduction to the design of engineering systems, and reviews how engineers in the various engineering disciplines are responsible for developing designs for complex man-made systems. It also addresses systematic design, the breadth and depth of disciplines associated with design activities, and the use of life cycle models and supporting processes in the systems design process. Chapter 2 provides a description of engineering design and explains how it fits within the larger scientific paradigm. It includes a description of the desirable features and thought processes invoked in good engineering design methodologies. The chapter contains a high-level overview of seven historically significant design methodologies. It concludes with a more detailed section on axiomatic design and explains why axiomatic design is proposed as an effective system-based approach to the design of engineering systems. Chapter 3 provides a formal definition for nonfunctional requirements and the role they play in the engineering design of man-made, complex systems. It addresses the wide range of nonfunctional requirements, and introduces a number of taxonomies that have been used to describe nonfunctional requirements. The chapter concludes by presenting a notional taxonomy or framework for understanding nonfunctional requirements and their role as part of any system design endeavor. This taxonomy distributes 27 nonfunctional requirements into four *concerns*: sustainment concerns, design concerns, adaptation concerns, and viability concerns. The four concerns serve as the headings for the next four Parts of the text.

Part II addresses sustainment concerns during systems design endeavors. It is divided into two chapters which address five nonfunctional requirements. Chapter 4 addresses the nonfunctional requirements for reliability and maintainability. The section on reliability reviews the basic theory, equations, and concepts that underlie its utilization, addresses how reliability is applied in engineering design, and also explains how reliability is used as a technique for determining component reliability. The section concludes with a metric and measureable characteristic for

reliability. The section on maintainability defines basic terminology, how maintainability is used in engineering design, and introduces the maintenance and support concept. It concludes with a metric and measureable characteristic for maintainability. Chapter 5 addresses the nonfunctional requirements of availability, operability, and testability. The topic on availability and operability introduces basic theory, equations and concepts that underlie availability, how availability is applied in engineering design, and concludes with a metric and measureable characteristic for reliability. The second major topic in the chapter defines testability, discusses how it is used in engineering design, establishes a relationship to availability, and concludes with a metric and measureable characteristic for testability.

Part III addresses design concerns during systems design endeavors. It is divided into three chapters which address nine nonfunctional requirements. Chapter 6 addresses the nonfunctional requirements for conciseness, modularity, simplicity, and traceability. The topic on conciseness reviews the basic terminology, equations, and concepts that underlie its utilization, and proposes a metric for measuring and evaluating conciseness. The next section discusses the concept of modularity and how it affects systems designs. A number of specific modularity measures from the extant literature are presented. The section concludes with the selection of a measure for modularity, and presents a structural map relating the metric and the measurement attributes for modularity. The section on simplicity contrasts it with complexity, reviews relevant measures for complexity, and presents a measureable characteristic for complexity. The chapter concludes by discussing traceability, in relation to how it impacts system design endeavors, and develops a metric for evaluating traceability in systems designs. Chapter 7 addresses the nonfunctional requirements for compatibility, consistency, and interoperability. The chapter begins by reviewing compatibility and the basic terminology, equations, and concepts that underlie its utilization. Compatibility and its relation to standards is addressed, and a measure for evaluating compatibility in systems design is provided. The second section discusses the concept of consistency in terms of how it affects systems designs, and proposes a measure for consistency that is based upon requirements validation, functional verification, and design verification activities. The final section in this chapter addresses interoperability by providing both a definition and models of interoperability, and proposes a formal method for evaluating interoperability. Chapter 8 addresses the nonfunctional requirement for safety. The chapter contrasts *machine age* systems safety with *systems-age* concerns, and provides a system-based model for system safety. The chapter concludes by relating the proposed measure for evaluating systems safety to a metric, and includes a structural map for systems safety.

Part IV addresses adaptation concerns during systems design endeavors. It is divided into two chapters which address nine nonfunctional requirements. Chapter 9 addresses the nonfunctional requirements for adaptability, flexibility, modifiability and scalability, and robustness. The chapter begins with a section that reviews the concept of changeability, its three unique elements, and presents a method for representing systems change using a state-transition-diagram. Both

adaptability and flexibility are defined, and a method for distinguishing between these two nonfunctional properties is proposed. Modifiability is defined, and a distinction between it and both scalability and maintainability is provided. Robustness is defined, and its impact on design considerations is discussed. The chapter concludes by defining a measure and a means for measuring changeability that is a function of all four nonfunctional requirements discussed in the chapter. Chapter 10 addresses the nonfunctional requirements for extensibility, portability, reusability, and self-descriptiveness. The chapter begins by reviewing extensibility, its definitions, and how it is approached as an aspect of purposeful systems design. Portability is defined, positioned as a desirable characteristic, and is discussed as it relates to the four factors designers must consider in order to achieve portable designs. Reusability is addressed by providing both a definition and an explanation of its role in systems designs. Both top-down or bottom-up approaches, and three unique techniques that address reusability are presented. The section concludes by recommending two strategies and ten heuristics that support reusability in systems designs. Self-descriptiveness is defined and discussed by emphasizing the types of problems associated with poor self-descriptiveness. Seven design principles for user-systems dialogue are proposed to decrease errors and improve system self-descriptiveness. The chapter concludes by defining a measure and a means for measuring adaptation concerns, which is a function of extensibility, portability, reusability, and self-descriptiveness.

Part V addresses viability concerns during systems design endeavors. It is divided into two chapters which address eight nonfunctional requirements. Chapter 11 addresses the nonfunctional requirements for understandability, usability, robustness, and survivability. The first three nonfunctional requirements are defined and positioned within the requirements for good system design. The fourth nonfunctional requirement, survivability, is defined and 17 design principles that may be invoked when designing for survivability are addressed. The chapter concludes by defining a measure and a means for measuring core viability concerns, which is a function of understandability, usability, robustness, and survivability. Chapter 12 addresses the nonfunctional requirements for accuracy, correctness, efficiency, and integrity. The chapter begins by reviewing accuracy, its definitions, and concepts related to reference value, precision, and trueness. The second section defines correctness, and demonstrate how both verification and validation activities provide evaluation opportunities to ensure correctness. Four design principles that support the development of systems that correctly represent the specified requirements for the system are reviewed. Efficiency is addressed by providing a clear definition for efficiency, and by establishing a proxy for system efficiency. Integrity and the concept that underlies its use as a nonfunctional requirement in systems designs is reviewed. Thirty-three security design principles, and the life cycle stages where they should be invoked when designing for systems for integrity are proposed. The chapter concludes by defining a measure and a means for measuring other viability concerns, which is a function of accuracy, correctness, efficiency, and integrity.

Part VI provides a conclusion in Chap. 13. The conclusion reviews the climate that led to the small crisis in engineering design during the late 1980s and the need

for revision of the engineering curricula and accreditation criteria. The major efforts to reinvigorate design in both undergraduate and graduate engineering programs in the United States which reflected the reemphasis of the role of design in the engineering curricula are covered. Finally, the rationale for the development of the text, and the need to address nonfunctional requirements in systems analysis and design endeavors are reviewed.

This book is intended for use by systems practitioners or in a graduate course in either systems engineering or systems design where an understanding of nonfunctional requirements as an element of the design process must be understood. Given its discipline-agnostic nature, it is just as appropriate for use in a software, mechanical, or civil engineering class on design or requirements. The book may be utilized in a traditional 12- or 14-week schedule of classes. Part I should be taught in order of appearance in the book to provide the proper theoretical foundation. Parts II–V can be taught in any order, although, lacking any other preference, they can be taught in the order in which they appear. The conclusion in Chap. 13 should follow the conclusion of Parts I–V, as it builds on the information developed in Chaps. 4–12.

Upon completion of the text, the reader or student should have an improved understanding and appreciation for the nonfunctional requirements present in complex, man-made systems. Although the text addresses only 27 nonfunctional requirements, the author recognizes that many additional nonfunctional requirements exist and that they may be required to be addressed in many systems design endeavors. However, armed with the approach used in understanding the 27 defined functional requirements (i.e., definition, design utilization, measurement, and evaluation), additional nonfunctional requirements may be similarly treated.

As always, the author takes responsibility for the thoughts, ideas, and concepts presented in this text. Readers are encouraged to submit corrections and suggestions through correspondence with the author in the spirit of continuous improvement.

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http://www.springer.com/978-3-319-18343-5

Non-functional Requirements in Systems Analysis and Design

Adams, K.

2015, XXIV, 264 p. 39 illus., Hardcover
ISBN: 978-3-319-18343-5