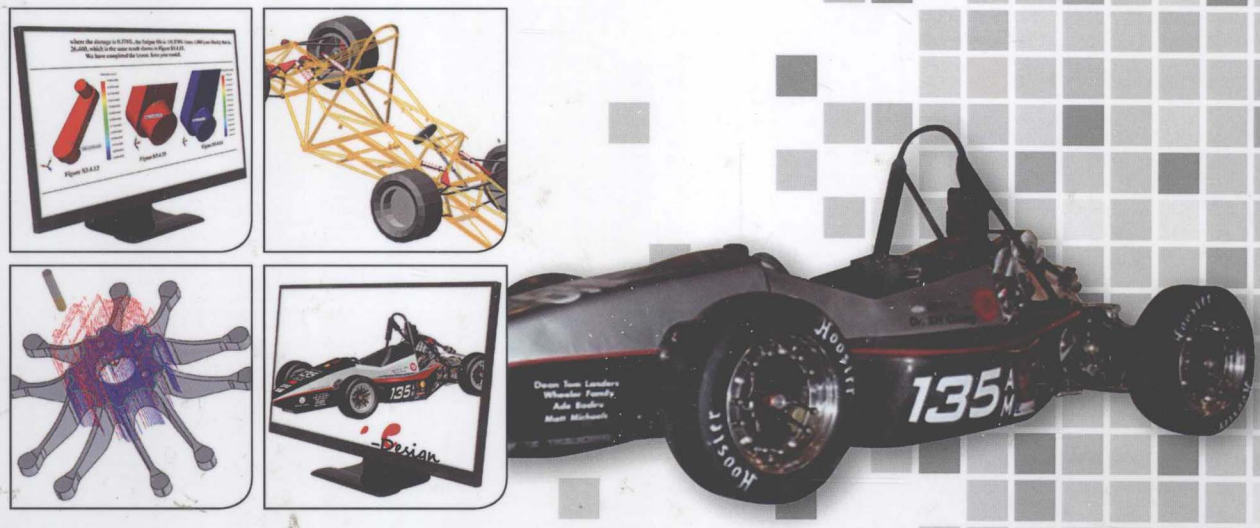
e-Design

Computer-Aided Engineering Design



Kuang-Hua Chang

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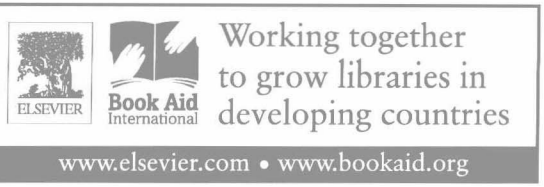

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Preface

The conventional product development process employs a design–build–test philosophy. The sequentially executed product development process often results in a prolonged lead time and an elevated product cost. The e-Design paradigm presented in this book employs IT-enabled technology, including computer-aided design, engineering, and manufacturing (CAD/CAE/CAM) tools, as well as advanced prototyping technology to support product design from concept to detailed designs, and ultimately manufacturing. This e-Design approach employs virtual prototyping (VP) technology to support a cross-functional team in analyzing product performance, reliability, and manufacturing costs early in the product development stage and in conducting quantitative trade-offs for design decision making. Physical prototypes of the product design are then produced using rapid prototyping (RP) technique mainly for design verification. The e-Design approach holds potential for shortening the overall product development cycle, improving product quality, and reducing product cost. This book intends to provide readers with a comprehensive coverage of essential elements for understanding and practicing the e-Design paradigm in support of product design, including design method and process, and computer-based tools and technology. The book consists of four parts: Product Design Modeling, Product Performance Evaluation, Product Manufacturing and Cost Estimating, and Design Theory and Methods. The Product Design Modeling discusses virtual mockup of the product that is first created in the CAD environment. The critical design parameterization that converts the product solid model into parametric representation, enabling the search for better designs, is an indispensable element of practicing the e-Design paradigm, especially in the detailed design stage. The second part, Product Performance Evaluation, focuses on applying computer-aided engineering (CAE) technology and software tools to support evaluation of product performance, including structural analysis, fatigue and fracture, rigid body kinematics and dynamics, and failure probability prediction and reliability analysis. The third part, Product Manufacturing and Cost Estimating, introduces computer-aided manufacturing (CAM) technology to support manufacturing simulations and process planning, RP technology, sheet-metal forming, and computer numerical control (CNC) machining for fast product prototyping, as well as manufacturing cost estimate that can be incorporated into product cost calculations. The product performance, reliability, and cost calculated can then be brought together to the cross-functional team for design trade-offs based on quantitative engineering data obtained from simulations. Design trade-off is one of the key topics included in the fourth part, Design Theory and Methods. In addition to conventional design optimization methods, we discuss decision theory, utility theory, and decision based design. Simple examples are included to help readers understand the fundamentals of concepts and methods introduced in this book.

In addition to the discussion on design principles, methods, and processes, this book offers detailed review on the commercial off-the-shelf software tools for the support of modeling, simulations, manufacturing, and product data management and data exchanges. Tutorial-style lessons on using commercial software tools are provided together with project-based exercises. Two suites of engineering software are covered: they are Pro/ENGINEER-based, including Pro/MECHANICA Structure, Pro/ENGINEER Mechanism Design, and Pro/MFG; and SolidWorks-based, including SolidWorks Simulation, SolidWorks Motion, and CAMWorks. In addition, Mastercam is included to enhance the learning experience in computer-aided machining simulation. These tutorial lessons are designed to help readers gain hands-on experience to practice the e-Design paradigm.

We start by providing a brief introduction to the e-Design paradigm and tool environment in Chapter 1, in which two practical examples, a simple airplane engine and a high-mobility multipurpose wheeled vehicle (HMMWV), are employed for illustration. Following this introduction, more details are offered in 18 chapters organized into four parts.

The objective of Part I, Product Design Modeling, is to provide readers with a fundamental understanding in product modeling principles and modern engineering tools for solid and assembly modeling, and apply the principles and software tools to support practical design applications. Important topics in product design modeling, including geometric and solid modeling, assembly modeling, design parameterization, and product data management and data exchange are discussed.

Chapter 2 focuses on geometric modeling, in which general geometric modeling techniques and methods commonly employed in CAD are discussed. Fundamentals in geometric modeling, such as mathematic representation of parametric curves and surfaces, continuity, and geometric transformations are presented to provide readers a basic understanding in geometric modeling. The goal of this chapter is to help readers understand how geometric entities, such as curves and surfaces, are created in CAD, which is critical to understanding the theories and methods that support part modeling in CAD.

Chapter 3 offers basic knowledge on the theories of solid modeling in CAD. Basic solid modeling theories, including constructive solid geometry (CSG), boundary representation (B-Rep), and feature-based parametric solid modeling, are briefly presented. The goal of this chapter is to help readers understand how solid parts are created in CAD and the theories and methods that support part modeling in CAD.

Chapter 4 provides a brief discussion on product assembly in CAD, which involves both modeling and analysis of the articulated assemblies for support of product design. In CAD, an assembly is created by defining relative position and orientation of parts, whereas a kinematic model is created by specifying kinematic constraints between parts. Both are important for engineers to create functional assemblies in CAD to support product design. The goal of this chapter is to help readers understand how solid parts are put together in CAD that perform desired functions and the theories and methods that do the tricks.

Chapter 5 is the key chapter of this part, in which design parameterization concept and method are discussed for the support of capturing design intents in the parts and assembly of the product model. A set of guidelines are presented for the designers to parameterize solid models at sketch, part, and assembly levels in order to properly capture design intents. The goal of the chapter is to provide design parameterization concept, methods, and guidelines that support designers to explore product design alternatives in the context of e-Design paradigm.

After learning how parts and assemblies are created in CAD, in Chapter 6 we discuss how to manage product data to support product design. In addition, data exchange between CAD systems, which is one of the major issues encountered in product design using e-Design paradigm, is discussed to offer readers practical approaches in dealing with such issues.

In addition to theories and methods, two companion projects are included: Project S1 Solid Modeling with SolidWorks and Project P1 Solid Modeling with Pro/ENGINEER. These projects offer tutorial lessons that help readers to learn and be able to use the respective software tools for support of solid modeling, assembly modeling, design parameterization, and model translations for practical applications. These tutorial lessons and example files needed for going through the lessons are available for download on the book's companion website.

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Part II, Product Performance Evaluation, provides readers with fundamental understanding in product performance evaluation, which enables them to apply the principles, methods, and software tools to support practical design applications. Important topics in product performance evaluation, including structural performance of critical components, kinematics and dynamics of mechanical systems, fatigue and fracture, as well as product reliability analysis at both component and system levels, will be discussed.

Chapter 7 focuses on structural analysis, including both analytical methods and finite element analysis (FEA), in which the essential elements in using FEA for modeling and analysis of structural performance are discussed. In addition, two companion projects are included: Project S3 Structural FEA and Fatigue Analysis Using SolidWorks Simulation and Project P3 Structural FEA and Fatigue Analysis Using Pro/MECHANICA Structure. These two projects offer tutorial lessons that help readers to learn and be able to use the software tools for solving problems that are beyond hand calculations using analytical methods. The goal of this chapter is to help readers become confident and competent in using FEA for creating adequate models and obtaining reasonably accurate results to support product design.

Chapter 8 provides an overview on motion analysis. Again, both analytical and computer-aided methods, that is, the so-called computer-aided kinematic and dynamic analyses, are included. General concept and process in carrying out motion simulation for kinematic and dynamic analysis are included in this chapter. In order to support readers to use the computer-aided analysis capability for general design applications, we have provided two companion projects: Project S2 Motion Analysis Using SolidWorks Motion and Project P2 Motion Analysis Using Pro/ENGINEER Mechanism Design. Tutorial lessons of these two projects should help readers to carry out motion simulations. Again, the goal of this chapter is to help readers become confident and competent in using motion software tools for engineering design.

Chapter 9 offers a brief discussion on structural fatigue and fracture, which is one of the most technically challenging issues facing aerospace and mechanical engineers. In addition to basic theory, this chapter provides a brief review on the computational methods that support structural fatigue and fracture analysis in various stages. Similar to the previous chapters, tutorial lessons that provide details in using SolidWorks Simulation and Pro/MECHANICA Structure for crack initiation calculations are offered. You may find these lessons in Projects S3 and P3. The goal of this chapter is to enable readers to create adequate models and obtain reasonable results that support design involving fatigue and fracture.

In engineering design, there are uncertainties we must consider. Uncertainties exist in loading, material properties, geometric size, material strength, and so on. Mechanical engineers must understand the importance of the probabilistic aspect in product design and must be able to apply adequate reliability analysis methods to solve engineering problems. Chapter 10 provides a brief overview on reliability analysis, which calculates failure probability of a prescribed performance measure considering uncertainties. This chapter also touches on design from a probabilistic perspective and compares the effectiveness of the probabilistic approach with conventional methods, such as safety factor and worst-case scenario. The goal of this chapter is to provide basic probabilistic theory and reliability analysis methods that enable readers to deal with basic engineering problems involving uncertainties.

The objective of Part III, Product Manufacturing and Cost Estimating, is to provide readers with a fundamental understanding of product manufacturing principles and modern engineering tools for

manufacturing simulation and cost estimating, and to enable readers to apply principles and software tools to support practical design applications. Important topics in product manufacturing and cost estimating, including CNC machining simulation, toolpath generation, sheet metal forming simulation, rapid prototyping, and cost estimate, will be discussed.

Chapter 11 focuses on virtual machining, which is a simulation-based technology that supports engineers in defining, simulating, and visualizing the manufacturing process in a computer environment using computer-aided manufacturing (CAM) tools. In addition to virtual machining, practical aspects of CNC machining, such as fixtures, cutters, machining parameters, and CNC mill operations, are included to aid readers in bringing such considerations into machining for support of design. Three companion projects are included: Project S4: Machining Simulation Using CAMWorks, Project P4: Machining Simulation Using Pro/MFG, and Project M4: Machining Simulation Using Mastercam. These three projects offer tutorial lessons that should help readers to learn and be able to use the software tools in machining simulations for practical applications. The goal of this chapter is to help readers become confident and competent in using CAM tools for creating adequate machining simulations to support product design.

Chapter 12 provides a brief discussion of toolpath generation for surface milling, which is one of the most important machining applications. The goal of this chapter is to provide readers with a general understanding of toolpath generation, specifically for surface milling; to help readers understand the impact of machining parameters and cutters on the resulting toolpath or CL data; and to offer a detailed discussion on scallop height calculations that determine the quality of a machined surface with a quantitative measure.

Chapter 13 offers a short introduction to simulation of sheet metal forming, which is one of the most widely used manufacturing processes for thin-shell parts in the automotive and aerospace industries. In addition to basic theory, this chapter provides a brief review on the computational method that supports forming simulation as well as tooling design and process planning using simulation. Software tools commercially available for forming simulations are briefly reviewed in hope of providing readers a general idea about the availability of such tools and engineering capabilities they offer. Case studies are provided that support readers to understand practical applications of such simulation technology. The goal of this chapter is to enable readers to understand basic forming theory, create adequate simulation models and obtain reasonable results that support product design and manufacturing involving thin-shell structures.

Chapter 14 introduces Rapid Prototyping (RP), also called 3D Printing or Solid Freeform Fabrication (SFF), which is the technology and apparatus that fabricate physical objects directly from parts created in CAD using additive layer manufacturing techniques without manufacturing process planning, tooling, or fixtures. This technology has the potential to reduce the turnaround time in product design and development. The goal is to provide readers with a general understanding of RP technology and various machines commercially available, to help readers become more familiar with emerging RP and its applications in micro-manufacturing and other fields, and, through case studies, to help readers apply the same principles and methods to their own applications.

In engineering design, cost is often the driving factor that shapes the final product. The actual setting of price is at the heart of the business and is crucial to survival. Chapter 15 introduces fundamental elements in modern methods of product cost estimating. In addition, software tools for fast cost estimates in support of product design are discussed. The goal of this chapter is to help readers

understand the basics of cost estimates, employ the methods in practical applications, and acquire adequate software tools for support of design.

Part IV, Design Theory and Methods, provides readers with a fundamental understanding in product design theory and methods, and apply the theory and methods to support engineering design applications in the context of e-Design. Important topics, including decision methods and theory in engineering design, design optimization, structural design sensitivity analysis, as well as multi-objective design optimization will be discussed.

Chapter 16 focuses on decision-making for engineering design, in which conventional decision methods and decision theory, as well as decision-based design developed recently, are discussed. The conventional methods, such as decision tree and decision table, have been widely employed by industry in support of design decision-making. On the other hand, decision theory offers a scientific and theoretical basis for design decision-making, which gained the attentions of researchers in recent years. This chapter offers a short review on popular decision methods, design theory, as well as the application of the theory to support engineering design. This chapter serves as a prelude to chapters that follow in Part IV.

Chapter 17 discusses design optimization, which is one of the mainstream methods in engineering design. We discuss linear and non-linear programming and offer a mathematical basis for design problem formulation and solutions. We include both gradient-based and non-gradient approaches for solving optimization problems. In this chapter, readers should see clearly the limitations of the non-gradient approaches in terms of the computational efforts of the design problems, especially large-scale problems. The gradient-based approaches are more suitable to the typical problems in the context of e-Design. We focus on single-objective optimization that serves as a gateway to understand multi-objective optimization to be discussed in Chapter 19 that is much more relevant to practical design applications. We address issues involved in dealing with practical engineering design problems and discuss an interactive design approach, including design trade-off and what-if study, which is more suitable for support of large-scale design problems. We offer case studies to illustrate practical applications of the methods discussed and a brief review on software tools that are commercially available for support of various types of optimization problems.

Chapter 18 provides a brief discussion on the sensitivity analysis, that is, gradient calculations of product performance with respect to design variables, which are essential for design using the gradient-based methods. In this chapter, we narrow our focus on structural problems in hope of introducing basic concept and methods. We include in this chapter popular topics, such as sizing, shape, and topology designs. We also offer case studies to illustrate practical applications of the methods discussed. Some aspect of the ideas and methods on gradient calculations for structural problems can be extended to support other engineering disciplines; for example, design for mechanical motion. A case study is presented to illustrate a practical scenario that involves integration of topology and shape optimization.

In Chapter 19 we introduce multi-objective design optimization concept and methods. We start with simple examples to illustrate the concept and introduce Pareto optimality. We then discuss major solution techniques categorized by the articulation of preferences. We also include multi-objective genetic algorithms that gained popularity in recent years. In addition, we revisit decision-based design using both utility theory and game theory introduced in Chapter 16. We make a few comments on the decision-based design approach from the context of multi-objective optimization. We include a discussion on software tools that offer readers knowledge on existing tools for adoption and further

investigation. We also include two advanced topics, reliability-based design optimization and design optimization for product manufacturing cost.

In addition to theories and methods, two companion projects are included: Project S5 Design with SolidWorks and Project P5 Design with Pro/ENGINEER. We include two examples in each project, design optimization of a cantilever beam, and multi-disciplinary design optimization for a single-piston engine. The goal of the projects is to help readers become confident and competent in using CAD/CAE/CAM and optimization tools for creating adequate product design models and adopt effective solution techniques in carrying out product design tasks.

As you may notice, any individual chapters in this book could easily be expanded to a full textbook. Please keep in mind, however, that this book is not intended to provide you with detailed and thorough discussions of their respective subjects, but to offer readers the concept and process of the e-Design paradigm and the applications of computer-aided engineering technology and software tools to support modeling, simulation, and manufacturing aspects of engineering design.

This book should serve well for a two-semester (30-week) instruction in engineering colleges of general universities. Typically, a 3-hour lecture and 1-hour laboratory exercise per week are desired. This book aims at providing engineering senior and first-year graduate students a comprehensive reference to learn advanced technology in support of engineering design using IT-enabled technology. Typical engineering courses that the book serves include Engineering Design, Integrated Product and Process Development, Concurrent Engineering, Design and Manufacturing, Modern Product Design, Computer-Aided Engineering, as well as Senior Capstone Design. In addition to classroom instruction, this book should support practicing engineers who wish to learn more about the e-Design paradigm at their own pace.

RESOURCES AVAILABLE WITH THIS BOOK

For Instructors using this book for a course, an instructor manual and set of PowerPoint slides are available by registering at www.textbooks.elsevier.com. For readers of this book, in addition to the companion projects, updates and other resources related to the book, including project tutorials using ProENGINEER and SolidWorks, are available by visiting http://booksite.elsevier.com/9780123820389.

About the Author

Dr. Kuang-Hua Chang is a David Ross Boyd Professor and Williams Companies Foundation Presidential Professor at the University of Oklahoma (OU), Norman, OK. He received his diploma in Mechanical Engineering from the National Taipei Institute of Technology, Taiwan, in 1980; and M.S. and Ph.D. degrees in Mechanical Engineering from the University of Iowa in 1987 and 1990, respectively. Since then, he joined the Center for Computer-Aided Design (CCAD) at Iowa as a Research Scientist and shortly after was promoted to CAE Technical Area Manager. In 1997, he joined OU as an Assistant Professor. In 2001, he was promoted to Associative Professor, and in 2005 to the rank of Professor.

Dr. Chang teaches mechanical design and manufacturing, in addition to conducting research in computer-aided modeling and simulation for design and manufacturing of mechanical systems. His work has been published in eight books and more than 150 articles in international journals and conference proceedings. He has also served as a technical consultant to US industry and foreign companies, including LG-Electronics, Seagate Technology, etc. Dr. Chang received numerous awards for his teaching and research in the past few years, including the Williams Companies Foundation presidential professorship in 2005 for meeting the highest standards of excellence in scholarship and teaching, OU Regents Award for Superior Accomplishment in Research and Creative Activity in 2004, OU BP AMOCO Foundation Good Teaching Award in 2002, and OU Regents Award for Superior Teaching in 2010. He is a five-time recipient of CoE Alumni Teaching Award between 2007 and 2009, given to top teachers in CoE. His research paper was given a Best Paper Award at the iCEER-2005 iNEER Conference for Engineering Education and Research in 2005. In 2006, he was awarded a Ralph R. Teetor Educational Award by SAE in recognition of significant contributions to teaching, research, and student development. Dr. Chang was honored by the OKC Mayor's Committee on Disability Concerns with the 2009 Don Davis Award, which is the highest honor granted in public recognition of extraordinarily meritorious service which has substantially advanced opportunities for people with disabilities by removing social, attitudinal and environmental barriers in the greater Oklahoma City area. In 2013, Dr. Chang was named David Ross Boyd Professor, one of the highest honors at the University of Oklahoma, for having consistently demonstrated outstanding teaching, guidance, and leadership for students in an academic discipline or in an interdisciplinary program within the University.

About the Cover

The picture shown on the book cover illustrates the concept of e-Design using a formula SAE (Society of Automotive Engineers) style racecar designed and built by engineering students at the University of Oklahoma (OU). The four pictures on the left show the computer modeling and simulation of the racecar design at numerous stages, including concept design of chassis frame (top right), detailed design of load carrying components (top-left), machining simulation of the wheel center (lower-left), and detailed design of the entire racecar (lower-right). The physical racecar fabricated by the student team in 2006 is shown to the right, which resembles very closely to the computer model (lower-right of the quad pictures). To the author's knowledge, this was the first such detailed CAD model built by engineering students for a racecar. This model was built in Pro/ENGINEER with about 1400 parts and assemblies. The computer model was created in such detail that it was within 0.7 lb. of the as-built car, which weights 445 lb. Among other factors, the e-Design paradigm and computer tools propel the student team from mediocre to a top-ten contender for the annual Formula SAE competitions in only three years.

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Acknowledgments

I would like to first thank Mr. Joseph P. Hayton for recognizing the need for such an engineering design book series that offers knowledge in modern engineering design principles, methods, and tools to mechanical engineering students. His enthusiasm in moving the book project forward and eventually publishing the book is highly appreciated. Mr. Hayton's colleagues at Elsevier, Ms. Lisa Jones and her production team, and Ms. Chelsea Johnson, have made significant contributions in transforming the original manuscripts into a well-organized and professionally polished book that is suitable and presentable to our readers.

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