

FIFTH EDITION

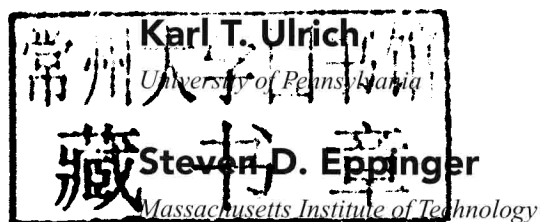
Product Design and Development



KARL T. ULRICH • STEVEN D. EPPINGER

Product Design and Development

Fifth Edition



McGraw-Hill
Irwin



PRODUCT DESIGN AND DEVELOPMENT, FIFTH EDITION

Published by McGraw-Hill, a business unit of The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY 10020. Copyright © 2012 by The McGraw-Hill Companies, Inc. All rights reserved. Previous editions © 2008, 2004, and 2000. No part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written consent of The McGraw-Hill Companies, Inc., including, but not limited to, in any network or other electronic storage or transmission, or broadcast for distance learning.

Some ancillaries, including electronic and print components, may not be available to customers outside the United States.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 0 DOC/DOC 1 0 9 8 7 6 5 4 3 2 1

ISBN 978-0-07-340477-6

MHID 0-07-340477-2

Vice President & Editor-in-Chief: *Brent Gordon*

Vice President & Director of Specialized Publishing: *Janice M. Roerig-Blong*

Editorial Director: *Paul Ducham*

Managing Developmental Editor: *Laura Hurst Spell*

Associate Marketing Manager: *Jaime Halteman*

Project Manager: *Erin Melloy*

Buyer: *Laura Fuller*

Design Coordinator: *Margarite Reynolds*

Cover Designer: *Studio Montage, St. Louis, Missouri*

Media Project Manager: *Balaji Sundararaman*

Compositor: *Aptara®, Inc.*

Typeface: *10/12 Times Roman*

Printer: *R. R. Donnelley*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Ulrich, Karl T.

Product design and development / Karl T. Ulrich, Steven D. Eppinger.—5th ed.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-07-340477-6 (hardback)

1. Industrial management. 2. Production management. 3. Industrial engineering.

4. New products—Management. I. Eppinger, Steven D. II. Title.

HD31.U47 2011

658.5'752—dc22

2011008557

To the professionals who shared their experiences with us and to the product development teams we hope will benefit from those experiences.

About the Authors

Karl T. Ulrich *University of Pennsylvania*

is the CIBC Professor and Vice Dean of Innovation at the Wharton School at the University of Pennsylvania and is also Professor of Mechanical Engineering. He received the S.B., S.M., and Sc.D. degrees in Mechanical Engineering from MIT. Professor Ulrich has led the development efforts for many products, including medical devices and sporting goods, and is the founder of several technology-based companies. As a result of this work, he has received more than 20 patents. His current research concerns technological innovation, product design, and environmental issues.

Steven D. Eppinger *Massachusetts Institute of Technology*

is the General Motors LGO Professor of Management Science and Innovation at the Massachusetts Institute of Technology Sloan School of Management and is also Professor of Engineering Systems at MIT. He received the S.B., S.M., and Sc.D. degrees in Mechanical Engineering from MIT and served as Deputy Dean of the MIT Sloan School for five years. He specializes in the management of complex product development processes and has worked extensively with the automobile, electronics, aerospace, medical devices, and capital equipment industries. His current research is aimed at the creation of improved product development practices and project management techniques.

Preface

This book contains material developed for use in the interdisciplinary courses on product development that we teach. Participants in these courses include graduate students in engineering, industrial design students, and MBA students. While we aimed the book at interdisciplinary graduate-level audiences such as this, many faculty teaching graduate and undergraduate courses in engineering design have also found the material useful. *Product Design and Development* is also for practicing professionals. Indeed, we could not avoid writing for a professional audience, because most of our students are themselves professionals who have worked either in product development or in closely related functions.

This book blends the perspectives of marketing, design, and manufacturing into a single approach to product development. As a result, we provide students of all kinds with an appreciation for the realities of industrial practice and for the complex and essential roles played by the various members of product development teams. For industrial practitioners, in particular, we provide a set of product development methods that can be put into immediate practice on development projects.

A debate often heard in the academic community relates to whether design should be taught primarily by establishing a foundation of theory or by engaging students in loosely supervised practice. For the broader activity of product design and development, we reject both approaches when taken to their extremes. Theory without practice is ineffective because there are many nuances, exceptions, and subtleties to be learned in practical settings and because some necessary tasks simply lack sufficient theoretical underpinnings. Practice without guidance can too easily result in frustration and fails to exploit the knowledge that successful product development professionals and researchers have accumulated over time. Product development, in this respect, is like sailing: proficiency is gained through practice, but some theory of how sails work and some instruction in the mechanics (and even tricks) of operating the boat help tremendously.

We attempt to strike a balance between theory and practice through our emphasis on methods. The methods we present are typically step-by-step procedures for completing tasks, but rarely embody a clean and concise theory. In some cases, the methods are supported in part by a long tradition of research and practice, as in the chapter on product development economics. In other cases, the methods are a distillation of relatively recent and *ad hoc* techniques, as in the chapter on design for environment. In all cases, the methods provide a concrete approach to solving a product development problem. In our experience, product development is best learned by applying structured methods to ongoing project work in either industrial or academic settings. Therefore, we intend this book to be used as a guide to completing development tasks either in the context of a course project or in industrial practice.

An industrial example or case study illustrates every method in the book. We chose to use different products as the examples for each chapter rather than carrying the same example through the entire book. We provide this variety because we think it makes the

book more interesting and because we hope to illustrate that the methods can be applied to a wide range of products, from industrial equipment to consumer products.

We designed the book to be extremely modular—it consists of 18 independent chapters. Each chapter presents a development method for a specific portion of the product development process. The primary benefit of the modular approach is that each chapter can be used independently of the rest of the book. This way, faculty, students, and practitioners can easily access the material they find most useful.

This fifth edition of the book includes new chapters on opportunity identification and design for environment, as well as updated examples and data, new insights from recent research and innovations in practice, and revisions throughout the book.

To supplement this textbook, we have developed a Web site on the Internet. This is intended to be a resource for instructors, students, and practitioners. We will keep the site current with additional references, examples, and links to available resources related to the product development topics in each chapter. Please make use of this information via the Internet at www.ulrich-eppinger.net.

The application of structured methods to product development also facilitates the study and improvement of development processes. We hope, in fact, that readers will use the ideas in this book as seeds for the creation of their own development methods, uniquely suited to their personalities, talents, and company environments. We encourage readers to share their experiences with us and to provide suggestions for improving this material. Please write to us with your ideas and comments at ulrich@wharton.upenn.edu and eppinger@mit.edu.

Acknowledgments

Hundreds of people contributed to this book in large and small ways. We are grateful to the many industrial practitioners who provided data, examples, and insights. We appreciate the assistance we have received from numerous academic colleagues, research assistants, and support staff, from our sponsors, and from the McGraw-Hill team. Indeed we could not have completed this project without the cooperation and collaboration of many professionals, colleagues, and friends. Thank you all.

Financial support for much of the development of this textbook came from the Alfred P. Sloan Foundation, from the MIT Leaders for Manufacturing Program, and from the MIT Center for Innovation in Product Development.

Many industrial practitioners helped us in gathering data and developing examples. We would particularly like to acknowledge the following: Richard Ahern, Liz Altman, Lindsay Anderson, Terri Anderson, Mario Belsanti, Mike Benjamin, Scott Beutler, Bill Burton, Michael Carter, Jim Caruso, Pat Casey, Scott Charon, Victor Cheung, Alan Cook, David Cutherell, Tim Davis, Tom Davis, John Elter, George Favaloro, Marc Filerman, David Fitzpatrick, Gregg Geiger, Anthony Giordano, David Gordon, Kamala Grasso, Matt Haggerty, Rick Harkey, Matthew Hern, Alan Huffenus, Art Janzen, Randy Jezowski, Carol Keller, Matt Kressy, Edward Kreuzer, David Lauzun, Peter Lawrence, Brian Lee, David Levy, Jonathan Li, Albert Lucchetti, Paul Martin, Doug Miller, Leo Montagna, Al Nagle, John Nicklaus, Hossain Nivi, Chris Norman, Paolo Pascarella, E. Timothy Pawl, Paul Piccolomini, Amy Potts, Earl Powell, Jason Ruble, Virginia Runkle, Nader Sabbaghian, Mark Schurman, Norm Seguin, David Shea, Wei-Ming Shen, Sonja Song, Leon Soren, Paul Staelin, Michael Stephens, Scott Stropkay, Larry Sullivan, Malcom Taylor, Brian Vogel, David Webb, Bob Weissappel, Dan Williams, Gabe Wing, and Mark Winter.

We have received tremendous assistance from our colleagues who have offered frequent encouragement and support for our somewhat unusual approach to teaching and research, some of which is reflected in this book. We are especially indebted to the MIT Leaders for Manufacturing (LFM) Program and to the MIT Center for Innovation in Product Development (CIPD), two exemplary partnerships involving major manufacturing firms and MIT's engineering and management schools. We have benefited from collaboration with the faculty and staff associated with these programs, especially Gabriel Bitran, Kent Bowen, Don Clausing, Tom Eagar, Charlie Fine, Woodie Flowers, Steve Graves, John Hauser, Rebecca Henderson, Maurice Holmes, Tom Magnanti, Kevin Otto, Don Rosenfield, Warren Seering, Shoji Shiba, Anna Thornton, Jim Utterback, Eric von Hippel, Dave Wallace, and Dan Whitney. We have received financial support from LFM, CIPD, and the Gordon Book Fund. Most important, LFM and CIPD partner companies have provided us with unparalleled access to industrial projects and research problems in product development and manufacturing.

Several faculty members have helped us by reviewing chapters and providing feedback from their in-class trials in teaching with this material. We are particularly grateful

to these reviewers and “beta testers”: Alice Agogino, Don Brown, Steve Brown, Charles Burnette, Gary Cadenhead, Roger Calantone, Cho Lik Chan, Kim Clark, Morris Cohen, Denny Davis, Michael Duffey, William Durfee, Donald Elger, Josh Eliashberg, David Ellison, Woodie Flowers, Gary Gabriele, Paulo Gomes, Abbie Griffin, Marc Harrison, Rebecca Henderson, Tim Hight, Mike Houston, Marco Iansiti, Kos Ishii, R. T. Johnson, Kyoung-Yun “Joseph” Kim, Annette Köhler, Viswanathan Krishnan, Yuyi Lin, Richard Locke, Bill Lovejoy, Jeff Meldman, Farrokh Mistree, Wanda Orlikowski, Louis Padulo, Matthew Parkinson, Robert Pelke, Warren Seering, Paul Sheng, Robert Smith, Carl Sorensen, Mark Steiner, Cassandra Telenko, Christian Terwiesch, Chuck Turtle, Marcie Tyre, Dan Whitney, Kristin Wood, and Khim-Teck Yeo.

Several industrial practitioners and training experts have also assisted us by reviewing and commenting on draft chapters: Wesley Allen, Geoffrey Boothroyd, Gary Burchill, Clay Burns, Eugene Cafarelli, James Carter, Kimi Ceridon, David Cutherell, Gerard Furburnshaw, Jack Harkins, Gerhard Jünemann, David Meeker, Ulrike Närger, B. Joseph Pine II, William Townsend, Brian Vogel, and John Wesner.

We also wish to acknowledge the more than 1,000 students in the classes in which we have tested these teaching materials. These students have been in several teaching programs at MIT, Helsinki University of Technology, Rhode Island School of Design, HEC Paris, STOA (Italy), University of Pennsylvania, and Nanyang Technological University (Singapore). Many students provided constructive comments for improving the structure and delivery of the material finally contained here. Also, our experiences in observing the students’ use of these methods in product development projects have greatly helped us refine the material.

Several MIT students served as research assistants to help investigate many of the development methods, examples, and data contained in the first edition of this book. These individuals are Michael Baeriswyl (Chapter 12), Paul Brody (Chapter 11), Tom Foody (Chapter 17), Amy Greenlief (Chapter 14), Christopher Hession (Chapter 4), Eric Howlett (Chapter 8), Tom Pimmler (Chapter 13 Appendices), Stephen Raab (Chapter 18), Harrison Roberts (Chapter 13 Appendices), Jonathan Sterrett (Chapter 5), and Gavin Zau (Chapter 7).

Other MIT students have also contributed by assisting with data collection and by offering comments and stimulating criticisms related to some of the chapters: Tom Abell, E. Yung Cha, Steve Daleiden, Russell Epstein, Matthew Fein, Brad Forry, Mike Frauens, Ben Goss, Daniel Hommes, Bill Liteplo, Habs Moy, Robert Northrop, Leslie Prince Rudolph, Vikas Sharma, and Ranjini Srikantiah. We also appreciate the assistance of the MIT Sloan support staff over several years: Stephen Arnold, Yubettys Baez, Cara Barber, Anna Piccolo, Kristin Rocheleau, and Kathy Sullivan.

The staff throughout the McGraw-Hill/Irwin organization has been superb. We are particularly grateful for the support of our sponsoring editor Laura Hurst Spell. We also appreciate the efforts of developmental editor Robin Bonner, project manager Erin Melloy, copy editor Rich Wright, photographer Stuart Cohen, and designer Margarite Reynolds.

Finally, we thank our families for their love and support. Our parents provided much encouragement. Nancy, Julie, Lauren, Andrew, Jamie, and Nathan have shown endless patience over the years of this ongoing product development project.

*Karl T. Ulrich
Steven D. Eppinger*

Brief Contents

About the Authors iv

Preface v

Acknowledgments vii

1 Introduction 1

2 Development Processes and
Organizations 11

3 Opportunity Identification 33

4 Product Planning 53

5 Identifying Customer Needs 73

6 Product Specifications 91

7 Concept Generation 117

8 Concept Selection 143

9 Concept Testing 165

10 Product Architecture 183

11 Industrial Design 207

12 Design for Environment 229

13 Design for Manufacturing 253

14 Prototyping 289

15 Robust Design 311

16 Patents and Intellectual Property 331

17 Product Development Economics 353

18 Managing Projects 379

Index 405

Contents

About the Authors iv

Preface v

Acknowledgments vii

Chapter 1

Introduction 1

Characteristics of Successful Product Development 2

Who Designs and Develops Products? 3

Duration and Cost of Product Development 5

The Challenges of Product Development 6

Approach of This Book 6

Structured Methods 7

Industrial Examples 7

Organizational Realities 7

Roadmap of the Book 8

References and Bibliography 10

Exercises 10

Thought Question 10

Chapter 2

Development Processes and Organizations 11

The Product Development Process 12

Concept Development: The Front-End

Process 16

Adapting the Generic Product Development

Process 18

Technology-Push Products 18

Platform Products 20

Process-Intensive Products 20

Customized Products 20

High-Risk Products 21

Quick-Build Products 21

Complex Systems 21

Product Development Process Flows 22

The Tyco Product Development Process 23

Product Development Organizations 25

Organizations Are Formed by Establishing Links among Individuals 25

Organizational Links May Be Aligned with Functions, Projects, or Both 25

Choosing an Organizational Structure 28

Distributed Product Development Teams 28

The Tyco Product Development Organization 30

Summary 30

References and Bibliography 31

Exercises 32

Thought Questions 32

Chapter 3

Opportunity Identification 33

What Is an Opportunity? 34

Types of Opportunities 34

Tournament Structure of Opportunity

Identification 36

Effective Opportunity Tournaments 37

Opportunity Identification Process 39

Step 1: Establish a Charter 39

Step 2: Generate and Sense Many

Opportunities 40

Techniques for Generating Opportunities 40

Step 3: Screen Opportunities 46

Step 4: Develop Promising Opportunities 47

Step 5: Select Exceptional Opportunities 47

Step 6: Reflect on the Results and the Process 49

Summary 50

References and Bibliography 50

Exercises 51

Thought Questions 51

Chapter 4

Product Planning 53

The Product Planning Process 54

Four Types of Product Development Projects 55

The Process 56

Step 1: Identify Opportunities	57
Step 2: Evaluate and Prioritize Projects	57
<i>Competitive Strategy</i>	58
<i>Market Segmentation</i>	58
<i>Technological Trajectories</i>	59
<i>Product Platform Planning</i>	60
<i>Evaluating Fundamentally New Product Opportunities</i>	61
<i>Balancing the Portfolio</i>	63
Step 3: Allocate Resources and Plan Timing	64
<i>Resource Allocation</i>	64
<i>Project Timing</i>	66
<i>The Product Plan</i>	66
Step 4: Complete Pre-Project Planning	66
<i>Mission Statements</i>	67
<i>Assumptions and Constraints</i>	68
<i>Staffing and Other Pre-Project Planning Activities</i>	69
Step 5: Reflect on the Results and the Process	69
Summary	70
References and Bibliography	70
Exercises	72
Thought Questions	72

Chapter 5

Identifying Customer Needs 73

Step 1: Gather Raw Data from Customers	76
<i>Choosing Customers</i>	78
<i>The Art of Eliciting Customer Needs Data</i>	79
<i>Documenting Interactions with Customers</i>	80
Step 2: Interpret Raw Data in Terms of Customer Needs	81
Step 3: Organize the Needs into a Hierarchy	83
Step 4: Establish the Relative Importance of the Needs	86
Step 5: Reflect on the Results and the Process	87
Summary	88
References and Bibliography	88
Exercises	89
Thought Questions	90

Chapter 6

Product Specifications 91

What Are Specifications?	92
When Are Specifications Established?	93

Establishing Target Specifications	94
<i>Step 1: Prepare the List of Metrics</i>	95
<i>Step 2: Collect Competitive Benchmarking Information</i>	99
<i>Step 3: Set Ideal and Marginally Acceptable Target Values</i>	99
<i>Step 4: Reflect on the Results and the Process</i>	103
Setting the Final Specifications	103
<i>Step 1: Develop Technical Models of the Product</i>	105
<i>Step 2: Develop a Cost Model of the Product</i>	106
<i>Step 3: Refine the Specifications, Making Trade-Offs Where Necessary</i>	108
<i>Step 4: Flow Down the Specifications as Appropriate</i>	109
<i>Step 5: Reflect on the Results and the Process</i>	111

Summary 111

References and Bibliography 112

Exercises 113

Thought Questions 113

Appendix

Target Costing 114

Chapter 7

Concept Generation 117

The Activity of Concept Generation	118
<i>Structured Approaches Reduce the Likelihood of Costly Problems</i>	119
<i>A Five-Step Method</i>	119
Step 1: Clarify the Problem	120
<i>Decompose a Complex Problem into Simpler Subproblems</i>	121
<i>Focus Initial Efforts on the Critical Subproblems</i>	123
Step 2: Search Externally	124
<i>Interview Lead Users</i>	124
<i>Consult Experts</i>	125
<i>Search Patents</i>	125
<i>Search Published Literature</i>	126
<i>Benchmark Related Products</i>	127
Step 3: Search Internally	127
<i>Both Individual and Group Sessions Can Be Useful</i>	128
<i>Hints for Generating Solution Concepts</i>	129

Step 4: Explore Systematically	130
<i>Concept Classification Tree</i>	132
<i>Concept Combination Table</i>	134
<i>Managing the Exploration Process</i>	137
Step 5: Reflect on the Solutions and the Process	139
Summary	140
References and Bibliography	141
Exercises	142
Thought Questions	142

Chapter 8

Concept Selection 143

Concept Selection Is an Integral Part of the Product Development Process	144
All Teams Use Some Method for Choosing a Concept	145
A Structured Method Offers Several Benefits	148
Overview of Methodology	149
Concept Screening	150
<i>Step 1: Prepare the Selection Matrix</i>	150
<i>Step 2: Rate the Concepts</i>	151
<i>Step 3: Rank the Concepts</i>	152
<i>Step 4: Combine and Improve the Concepts</i>	152
<i>Step 5: Select One or More Concepts</i>	152
<i>Step 6: Reflect on the Results and the Process</i>	153
Concept Scoring	154
<i>Step 1: Prepare the Selection Matrix</i>	154
<i>Step 2: Rate the Concepts</i>	155
<i>Step 3: Rank the Concepts</i>	156
<i>Step 4: Combine and Improve the Concepts</i>	156
<i>Step 5: Select One or More Concepts</i>	156
<i>Step 6: Reflect on the Results and the Process</i>	157

Caveats 157

Summary 159

References and Bibliography 159

Exercises 160

Thought Questions 161

Appendix A

Concept-Screening Matrix Example 162

Appendix B

Concept-Scoring Matrix Example 163

Chapter 9

Concept Testing 165

Step 1: Define the Purpose of the Concept Test	167
Step 2: Choose a Survey Population	167
Step 3: Choose a Survey Format	168
Step 4: Communicate the Concept	169
<i>Matching the Survey Format with the Means of Communicating the Concept</i>	173
<i>Issues in Communicating the Concept</i>	173
Step 5: Measure Customer Response	175
Step 6: Interpret the Results	175
Step 7: Reflect on the Results and the Process	178
Summary	179
References and Bibliography	179
Exercises	180
Thought Questions	180

Appendix

Estimating Market Sizes 181

Chapter 10

Product Architecture 183

What Is Product Architecture?	184
<i>Types of Modularity</i>	186
<i>When Is the Product Architecture Defined?</i>	187
Implications of the Architecture	187
<i>Product Change</i>	187
<i>Product Variety</i>	188
<i>Component Standardization</i>	189
<i>Product Performance</i>	189
<i>Manufacturability</i>	190
<i>Product Development Management</i>	191
Establishing the Architecture	191
<i>Step 1: Create a Schematic of the Product</i>	192
<i>Step 2: Cluster the Elements of the Schematic</i>	193
<i>Step 3: Create a Rough Geometric Layout</i>	195
<i>Step 4: Identify the Fundamental and Incidental Interactions</i>	196
Delayed Differentiation	197
Platform Planning	200
<i>Differentiation Plan</i>	200
<i>Commonality Plan</i>	201
<i>Managing the Trade-Off between Differentiation and Commonality</i>	202

Related System-Level Design Issues	202
<i>Defining Secondary Systems</i>	203
<i>Establishing the Architecture of the Chunks</i>	203
<i>Creating Detached Interface Specifications</i>	204
Summary	204
References and Bibliography	205
Exercises	206
Thought Questions	206

Chapter 11

Industrial Design 207

What Is Industrial Design?	209
Assessing the Need for Industrial Design	211
<i>Expenditures for Industrial Design</i>	211
<i>How Important Is Industrial Design to a Product?</i>	211
<i>Ergonomic Needs</i>	212
<i>Aesthetic Needs</i>	213
The Impact of Industrial Design	213
<i>Is Industrial Design Worth the Investment?</i>	213
<i>How Does Industrial Design Establish a Corporate Identity?</i>	216
The Industrial Design Process	217
1. <i>Investigation of Customer Needs</i>	217
2. <i>Conceptualization</i>	217
3. <i>Preliminary Refinement</i>	218
4. <i>Further Refinement and Final Concept Selection</i>	218
5. <i>Control Drawings or Models</i>	220
6. <i>Coordination with Engineering, Manufacturing, and External Vendors</i>	220
<i>The Impact of Computer-Based Tools on the ID Process</i>	220
Management of the Industrial Design Process	221
<i>Timing of Industrial Design Involvement</i>	222
Assessing the Quality of Industrial Design	224
1. <i>Quality of the User Interface</i>	224
2. <i>Emotional Appeal</i>	224
3. <i>Ability to Maintain and Repair the Product</i>	224
4. <i>Appropriate Use of Resources</i>	226
5. <i>Product Differentiation</i>	226
Summary	226
References and Bibliography	227
Exercises	228
Thought Questions	228

Chapter 12

Design for Environment 229

What Is Design for Environment?	231
<i>Two Life Cycles</i>	232
<i>Environmental Impacts</i>	233
<i>History of Design for Environment</i>	234
<i>Herman Miller's Journey toward Design for Environment</i>	234
The Design for Environment Process	235
Step 1: Set the DFE Agenda: Drivers, Goals, and Team	236
<i>Identify the Internal and External Drivers of DFE</i>	236
<i>Set the DFE Goals</i>	237
<i>Set Up the DFE Team</i>	237
Step 2: Identify Potential Environmental Impacts	239
Step 3: Select DFE Guidelines	240
Step 4: Apply the DFE Guidelines to the Initial Product Design	242
Step 5: Assess the Environmental Impacts	243
<i>Compare the Environmental Impacts to DFE Goals</i>	244
Step 6: Refine the Product Design to Reduce or Eliminate the Environmental Impacts	244
Step 7: Reflect on the DFE Process and Results	245
Summary	247
References and Bibliography	247
Exercises	248
Thought Questions	249
Appendix	
Design for Environment Guidelines	250

Chapter 13

Design for Manufacturing 253

Design for Manufacturing Defined	255
<i>DFM Requires a Cross-Functional Team</i>	255
<i>DFM Is Performed throughout the Development Process</i>	255
<i>Overview of the DFM Process</i>	256
Step 1: Estimate the Manufacturing Costs	256
<i>Transportation Costs</i>	259
<i>Fixed Costs versus Variable Costs</i>	259
<i>The Bill of Materials</i>	260
<i>Estimating the Costs of Standard Components</i>	261

Estimating the Costs of Custom Components 261

Estimating the Cost of Assembly 262

Estimating the Overhead Costs 263

Step 2: Reduce the Costs of Components 264

Understand the Process Constraints and Cost Drivers 264

Redesign Components to Eliminate Processing Steps 265

Choose the Appropriate Economic Scale for the Part Process 265

Standardize Components and Processes 266

Adhere to “Black Box” Component Procurement 267

Step 3: Reduce the Costs of Assembly 268

Keeping Score 268

Integrate Parts 268

Maximize Ease of Assembly 269

Consider Customer Assembly 270

Step 4: Reduce the Costs of Supporting Production 270

Minimize Systemic Complexity 271

Error Proofing 271

Step 5: Consider the Impact of DFM Decisions on Other Factors 272

The Impact of DFM on Development Time 272

The Impact of DFM on Development Cost 272

The Impact of DFM on Product Quality 273

The Impact of DFM on External Factors 273

Results 273

Summary 275

References and Bibliography 276

Exercises 277

Thought Questions 278

Appendix A

Materials Costs 279

Appendix B

Component Manufacturing Costs 280

Appendix C

Assembly Costs 286

Appendix D

Cost Structures 287

Chapter 14

Prototyping 289

Understanding Prototypes 291

Types of Prototypes 291

What Are Prototypes Used For? 294

Principles of Prototyping 297

Analytical Prototypes Are Generally More Flexible Than Physical Prototypes 297

Physical Prototypes Are Required to Detect Unanticipated Phenomena 297

A Prototype May Reduce the Risk of Costly Iterations 298

A Prototype May Expedite Other Development Steps 300

A Prototype May Restructure Task Dependencies 301

Prototyping Technologies 301

3D CAD Modeling and Analysis 301

Free-Form Fabrication 302

Planning for Prototypes 303

Step 1: Define the Purpose of the Prototype 303

Step 2: Establish the Level of Approximation of the Prototype 304

Step 3: Outline an Experimental Plan 304

Step 4: Create a Schedule for Procurement, Construction, and Testing 304

Planning Milestone Prototypes 305

Summary 306

References and Bibliography 307

Exercises 308

Thought Questions 308

Chapter 15

Robust Design 311

What Is Robust Design? 312

Design of Experiments 314

The Robust Design Process 315

Step 1: Identify Control Factors, Noise Factors, and Performance Metrics 315

Step 2: Formulate an Objective Function 316

Step 3: Develop the Experimental Plan 317

Experimental Designs 317

Testing Noise Factors 319

Step 4: Run the Experiment 321

Step 5: Conduct the Analysis 321

Computing the Objective Function 321

Computing Factor Effects by Analysis of Means 322

Step 6: Select and Confirm Factor Setpoints 323

Step 7: Reflect and Repeat 323

Caveats	324
Summary	324
References and Bibliography	325
Exercises	326
Thought Questions	326

Appendix

Orthogonal Arrays	327
--------------------------	------------

Chapter 16

Patents and Intellectual Property 331

What Is Intellectual Property?	332
<i>Overview of Patents</i>	333
<i>Utility Patents</i>	334
<i>Preparing a Disclosure</i>	334
Step 1: Formulate a Strategy and Plan	336
<i>Timing of Patent Applications</i>	336
<i>Type of Application</i>	337
<i>Scope of Application</i>	338
Step 2: Study Prior Inventions	338
Step 3: Outline Claims	339
Step 4: Write the Description of the Invention	340
<i>Figures</i>	341
<i>Writing the Detailed Description</i>	341
<i>Defensive Disclosure</i>	342
Step 5: Refine Claims	343
<i>Writing the Claims</i>	343
<i>Guidelines for Crafting Claims</i>	346
Step 6: Pursue Application	346
Step 7: Reflect on the Results and the Process	348
Summary	348
References and Bibliography	349
Exercises	349
Thought Questions	349
Appendix A	
Trademarks	350
Appendix B	
Advice to Individual Inventors	350

Chapter 17

Product Development Economics 353

Elements of Economic Analysis	354
<i>Quantitative Analysis</i>	354
<i>Qualitative Analysis</i>	354

<i>When Should Economic Analysis Be Performed?</i>	355
<i>Economic Analysis Process</i>	356
Step 1: Build a Base-Case Financial Model	356
<i>Estimate the Timing and Magnitude of Future Cash Inflows and Outflows</i>	356
<i>Compute the Net Present Value of the Cash Flows</i>	358
<i>The Base-Case Financial Model Can Support Go/No-Go Decisions and Major Investment Decisions</i>	359
Step 2: Perform Sensitivity Analysis	359
<i>Development Cost Example</i>	360
<i>Development Time Example</i>	361
Step 3: Use Sensitivity Analysis to Understand Project Trade-Offs	363
<i>Six Potential Interactions</i>	364
<i>Trade-Off Rules</i>	365
<i>Limitations of Quantitative Analysis</i>	366
Step 4: Consider the Influence of the Qualitative Factors on Project Success	367
<i>Projects Interact with the Firm, the Market, and the Macro Environment</i>	367
<i>Carrying Out Qualitative Analysis</i>	369
Summary	370
References and Bibliography	371
Exercises	372
Thought Questions	372
Appendix A	
Time Value of Money and the Net Present Value Technique	373
Appendix B	
Modeling Uncertain Cash Flows Using Net Present Value Analysis	375

Chapter 18

Managing Projects 379

Understanding and Representing Tasks	380
<i>Sequential, Parallel, and Coupled Tasks</i>	380
<i>The Design Structure Matrix</i>	382
<i>Gantt Charts</i>	383
<i>PERT Charts</i>	384
<i>The Critical Path</i>	384
Baseline Project Planning	385
<i>The Contract Book</i>	385
<i>Project Task List</i>	385

<i>Team Staffing and Organization</i>	387	Postmortem Project Evaluation	398
<i>Project Schedule</i>	388	Summary	399
<i>Project Budget</i>	389	References and Bibliography	400
<i>Project Risk Plan</i>	389	Exercises	402
<i>Modifying the Baseline Plan</i>	391	Thought Questions	402
Accelerating Projects	391	Appendix	
Project Execution	394	Design Structure Matrix Example	403
<i>Coordination Mechanisms</i>	394		
<i>Assessing Project Status</i>	396	Index	405
<i>Corrective Actions</i>	396		