



SIXTH EDITION

PRODUCT DESIGN AND DEVELOPMENT

Karl T. Ulrich | Steven D. Eppinger

**Mc
Graw
Hill**
Education

Product Design and Development

Sixth Edition

Karl T. Ulrich

University of Pennsylvania

Steven D. Eppinger

Massachusetts Institute of Technology





PRODUCT DESIGN AND DEVELOPMENT, SIXTH EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121. Copyright © 2016 by McGraw-Hill Education. All rights reserved. Printed in the United States of America. Previous editions © 2012, 2008, and 2004. 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 McGraw-Hill Education, 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

ISBN 978-0-07-802906-6

MHID 0-07-802906-6

Senior Vice President, Products & Markets: *Kurt L. Strand*
Vice President, General Manager,
Products & Markets: *Michael Ryan*
Vice President, Content Design & Delivery: *Kimberly Meriwether David*
Managing Director: *Susan Gouijnstook*
Brand Manager: *Kim Leistner*
Director, Product Development: *Meghan Campbell*
Product Developer: *Laura Hurst Spell*
Marketing Specialist: *Liz Steiner*
Digital Product Analyst: *Kerry Shanahan*
Director, Content Design & Delivery: *Terri Schiesl*

Executive Program Manager: *Faye M. Herrig*
Content Project Manager: *Mary Jane Lampe*
Buyer: *Laura M. Fuller*
Design: *Studio Montage*
Content Licensing Specialist: *Deanna Dausener*
Cover Images: *Tesla Model S Automobile (Ex. 1.1)*, © *Oleksiy Maksymenko Photography/Alamy*; *Nest thermostat (Ex. 5.1)*, *Courtesy of Nest Labs*; & *Nespresso coffee maker (Ex. 18.1)*, © *Niels Poulsen std/Alamy*
Compositor: *Aptara®*, Inc.
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, University of Pennsylvania, Steven D. Eppinger, Massachusetts Institute of Technology. —Sixth edition.

pages cm

ISBN 978-0-07-802906-6 (alk. paper) — ISBN 0-07-802906-6 (alk. paper) 1. New Products—Decision making—Methodology—Case studies. 2. Product design—Cost effectiveness—Case studies.

3. Production engineering—Case studies. I. Eppinger, Steven D. II. Title.

TS171.U47 2015

658.5'752—dc23

2015001250

The Internet addresses listed in the text were accurate at the time of publication. The inclusion of a website does not indicate an endorsement by the authors or McGraw-Hill Education, and McGraw-Hill Education does not guarantee the accuracy of the information presented at these sites.

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 24 patents. His current research concerns technological innovation, product design, and entrepreneurship.

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, systems engineering methods, 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 19 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 sixth edition of the book includes a new chapter on design of services, as well as updated examples and data. We have also revised the book throughout with insights from recent research and innovations in practice.

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 the initial 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, James Christian, 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, Brint Markle, 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, Steven Beyerlein, Don Brown, Steve Brown, Charles Burnette, Gary Cadenhead, Roger Calantone, Cho Lik Chan, Kim Clark, Richard L. Clark, Jr., 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, Nitin Joglekar, R. T. Johnson, Kyoung-Yun “Joseph” Kim, Annette Köhler, Viswanathan Krishnan, Yuyi Lin, Richard Locke, Bill Lovejoy, Jeff Meldman, Farrokh Mistree, Donatus Ohanehi, 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, Maria Yang, 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 Furburshaw, Jack Harkins, Gerhard Jünemann, David Meeker, Ulrike Närgel, 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 students served as research assistants to help investigate many of the development methods, examples, and data contained in the book. These individuals are Michael Baeriswyl (Chapters 12, 17, and 18), Anitha Balasubramaniam (Chapter 18), Paul Brody (Chapter 11), Tom Foody (Chapter 18), Amy Greenlief (Chapter 14), Christopher Hession (Chapter 4), Eric Howlett (Chapter 8), Timothy Li (Chapter 5), Tom Pimmler (Chapter 13 Appendices), Stephen Raab (Chapter 19), 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.

The staff throughout the McGraw-Hill Education organization has been superb. We are particularly grateful for the support of our sponsoring editor Laura Hurst Spell. We also appreciate the efforts of project managers Heather Ervolino and Mary Jane Lampe, copy editor Rich Wright, photo researcher Mary Reeg.

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	10	Product Architecture	185	
Preface	v	11	Industrial Design	209	
Acknowledgments	vii	12	Design for Environment	231	
1	Introduction	1	13	Design for Manufacturing	255
2	Development Processes and Organizations	11	14	Prototyping	291
3	Opportunity Identification	33	15	Robust Design	313
4	Product Planning	53	16	Patents and Intellectual Property	333
5	Identifying Customer Needs	73	17	Design of Services	355
6	Product Specifications	91	18	Product Development Economics	369
7	Concept Generation	117	19	Managing Projects	397
8	Concept Selection	145	Index	423	
9	Concept Testing	167			

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

Product-Service Systems 21

Complex Systems 22

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
 - Competitive Strategy* 58
 - Market Segmentation* 58
 - Technological Trajectories* 59
 - Product Platform Planning* 60
 - Evaluating Fundamentally New Product Opportunities* 61
 - Balancing the Portfolio* 63
- Step 3: Allocate Resources and Plan Timing 64
 - Resource Allocation* 64
 - Project Timing* 66
 - The Product Plan* 66
- Step 4: Complete Pre-Project Planning 66
 - Mission Statements* 67
 - Assumptions and Constraints* 68
 - Staffing and Other Pre-Project Planning Activities* 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

- The Importance of Latent Needs 75
- The Process of Identifying Customer Needs 75
- Step 1: Gather Raw Data from Customers 77
 - Choosing Customers* 78
 - The Art of Eliciting Customer Needs Data* 79
 - Documenting Interactions with Customers* 81
- Step 2: Interpret Raw Data in Terms of Customer Needs 82
- Step 3: Organize the Needs into a Hierarchy 84
- 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 89
- Exercises 90
- Thought Questions 90

Chapter 6 Product Specifications 91

- What Are Specifications? 92
- When Are Specifications Established? 93
- Establishing Target Specifications 94
 - Step 1: Prepare the List of Metrics* 95
 - Step 2: Collect Competitive Benchmarking Information* 99
 - Step 3: Set Ideal and Marginally Acceptable Target Values* 99
 - Step 4: Reflect on the Results and the Process* 103
- Setting the Final Specifications 103
 - Step 1: Develop Technical Models of the Product* 105
 - Step 2: Develop a Cost Model of the Product* 106
 - Step 3: Refine the Specifications, Making Trade-Offs Where Necessary* 108
 - Step 4: Flow Down the Specifications as Appropriate* 109
 - Step 5: Reflect on the Results and the Process* 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
 - Structured Approaches Reduce the Likelihood of Costly Problems* 119
 - A Five-Step Method* 119
- Step 1: Clarify the Problem 120
 - Decompose a Complex Problem into Simpler Subproblems* 121
 - Focus Initial Efforts on the Critical Subproblems* 123
- Step 2: Search Externally 124
 - Interview Lead Users* 124
 - Consult Experts* 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	131
<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	143
Thought Questions	143
Chapter 8	
Concept Selection	145
Concept Selection Is an Integral Part of the Product Development Process	146
All Teams Use Some Method for Choosing a Concept	147
A Structured Method Offers Several Benefits	150
Overview of Methodology	151
Concept Screening	152
<i>Step 1: Prepare the Selection Matrix</i>	152
<i>Step 2: Rate the Concepts</i>	153
<i>Step 3: Rank the Concepts</i>	154
<i>Step 4: Combine and Improve the Concepts</i>	154
<i>Step 5: Select One or More Concepts</i>	154
<i>Step 6: Reflect on the Results and the Process</i>	155
Concept Scoring	156
<i>Step 1: Prepare the Selection Matrix</i>	156
<i>Step 2: Rate the Concepts</i>	157
<i>Step 3: Rank the Concepts</i>	158
<i>Step 4: Combine and Improve the Concepts</i>	158
<i>Step 5: Select One or More Concepts</i>	158
<i>Step 6: Reflect on the Results and the Process</i>	159
Caveats	159
Summary	161
References and Bibliography	161
Exercises	162
Thought Questions	163

Appendix A	
Concept-Screening Matrix Example	164

Appendix B	
Concept-Scoring Matrix Example	165

Chapter 9

Concept Testing 167

Step 1: Define the Purpose of the Concept Test	169
Step 2: Choose a Survey Population	169
Step 3: Choose a Survey Format	170
Step 4: Communicate the Concept	171
<i>Matching the Survey Format with the Means of Communicating the Concept</i>	175
<i>Issues in Communicating the Concept</i>	175
Step 5: Measure Customer Response	177
Step 6: Interpret the Results	177
Step 7: Reflect on the Results and the Process	180
Summary	181
References and Bibliography	181
Exercises	182
Thought Questions	182

Appendix	
Estimating Market Sizes	183

Chapter 10

Product Architecture 185

What Is Product Architecture?	186
<i>Types of Modularity</i>	188
<i>When Is the Product Architecture Defined?</i>	189
Implications of the Architecture	189
<i>Product Change</i>	189
<i>Product Variety</i>	190
<i>Component Standardization</i>	191
<i>Product Performance</i>	191
<i>Manufacturability</i>	192
<i>Product Development Management</i>	192
Establishing the Architecture	193
<i>Step 1: Create a Schematic of the Product</i>	193
<i>Step 2: Cluster the Elements of the Schematic</i>	195
<i>Step 3: Create a Rough Geometric Layout</i>	197
<i>Step 4: Identify the Fundamental and Incidental Interactions</i>	198
Delayed Differentiation	199
Platform Planning	202

<i>Differentiation Plan</i>	202
<i>Commonality Plan</i>	202
<i>Managing the Trade-Off between Differentiation and Commonality</i>	203
Related System-Level Design Issues	204
<i>Defining Secondary Systems</i>	204
<i>Establishing the Architecture of the Chunks</i>	205
<i>Creating Detailed Interface Specifications</i>	205
Summary	206
References and Bibliography	206
Exercises	208
Thought Questions	208

Chapter 11

Industrial Design 209

What Is Industrial Design?	211
Assessing the Need for Industrial Design	213
<i>Expenditures for Industrial Design</i>	213
<i>How Important Is Industrial Design to a Product?</i>	213
<i>Ergonomic Needs</i>	214
<i>Aesthetic Needs</i>	215
The Impact of Industrial Design	215
<i>Is Industrial Design Worth the Investment?</i>	215
<i>How Does Industrial Design Establish a Corporate Identity?</i>	218
The Industrial Design Process	219
1. <i>Investigation of Customer Needs</i>	219
2. <i>Conceptualization</i>	219
3. <i>Preliminary Refinement</i>	220
4. <i>Further Refinement and Final Concept Selection</i>	221
5. <i>Control Drawings or Models</i>	222
6. <i>Coordination with Engineering, Manufacturing, and External Vendors</i>	222
<i>The Impact of Computer-Based Tools on the ID Process</i>	222
Management of the Industrial Design Process	223
<i>Timing of Industrial Design Involvement</i>	224
Assessing the Quality of Industrial Design	226
1. <i>Quality of the User Interface</i>	226
2. <i>Emotional Appeal</i>	226
3. <i>Ability to Maintain and Repair the Product</i>	226
4. <i>Appropriate Use of Resources</i>	228
5. <i>Product Differentiation</i>	228
Summary	228

References and Bibliography	229
Exercises	230
Thought Questions	230

Chapter 12

Design for Environment 231

What Is Design for Environment?	233
<i>Two Life Cycles</i>	234
<i>Environmental Impacts</i>	235
<i>History of Design for Environment</i>	236
<i>Herman Miller's Journey toward Design for Environment</i>	236
The Design for Environment Process	237
Step 1: Set the DFE Agenda: Drivers, Goals, and Team	238
<i>Identify the Internal and External Drivers of DFE</i>	238
<i>Set the DFE Goals</i>	239
<i>Set Up the DFE Team</i>	240
Step 2: Identify Potential Environmental Impacts	241
Step 3: Select DFE Guidelines	242
Step 4: Apply the DFE Guidelines to the Initial Product Design	244
Step 5: Assess the Environmental Impacts	245
<i>Compare the Environmental Impacts to DFE Goals</i>	246
Step 6: Refine the Product Design to Reduce or Eliminate the Environmental Impacts	246
Step 7: Reflect on the DFE Process and Results	247
Summary	249
References and Bibliography	249
Exercises	250
Thought Questions	251
Appendix	
Design for Environment Guidelines	252
Chapter 13	
Design for Manufacturing 255	
Design for Manufacturing Defined	257
<i>DFM Requires a Cross-Functional Team</i>	257
<i>DFM Is Performed throughout the Development Process</i>	257
<i>Overview of the DFM Process</i>	258

Step 1: Estimate the Manufacturing Costs 258
Transportation Costs 261
Fixed Costs versus Variable Costs 261
The Bill of Materials 262
Estimating the Costs of Standard Components 263
Estimating the Costs of Custom Components 263
Estimating the Cost of Assembly 264
Estimating the Overhead Costs 265

Step 2: Reduce the Costs of Components 266
Understand the Process Constraints and Cost Drivers 266
Redesign Components to Eliminate Processing Steps 267
Choose the Appropriate Economic Scale for the Part Process 267
Standardize Components and Processes 268
Adhere to “Black Box” Component Procurement 269

Step 3: Reduce the Costs of Assembly 270
Keeping Score 270
Integrate Parts 270
Maximize Ease of Assembly 271
Consider Customer Assembly 272

Step 4: Reduce the Costs of Supporting Production 272
Minimize Systemic Complexity 273
Error Proofing 273

Step 5: Consider the Impact of DFM Decisions on Other Factors 274
The Impact of DFM on Development Time 274
The Impact of DFM on Development Cost 274
The Impact of DFM on Product Quality 275
The Impact of DFM on External Factors 275

Results 275
 Summary 277
 References and Bibliography 278
 Exercises 279
 Thought Questions 280

Appendix A
Materials Costs 281

Appendix B
Component Manufacturing Costs 282

Appendix C
Assembly Costs 288

Appendix D
Cost Structures 289

Chapter 14 Prototyping 291

Understanding Prototypes 293
Types of Prototypes 293
What Are Prototypes Used For? 296

Principles of Prototyping 299
Analytical Prototypes Are Generally More Flexible Than Physical Prototypes 299
Physical Prototypes Are Required to Detect Unanticipated Phenomena 299
A Prototype May Reduce the Risk of Costly Iterations 300
A Prototype May Expedite Other Development Steps 302
A Prototype May Restructure Task Dependencies 303

Prototyping Technologies 303
3D CAD Modeling and Analysis 303
3D Printing 304

Planning for Prototypes 305
Step 1: Define the Purpose of the Prototype 305
Step 2: Establish the Level of Approximation of the Prototype 306
Step 3: Outline an Experimental Plan 306
Step 4: Create a Schedule for Procurement, Construction, and Testing 306
Planning Milestone Prototypes 307

Summary 308
 References and Bibliography 309
 Exercises 310
 Thought Questions 310

Chapter 15 Robust Design 313

What Is Robust Design? 314
Design of Experiments 316
The Robust Design Process 317

Step 1: Identify Control Factors, Noise Factors, and Performance Metrics 317

Step 2: Formulate an Objective Function 318

Step 3: Develop the Experimental Plan 319
Experimental Designs 319
Testing Noise Factors 321

Step 4: Run the Experiment 323

Step 5: Conduct the Analysis 323

<i>Computing the Objective Function</i>	323
<i>Computing Factor Effects by Analysis of Means</i>	324
Step 6: Select and Confirm Factor Setpoints	325
Step 7: Reflect and Repeat	325
Caveats	326
Summary	326
References and Bibliography	327
Exercises	328
Thought Questions	328
Appendix	
Orthogonal Arrays	329

Chapter 16

Patents and Intellectual Property 333

What Is Intellectual Property?	334
<i>Overview of Patents</i>	335
<i>Utility Patents</i>	336
<i>Preparing a Disclosure</i>	336
Step 1: Formulate a Strategy and Plan	338
<i>Timing of Patent Applications</i>	338
<i>Type of Application</i>	339
<i>Scope of Application</i>	340
Step 2: Study Prior Inventions	340
Step 3: Outline Claims	341
Step 4: Write the Description of the Invention	342
<i>Figures</i>	343
<i>Writing the Detailed Description</i>	343
<i>Defensive Disclosure</i>	344
Step 5: Refine Claims	345
<i>Writing the Claims</i>	345
<i>Guidelines for Crafting Claims</i>	348
Step 6: Pursue Application	348
Step 7: Reflect on the Results and the Process	350
Summary	350
References and Bibliography	351
Exercises	351
Thought Questions	351

Appendix A

Trademarks 352

Appendix B

Advice to Individual Inventors 352

Chapter 17

Design of Services 355

Product-Service Systems	356
-------------------------	-----

In What Ways Are Services and Products Different?	357
---	-----

The Service Design Process	358
----------------------------	-----

<i>The Service Concept</i>	358
----------------------------	-----

<i>Concept Development at Zipcar</i>	360
--------------------------------------	-----

<i>The Service Process Flow Diagram</i>	361
---	-----

<i>Subsequent Refinement</i>	362
------------------------------	-----

Downstream Development Activities in Services	362
---	-----

<i>Prototyping a Service</i>	363
------------------------------	-----

<i>Growing Services</i>	364
-------------------------	-----

<i>Continuous Improvement</i>	364
-------------------------------	-----

Summary	365
---------	-----

References and Bibliography	366
-----------------------------	-----

Exercises	366
-----------	-----

Thought Questions	367
-------------------	-----

Chapter 18

Product Development Economics 369

Elements of Economic Analysis	370
-------------------------------	-----

<i>Quantitative Analysis</i>	370
------------------------------	-----

<i>Qualitative Analysis</i>	371
-----------------------------	-----

<i>When Should Economic Analysis Be Performed?</i>	371
--	-----

<i>Economic Analysis Process</i>	372
----------------------------------	-----

Step 1: Build a Base-Case Financial Model	372
---	-----

<i>Estimate the Timing and Magnitude of Future Cash Inflows and Outflows</i>	372
--	-----

<i>Compute the Net Present Value of the Cash Flows</i>	374
--	-----

<i>Other Cash Flows</i>	375
-------------------------	-----

<i>Supporting Go/No-Go and Major Investment Decisions</i>	376
---	-----

Step 2: Perform Sensitivity Analysis	377
--------------------------------------	-----

<i>Development Cost Example</i>	377
---------------------------------	-----

<i>Development Time Example</i>	379
---------------------------------	-----

<i>Understanding Uncertainties</i>	380
------------------------------------	-----

Step 3: Use Sensitivity Analysis to Understand Trade-Offs	380
---	-----

<i>Potential Interactions</i>	382
-------------------------------	-----

<i>Trade-Off Rules</i>	383
------------------------	-----

<i>Limitations of Quantitative Analysis</i>	384
---	-----

Step 4: Consider the Influence of Qualitative Factors	385
---	-----

<i>Projects Interact with the Firm, the Market, and the Macro Environment</i>	385
---	-----

<i>Carrying Out Qualitative Analysis</i>	387
--	-----

Summary	388	<i>The Contract Book</i>	403
References and Bibliography	389	<i>Project Task List</i>	403
Exercises	390	<i>Team Staffing and Organization</i>	405
Thought Questions	390	<i>Project Schedule</i>	406
Appendix A		<i>Project Budget</i>	407
Time Value of Money and the Net Present Value Technique	391	<i>Project Risk Plan</i>	407
Appendix B		<i>Modifying the Baseline Plan</i>	409
Modeling Uncertain Cash Flows Using Net Present Value Analysis	393	Accelerating Projects	409
		Project Execution	412
Chapter 19		<i>Coordination Mechanisms</i>	412
Managing Projects	397	<i>Assessing Project Status</i>	414
		<i>Corrective Actions</i>	414
Understanding and Representing Tasks	398	Postmortem Project Evaluation	416
<i>Sequential, Parallel, and Coupled Tasks</i>	398	Summary	417
<i>The Design Structure Matrix</i>	400	References and Bibliography	418
<i>Gantt Charts</i>	401	Exercises	420
<i>PERT Charts</i>	402	Thought Questions	420
<i>The Critical Path</i>	402	Appendix	
Baseline Project Planning	403	Design Structure Matrix Example	421
		Index	423

Introduction



Clockwise from top left: Courtesy of Belle-V LLC; Courtesy of AvaTech; ©Oleksiy Maksymenko Photography/Alamy; ©Oleksiy Maksymenko Photography/Alamy; ©Robert Clayton/Alamy.

EXHIBIT 1-1

Examples of engineered, discrete, physical products (clockwise from top left): Belle-V Ice Cream Scoop, AvaTech Avalanche Probe, iRobot Roomba Vacuum Cleaner, Tesla Model S Automobile, Boeing 787 Aircraft.

The economic success of most firms depends on their ability to identify the needs of customers and to quickly create products that meet these needs and can be produced at low cost. Achieving these goals is not solely a marketing problem, nor is it solely a design problem or a manufacturing problem; it is a product development problem involving all of these functions. This book provides a collection of methods intended to enhance the abilities of cross-functional teams to work together to develop products.

A *product* is something sold by an enterprise to its customers. *Product development* is the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product. Although much of the material in this book is useful in the development of any product, we explicitly focus on products that are engineered, discrete, and physical. Exhibit 1-1 displays several examples of products from this category. Because we focus on engineered products, the book applies better to the development of power tools and computer peripherals than to magazines or sweaters. Our focus on discrete goods makes the book less applicable to the development of products such as gasoline, nylon, and paper. Because of the focus on physical products, we do not emphasize the specific issues involved in developing services or software. Even with these restrictions, the methods presented apply well to a broad range of products, including, for example, consumer electronics, sports equipment, scientific instruments, machine tools, and medical devices.

The goal of this book is to present in a clear and detailed way a set of product development methods aimed at bringing together the marketing, design, and manufacturing functions of the enterprise. In this introductory chapter, we describe some aspects of the industrial practice of product development and provide a roadmap of the book.

Characteristics of Successful Product Development

From the perspective of the investors in a for-profit enterprise, successful product development results in products that can be produced and sold profitably, yet profitability is often difficult to assess quickly and directly. Five more specific dimensions, all of which ultimately relate to profit, are commonly used to assess the performance of a product development effort:

- **Product quality:** How good is the product resulting from the development effort? Does it satisfy customer needs? Is it robust and reliable? Product quality is ultimately reflected in market share and the price that customers are willing to pay.
- **Product cost:** What is the manufacturing cost of the product? This cost includes spending on capital equipment and tooling as well as the incremental cost of producing each unit of the product. Product cost determines how much profit accrues to the firm for a particular sales volume and a particular sales price.
- **Development time:** How quickly did the team complete the product development effort? Development time determines how responsive the firm can be to competitive forces and to technological developments, as well as how quickly the firm receives the economic returns from the team's efforts.
- **Development cost:** How much did the firm have to spend to develop the product? Development cost is usually a significant fraction of the investment required to achieve the profits.

- **Development capability:** Are the team and the firm better able to develop future products as a result of their experience with a product development project? Development capability is an asset the firm can use to develop products more effectively and economically in the future.

High performance, along these five dimensions, should ultimately lead to economic success; however, other performance criteria are also important. These criteria arise from interests of other stakeholders in the enterprise, including the members of the development team, other employees, and the community in which the product is manufactured. Members of the development team may be interested in creating an inherently exciting product. Members of the community in which the product is manufactured may be concerned about the degree to which the product creates jobs. Both production workers and users of the product hold the development team accountable to high safety standards, whether or not these standards can be justified on the strict basis of profitability. Other individuals, who may have no direct connection to the firm or the product, may demand that the product make ecologically sound use of resources and create minimal dangerous waste products.

Who Designs and Develops Products?

Product development is an interdisciplinary activity requiring contributions from nearly all the functions of a firm; however, three functions are almost always central to a product development project:

- **Marketing:** The marketing function mediates the interactions between the firm and its customers. Marketing often facilitates the identification of product opportunities, the definition of market segments, and the identification of customer needs. Marketing also typically arranges for communication between the firm and its customers, sets target prices, and oversees the launch and promotion of the product.
- **Design:** The design function plays the lead role in defining the physical form of the product to best meet customer needs. In this context, the design function includes engineering design (mechanical, electrical, software, etc.) and industrial design (aesthetics, ergonomics, user interfaces).
- **Manufacturing:** The manufacturing function is primarily responsible for designing, operating, and/or coordinating the production system in order to produce the product. Broadly defined, the manufacturing function also often includes purchasing, distribution, and installation. This collection of activities is sometimes called the *supply chain*.

Different individuals within these functions often have specific disciplinary training in areas such as market research, mechanical engineering, electrical engineering, materials science, or manufacturing operations. Several other functions, including finance and sales, are frequently involved on a part-time basis in the development of a new product. Beyond these broad functional categories, the specific composition of a development team depends on the particular characteristics of the product.

Rarely are products developed by a single individual. The collection of individuals developing a product forms the *project team*. This team usually has a single team leader, who could be drawn from any of the functions of the firm. The team can be thought of as

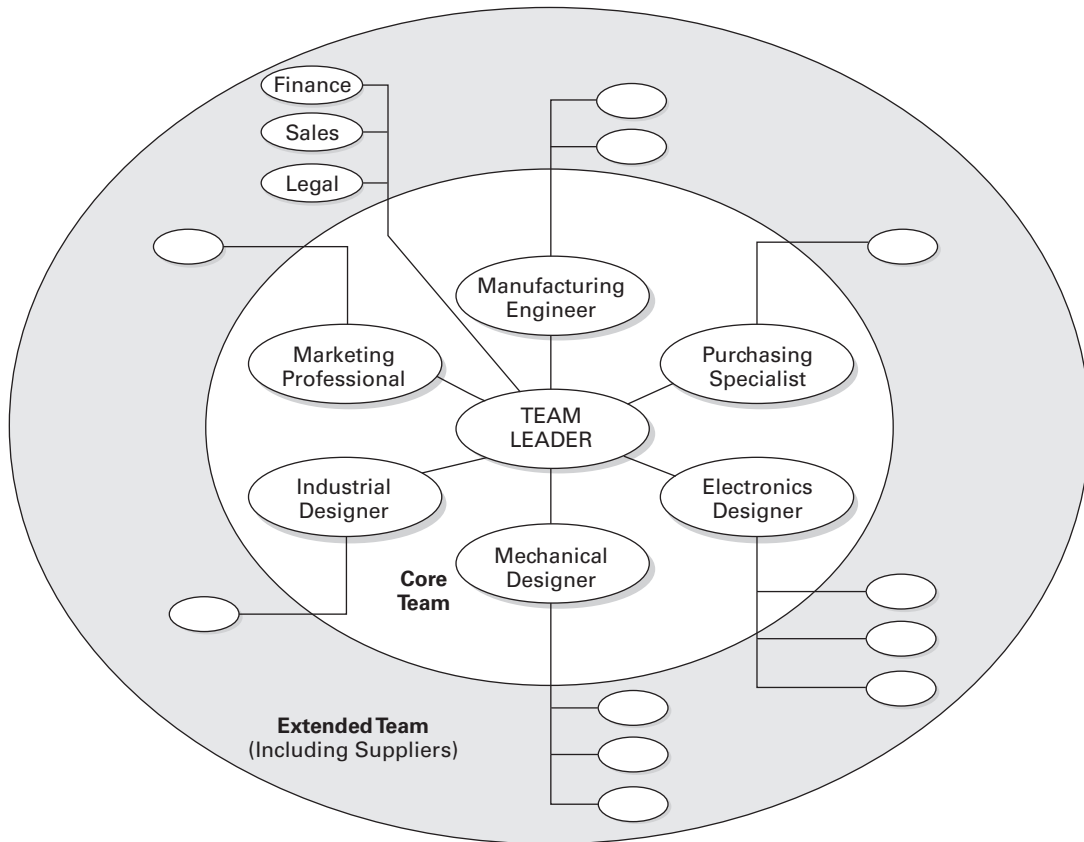


EXHIBIT 1-2 The composition of a product development team for an electromechanical product of modest complexity.

consisting of a *core team* and an *extended team*. In order to work together effectively, the core team usually remains small enough to meet in a conference room, while the extended team may consist of dozens, hundreds, or even thousands of other members. (Even though the term *team* is inappropriate for a group of thousands, the word is often used in this context to emphasize that the group must work toward a common goal.) In most cases, a team within the firm will be supported by individuals or teams at partner companies, suppliers, and consulting firms. Sometimes, as is the case for the development of a new airplane, the number of external team members may be even greater than that of the team within the company whose name will appear on the final product. The composition of a team for the development of an electromechanical product of modest complexity is shown in Exhibit 1-2.

Throughout this book we assume that the team is situated within a firm. In fact, a for-profit manufacturing company is the most common institutional setting for product development, but other settings are possible. Product development teams sometimes work within consulting firms, universities, government agencies, and nonprofit organizations.

	Belle-V Ice Cream Scoop	AvaTech Avalanche Probe	iRobot Roomba Vacuum Cleaner	Tesla Model S Automobile	Boeing 787 Aircraft
Annual production volume	10,000 units/year	1,000 units/year	2,000,000 units/year	50,000 units/year	120 units/year
Sales lifetime	10 years	3 years	2 years	5 years	40 years
Sales price	\$40	\$2,250	\$500	\$80,000	\$250 million
Number of unique parts (part numbers)	2 parts	175 parts	1,000 parts	10,000 parts	130,000 parts
Development time	1 year	2 years	2 years	4 years	7 years
Internal development team (peak size)	4 people	6 people	100 people	1000 people	7,000 people
External development team (peak size)	2 people	12 people	100 people	1000 people	10,000 people
Development cost	\$100,000	\$1 million	\$50 million	\$500 million	\$15 billion
Production investment	\$20,000	\$250,000	\$10 million	\$500 million	\$15 billion

EXHIBIT 1-3 Attributes of five products and their associated development efforts. All figures are approximate, based on publicly available information, estimates, and company sources.

Duration and Cost of Product Development

Most people without experience in product development are astounded by how much time and money are required to develop a new product. The reality is that very few products can be developed in less than 1 year, many require 3 to 5 years, and some take as long as 10 years. Exhibit 1-1 shows five engineered, discrete products. Exhibit 1-3 is a table showing the approximate scale of the associated product development efforts along with some distinguishing characteristics of the products.

The cost of product development is roughly proportional to the number of people on the project team and to the duration of the project. In addition to expenses for development effort, a firm will almost always have to make some investment in the tooling and equipment required for production. This expense is often as large as the rest of the product development budget; however, it is sometimes useful to think of these expenditures as part of the *fixed costs* of production. For reference purposes, this production investment is listed in Exhibit 1-3 along with the development expenditures.

The Challenges of Product Development

Developing great products is hard. Few companies are highly successful more than half the time. These odds present a significant challenge for a product development team. Some of the characteristics that make product development challenging are:

- **Trade-offs:** An airplane can be made lighter, but this action will probably increase manufacturing cost. One of the most difficult aspects of product development is recognizing, understanding, and managing such trade-offs in a way that maximizes the success of the product.
- **Dynamics:** Technologies improve, customer preferences evolve, competitors introduce new products, and the macroeconomic environment shifts. Decision making in an environment of constant change is a formidable task.
- **Details:** The choice between using screws or snap-fits on the enclosure of a computer can have economic implications of millions of dollars. Developing a product of even modest complexity may require thousands of such decisions.
- **Time pressure:** Any one of these difficulties would be easily manageable by itself given plenty of time, but product development decisions must usually be made quickly and without complete information.
- **Economics:** Developing, producing, and marketing a new product requires a large investment. To earn a reasonable return on this investment, the resulting product must be both appealing to customers and relatively inexpensive to produce.

For many people, product development is interesting precisely because it is challenging. For others, several intrinsic attributes also contribute to its appeal:

- **Creation:** The product development process begins with an idea and ends with the production of a physical artifact. When viewed both in its entirety and at the level of individual activities, the product development process is intensely creative.
- **Satisfaction of societal and individual needs:** All products are aimed at satisfying needs of some kind. Individuals interested in developing new products can almost always find institutional settings in which they can develop products satisfying what they consider to be important needs.
- **Team diversity:** Successful development requires many different skills and talents. As a result, development teams involve people with a wide range of different training, experience, perspectives, and personalities.
- **Team spirit:** Product development teams are often highly motivated, cooperative groups. The team members may be colocated so they can focus their collective energy on creating the product. This situation can result in lasting camaraderie among team members.

Approach of This Book

We focus on product development activities that benefit from the participation of all the core functions of the firm. For our purposes, we define the core functions as marketing, design, and manufacturing. We expect that team members have competence in one or

more specific disciplines such as mechanical engineering, electrical engineering, industrial design, market research, or manufacturing operations. For this reason, we do not discuss, for example, how to perform a stress analysis or to create a conjoint survey. These are disciplinary skills we expect someone on the development team to possess. The integrative methods in this book are intended to facilitate problem solving and decision making among people with different disciplinary perspectives.

Structured Methods

The book consists of methods for completing development activities. The methods are structured, which means we generally provide a step-by-step approach and often provide templates for the key information systems used by the team. We believe structured methods are valuable for three reasons: First, they make the decision process explicit, allowing everyone on the team to understand the decision rationale and reducing the possibility of moving forward with unsupported decisions. Second, by acting as “checklists” of the key steps in a development activity they ensure that important issues are not forgotten. Third, structured methods are largely self-documenting; in the process of executing the method, the team creates a record of the decision-making process for future reference and for educating newcomers.

Although the methods are structured, they are not intended to be applied blindly. The methods are a starting point for continuous improvement. Teams should adapt and modify the approaches to meet their own needs and to reflect the unique character of their institutional environment.

Industrial Examples

Each remaining chapter is built around an example drawn from industrial practice. The major examples include the following: a wireless security system, a laser-based cat toy, a digital copier, a thermostat, a mountain bike suspension fork, a power nailer, a dose-metering syringe, an electric scooter, a computer printer, a mobile telephone, office seating products, an automobile engine, a mobile robot, a seat belt system, a coffee-cup insulator, a coffee maker, and a microfilm cartridge. In most cases we use as examples the simplest products we have access to that illustrate the important aspects of the methods. When a syringe illustrates an idea as well as a jet engine, we use the syringe. However, every method in this book has been used successfully in industrial practice by hundreds of people on both large and small projects.

Although built around examples, the chapters are not intended to be historically accurate case studies. We use the examples as a way to illustrate development methods, and in doing so we recast some historical details in a way that improves the presentation of the material. We also disguise much of the quantitative information in the examples, especially financial data.

Organizational Realities

We deliberately chose to present the methods with the assumption that the development team operates in an organizational environment conducive to success. In reality, some organizations exhibit characteristics that lead to dysfunctional product development teams. These characteristics include:

- **Lack of empowerment of the team:** General managers or functional managers may engage in continual intervention in the details of a development project without a full understanding of the basis for the team’s decisions.

- **Functional allegiances transcending project goals:** Representatives of marketing, design, or manufacturing may influence decisions in order to increase the political standing of themselves or their functions without regard for the overall success of the product.
- **Inadequate resources:** A team may be unable to complete development tasks effectively because of a lack of staff, a mismatch of skills, or a lack of money, equipment, or tools.
- **Lack of cross-functional representation on the project team:** Key development decisions may be made without involvement of marketing, design, manufacturing, or other critical functions.

While most organizations exhibit one or more of these characteristics to some degree, the significant presence of these problems can be so stifling that sound development methods are rendered ineffective. While recognizing the importance of basic organizational issues, we assume, for clarity of explanation, that the development team operates in an environment in which the most restrictive organizational barriers have been removed.

Roadmap of the Book

We divide the product development process into six phases, as shown in Exhibit 1-4. (These phases are described in more detail in Chapter 2, Development Processes and Organizations.) This book describes the concept development phase in its entirety and the remaining phases less completely, because we do not provide methods for the more focused development activities that occur later in the process. Each of the remaining chapters in this book can be read, understood, and applied independently.

- Chapter 2, Development Processes and Organizations, presents a generic product development process and shows how variants of this process are used in different industrial situations. The chapter also discusses the way individuals are organized into groups in order to undertake product development projects.
- Chapter 3, Opportunity Identification, describes a process for creating, identifying, and screening ideas for new products.
- Chapter 4, Product Planning, presents a method for deciding which products to develop. The output of this method is a mission statement for a particular project.
- Chapters 5 through 9, Identifying Customer Needs, Product Specifications, Concept Generation, Concept Selection, and Concept Testing, present the key activities of the concept development phase. These methods guide a team from a mission statement through a selected product concept.
- Chapter 10, Product Architecture, discusses the implications of product architecture on product change, product variety, component standardization, product performance, manufacturing cost, and project management; it then presents a method for establishing the architecture of a product.
- Chapter 11, Industrial Design, discusses the role of the industrial designer and how human interaction issues, including aesthetics and ergonomics, are treated in product development.
- Chapter 12, Design for Environment, considers the environmental impacts associated with products and presents a method for reducing these impacts through better design decisions.
- Chapter 13, Design for Manufacturing, discusses techniques used to reduce manufacturing cost. These techniques are primarily applied during the system-level and detail-design phases of the process.

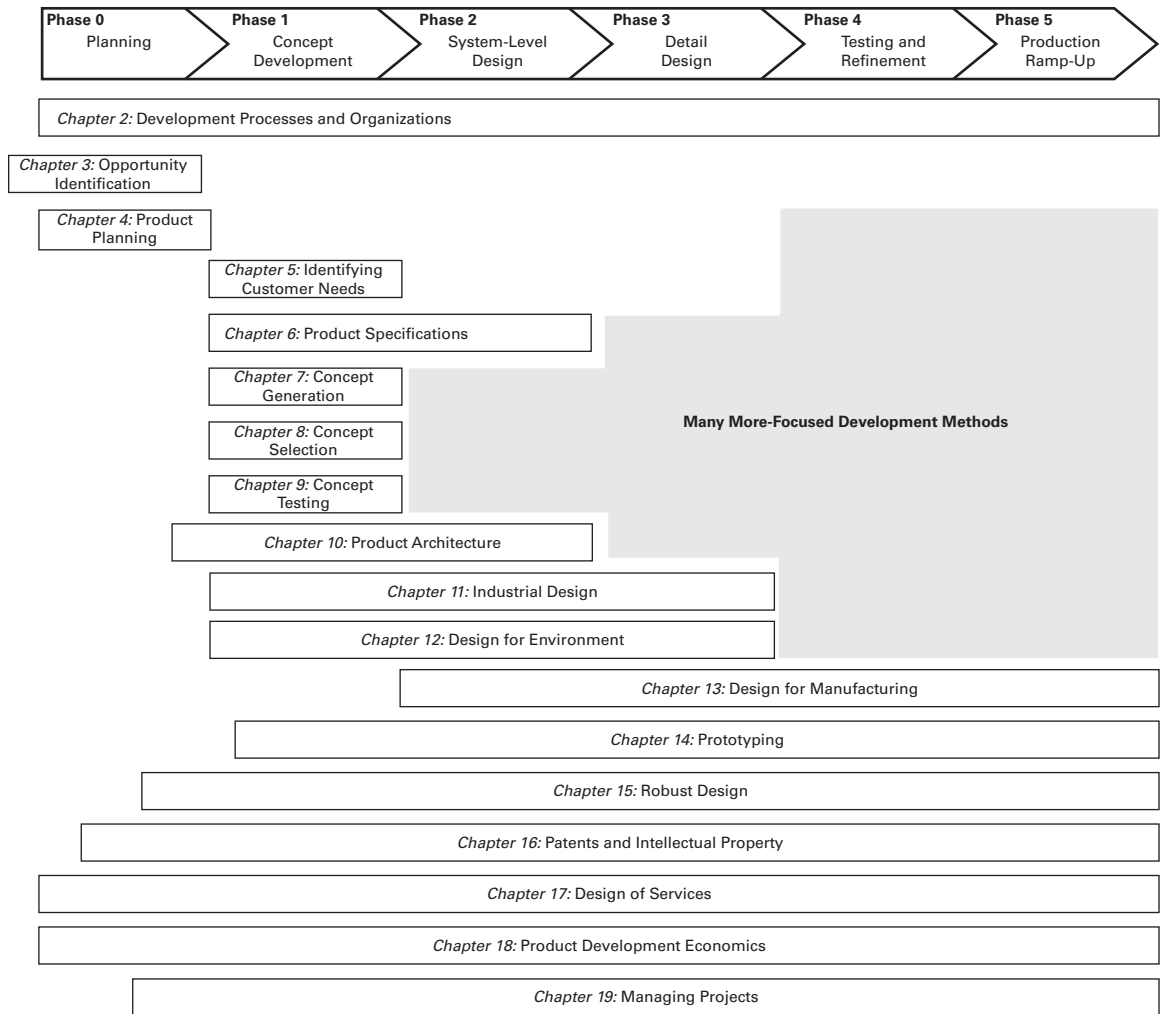


EXHIBIT 1-4 The product development process. The diagram shows where each of the integrative methods presented in the remaining chapters is most applicable.

- Chapter 14, Prototyping, presents a method to ensure that prototyping efforts, which occur throughout the process, are applied effectively.
- Chapter 15, Robust Design, explains methods for choosing values of design variables to ensure reliable and consistent performance.
- Chapter 16, Patents and Intellectual Property, presents an approach to creating a patent application and discusses the role of intellectual property in product development.
- Chapter 17, Design of Services, shows how the methods in this book can be applied to the development of intangible products, and introduces a method for representing those products, the service process flow diagram.