

# 产品设计

PEARSON  
Prentice  
Hall

## 反求工程和新产品开发技术

Kevin N. Otto 著  
Kristin L. Wood

Techniques in Reverse Engineering and New Product Development

# Product Design

清华大学出版社



# 产品设计

反求工程和新产品开发技术

Kevin N. Otto    著  
Kristin L. Wood

Techniques in Reverse Engineering and New Product Development  
**Product Design**

清华大学出版社  
北京

English reprint edition copyright © 2003 by **PEARSON EDUCATION ASIA LIMITED and TSINGHUA UNIVERSITY PRESS.**

Original English language title from Proprietor's edition of the Work.

Original English language title: Product Design: Techniques in Reverse Engineering and New Product Development,  
by Kevin N. Otto & Kristin L. Wood, Copyright © 2001  
All Rights Reserved.

Published by arrangement with the original publisher, Pearson Education, Inc., publishing as Prentice Hall, Inc.

This edition is authorized for sale and distribution only in the People's Republic of China (excluding the Special Administrative Region of Hong Kong, Macau SAR and Taiwan).

本书影印版由 Prentice Hall, Inc. 授权给清华大学出版社出版发行。

**For sale and distribution in the People's Republic of China exclusively  
(except Taiwan, Hong Kong SAR and Macau SAR).**

**仅限于中华人民共和国境内(不包括中国香港、澳门特别行政区和中国台湾地区)销售发行。**

北京市版权局著作权合同登记号 图字: 01-2002-3024

本书封面贴有 **Pearson Education** (培生教育出版集团) 激光防伪标签, 无标签者不得销售。

图书在版编目(CIP)数据

产品设计: 反求工程和新产品开发技术/(美)奥托,(美)伍德著. —北京: 清华大学出版社, 2003

书名原文: Product Design: Techniques in Reverse Engineering and New Product Development

ISBN 7-302-07048-2

I. 产… II. ①奥… ②伍… III. 产品—设计 IV. TB472

中国版本图书馆 CIP 数据核字 (2003) 第 071066 号

出 版 者: 清华大学出版社

<http://www.tup.com.cn>

社总机: (010) 6277 0175

组稿编辑: 金文织 张秋玲

封面设计: 常雪影

印 刷 者: 北京四季青印刷厂

发 行 者: 新华书店总店北京发行所

开 本: 185×230 印 张: 68

版 次: 2003 年 10 月第 1 版 2003 年 10 月第 1 次印刷

书 号: ISBN 7-302-07048-2/TH·116

印 数: 1~2000

定 价: 90.00 元

地 址: 北京清华大学学研大厦

邮 编: 100084

客户服务: (010) 6277 6969



# Foreword

Many American companies have come to realize that the ability to consistently define and deliver products to the marketplace more rapidly and efficiently than their competitors can become a source of sustainable competitive advantage. These companies have moved to view their product development capability as an end-to-end business process that can be greatly enhanced through re-engineering and can be continuously improved through total quality management. In this environment, the practice of engineering is critical to the success of the process and is as important as the implementation of the engineering sciences. K. N. Otto and K. L. Wood have presented an approach to product design based on "state of the art" engineering methods, tools, and processes that when utilized within the discipline of an overall product development process, depicts a very powerful practice of design. Both students and practitioners will find this approach not only effective and practical, but also immediately applicable to today's design challenges.

Maurice F. Holmes  
Vice President, Chief Engineer of Product Design  
Xerox Corporation



# Preface

*Product Design* presents an in-depth study of structured design processes and methods. In general, we have found that the exercise of a structured design process has many benefits in education and industry. On the industrial side, a structured design process is mandatory to effectively decide what projects to bring to market, schedule this development pipeline in a changing uncertain world, and effectively create robust delightful products. On the educational side, the benefits of using structured design methods include concrete experiences with hands-on products, applications of contemporary technologies, realistic and fruitful applications of applied mathematics and scientific principles, studies of systematic experimentation, exploration of the boundaries of design methodology, and decision making for real product development. These results have proven true whether at the sophomore introductory level with students of limited practice, or at the advanced graduate student level with students having years of practical design experience.

Based on these observations, this book is intended for undergraduate, graduate, and practicing engineers. Chapter 1 of the book discusses the foundation material of product design, including our philosophy for learning and implementing product design methods. Each subsequent chapter then includes both basic and advanced techniques for particular phases of product development. Depending on the background of the reader, these methods may be understood at a rudimentary level or at a level that pushes the current frontiers of product design.

Historically, this work grew out of a partnership effort between the authors, while we were both teaching product development courses and carrying out research in mechanical design. We both share similar philosophies on design, teaching, and research. Having each developed new methods in design, we were interested in transferring

these and others' methods into practice. We also strongly wanted to bring the excitement of the real world, both in physics and the marketplace, to the design classroom.

A fundamental premise of our teaching approach is that reverse engineering and teardowns offer a better paradigm for design instruction, permitting a modern learning cycle of experience, hypothesis, understanding, and then execution. Design instruction is no different than other domains; to learn design one should both follow this learning cycle and DO design. Reverse engineering and teardowns permit us to achieve this combined goal. We begin with a concrete product in our hands, seeing how others have designed products well, rather than rushing straight to the execution stage. With this in mind, we both independently set out to teach and successfully apply advanced methods, such as customer needs analysis, functional modeling, optimization, and designed experiments on real products.

We quickly started sharing experiences, what worked and what did not, and progressively began to string together a series of techniques and that fit naturally together. When one of us had a success, we would brag to the other, or when something failed, we'd lament together. After a bit of systematic testing, we developed the methodology presented in this book, which has proved remarkably robust when applied.

We would like to extend our special thanks to the many persons who directly contributed to this book. These include John Baker, Joseph Beaman, Geoffrey Boothroyd, Ilene Busch-Vishniac, Jim Claypool, Richard Crawford, David Cutherell, Michael Fang, Conger Gable, Javier Gonzales-Zugasti, Matthew Haggerty, Nicholas Hirschi, Maurice Holmes, Jerry Jackson, Jerry Jones, Jennie Kwo, Doug Lefever, Aaron Little, Michael Manente, Robert Matulka, Dan McAdams, David Meeker, Jon Miller, Steve Moore, Jeff Norrell, Caroline Pan, Erick Rios, David Roggenkamp, JoRuetta Roberson, Phil Schmidt, Stephen Shuler, R. S. Srinivasan, Robert Stone, Carlos Tapia, David Wallace, Joe Wysocki, Janet Yu, and Erik Zamirowski. Without their intellectual help, this book would not be.

Many others have sparked our thoughts and inspired us in many ways. These persons include Erik Antonsson, Wolfgang Beitz, Joe Bezdek, Bert Bras, Jonathon Cagan, Uichung Cho, Chin-Seng Chu, Don Clausing, Jim Coles, Ray Corvair, Michael Cusumano, Jack Dixon, John Elder, Steven Eppinger, Rolf Faste, Woodie Flowers, Mark Foohey, Chee-Seng Foong, Douglas Hart, John Hauser, Chester Hearn, Alberto Hernandez, Steve Hoover, Kos Ishii, Gerry Johnson, Nathan Kane, Paul Koeneman, Sridhar Kota, Bill Maddox, Spencer Magleby, David Masser, Ryan Ratliff, David Rosen, Bernard Roth, Warren Seering, Jami Shah, Sheri Sheppard, Alexander Slocum,

## PREFACE

---

George Stiny, David Thompson, Irem Tumer, David Ullman, Bill Weldon, Daniel Whitney, Joseph Wieck, Doug Wilde, and Rick Zayed.

We would like to thank the many persons, companies, and organizations that contributed case studies, important data, and funding that make the examples real world. These include A.T.&T. Corp., W. E. Bassett Co., Design Edge Inc., Desktop Manufacturing Co., Digital Equipment Corporation, Eastman Kodak Co., Ford Motor Co., MIT Bernard Gordon Curriculum Development Fund, June and Gene Gillis, General Electric Inc., International Business Machines Corp., Keurig Inc., Microsoft Corporation, NASA Jet Propulsion Laboratory, National Science Foundation, Robert Noyce, Pré Associates, Product Genesis Inc., Polaroid Corporation, Raychem Corp., Raytheon Corp., Texas Instruments Inc., Verein Deutsches Ingenieur, and the Xerox Corp.

We would especially like to thank MIT's Bernard Gordon Curriculum Development Fund and to the NSF Center for Innovation in Product Development at MIT, which provided necessary funds to make this book possible. More importantly, the supportive, dynamic and perceptive environment of academic faculty, students, staff and industrial researchers at MIT's Center for Innovation in Product Development cannot be understated, they have made many insights possible. Warren Seering in particular is a great help; he cannot be sufficiently thanked for his vision, insight, advice, and outright help in working in product development.

We would also like to thank the colleagues who reviewed early drafts of the book and provided constructive criticisms. A special group of early reviewers are the faculty of the United States Air Force Academy, Engineering Mechanics Department, including Col. Cary Fisher, Dr. Dan Jensen, Maj. John Wood, Capt. Michael Murphy, and Maj. Mark Nowak. We appreciate their assistance in implementing the material in their courses during Dr. Wood's sabbatical. They truly tested, twisted, shaped, and criticized the material at the most fundamental of levels.

Many others have contributed to the organization and form of the book. In particular, the authors wish to thank Neal Blumhagen, who created the cover artwork and a number of hand drawings in the text. Ann Weeks, artist, Erik Zumalt, digital artist, Michael Young, media coordinator, and Sicily Dickenson, director of the UT Instructional Media Lab, contributed wonderfully to the numerous illustrations and photographs in the book. Finally, Laurie Wood contributed her creativity to a number of the illustrations.

Kevin Otto  
Kristin Wood



# Table of Contents

Foreword .....	xiii
Preface .....	xv

## Chapter 1: Journeys in Product Development 1

1.1 Chapter Roadmap .....	3
1.2 An Introduction to Product Design .....	3
Thoughts for the Reader and Student of Product Design .....	3
Product Development versus Design .....	5
Types of Design and Redesign .....	7
What is Engineering Design? .....	9
1.3 Modern Product Development .....	12
A Modern Product Development Process .....	13
A Reverse Engineering and Redesign Product Development Process .....	21
1.4 Examples of Product Development Processes .....	27
Systems: Xerox Corporation .....	27
Industrial Design: Design EDGE, Austin TX Product Design Firm .....	30
Rapid: Microsoft Corporation .....	32
Research Intensive: Raychem Corporation .....	35
Complex: Ford Motor Company .....	38
Technical: Raytheon Corporation .....	40
1.5 Theories and Methodologies in Design .....	41
1.6 Summary and "Golden Nuggets" .....	48
References .....	48

## Chapter 2: Product Development Process Tools 51

2.1 Chapter Roadmap .....	53
2.2 Product Development Teams .....	54
The Basics of Teams .....	55



## TABLE OF CONTENTS

Team Composition: Seeking Synergy, Unity, Competence, and Consensus . . . . .	56
Strategies: Team Structures . . . . .	62
Team Building (Basic Activities) . . . . .	65
Team Evaluation . . . . .	71
Closing: Product Development Teams . . . . .	74
2.3 Product Development Planning . . . . .	74
Planning Process . . . . .	75
Basic Planning and Scheduling Tools . . . . .	77
2.4 Summary and "Golden Nuggets" . . . . .	79
References . . . . .	81

## Chapter 3: Scoping Product Developments: Technical and Business Concerns 83

---

3.1 Chapter Roadmap . . . . .	85
3.2 Determining What to Develop . . . . .	86
S-Curves . . . . .	86
S-Curves and New Product Development . . . . .	88
Comments on S-curves and Technology Forecasting . . . . .	91
3.3 Basic Method: Mission Statement and Technical Questioning . . . . .	93
Technical Questioning . . . . .	93
Mission Statements . . . . .	94
Finger Nail Clipper: Clarification and Mission Statement . . . . .	95
3.4 Advanced Method: Business Case Analysis . . . . .	97
Harvard Business Case Methodology: Product Evolution . . . . .	98
Product Development Economic Analysis . . . . .	99
3.5 Advanced Method: Design Drivers . . . . .	104
Design Drivers . . . . .	104
Example: Finger Nail Clipper . . . . .	108
3.6 Summary and "Golden Nuggets" . . . . .	110
References . . . . .	110

## Chapter 4: Understanding Customer Needs 111

---

4.1 Chapter Roadmap . . . . .	112
4.2 Customer Satisfaction . . . . .	112
Voice of the Customer . . . . .	112
Customer Populations . . . . .	115
Types of Customer Needs . . . . .	116
Customer Need Models . . . . .	117
4.3 Gathering Customer Needs . . . . .	118
Need Gathering Methods . . . . .	118

## TABLE OF CONTENTS

---

Conducting Interviews: Like/Dislike Method . . . . .	120
Conducting Interviews: Articulated-Use Method . . . . .	123
Customer Interviews: Product Feel and Industrial Design . . . . .	129
4.4 Organizing and Prioritizing Customer Needs . . . . .	130
Grouping Interpreted Needs . . . . .	130
Grouping the Needs--Affinity Diagram Method . . . . .	130
Determining Need Importance . . . . .	133
Customer Use Patterns . . . . .	141
Customer Needs Documentation . . . . .	144
4.5 Summary and "Golden Nuggets" . . . . .	145
References . . . . .	145

## **Chapter 5: Establishing Product Function** **147**

---

5.1 Chapter Roadmap . . . . .	148
5.2 Why Functional Decomposition? . . . . .	148
Motivation . . . . .	148
Function Modeling Basics . . . . .	151
Functions and Constraints . . . . .	152
5.3 Modeling Process . . . . .	153
5.4 A Simple Approach: Function Trees . . . . .	154
The FAST Method . . . . .	154
The Subtract and Operate Procedure . . . . .	159
5.5 Establishing System Functionality: Creating a Function Structure . . . . .	162
The Basics of Function Structures: Black Box and Definitions . . . . .	162
The Function Structure Modeling Process . . . . .	167
Phase 1 — Develop Process Descriptions as Activity Diagrams . . . . .	167
Phase 2 — Formulate Subfunctions Through Task Listing . . . . .	168
Phase 3 — Aggregate Subfunctions into a Refined Function Structure . . . . .	174
Phase 4 — Validate the Functional Decomposition . . . . .	174
Phase 5 — Establish and Identify Product Architecture and Assemblies . . . . .	176
5.6 Augmentation: From Simple Function Trees to Complete Models . . . . .	177
An Example of Hierarchical Function Structure Decomposition . . . . .	179
Bringing Flows into the Functional Hierarchical Decomposition . . . . .	180
5.7 Aggregation Revisited: Simplicity of Shooting Darts . . . . .	181
5.8 A Functional Common Basis . . . . .	187
The Common Basis . . . . .	188
Transforming Functional Models . . . . .	189
Uses of a Common Basis . . . . .	190
Aggregate Function Study . . . . .	191
5.9 Critique of Functional Modeling Methods . . . . .	192
5.10 Summary and "Golden Nuggets" . . . . .	194
References . . . . .	194

## Chapter 6: Product Teardown and Experimentation

197

6.1 Chapter Roadmap .....	198
6.2 Teardown Process .....	200
Overview .....	200
STEP 1. List the Design Issues .....	201
STEP 2. Prepare for Product Tear Downs .....	202
STEP 3. Examine the Distribution and Installation .....	202
STEP 4. Disassemble, Measure, and Analyze Data by Assemblies .....	203
STEP 5. Form a Bill of Materials .....	203
6.3 Teardown Methods .....	204
Subtract and Operate Procedure .....	204
SOP Examples .....	206
Force Flow (Energy Flow Field) Diagrams .....	212
Measurement and Experimentation .....	220
6.4 Post Teardown Reporting .....	234
Disassembly Plan and BOM .....	234
Exploded Views with Highlighted Features .....	236
Actual Product Function Structure (Network) .....	236
6.5 Applications of Product Teardown .....	238
Application: Slide-Out Auxiliary Visor .....	239
Case Study of an Automatic Iced Tea Maker .....	249
6.6 Summary and "Golden Nuggets" .....	256
References .....	256

## Chapter 7: Benchmarking and Establishing Engineering Specifications

259

7.1 Chapter Roadmap .....	260
7.2 Background: Know Your Enemy to Know Yourself .....	260
7.3 A Benchmarking Approach .....	262
STEP 1: Form a List of Design Issues .....	262
STEP 2. Form a List of Competitive or Related Products .....	263
STEP 3: Conduct an Information Search .....	263
STEP 4: Teardown Multiple Products in Class .....	268
STEP 5: Benchmark by Function .....	268
STEP 6: Establish Best in Class Competitors by Function .....	268
STEP 7: Plot Industry Trends .....	269
Benchmarking Example: Coffee Mills .....	270

## TABLE OF CONTENTS

---

7.4 Support Tools for the Benchmarking Process .....	274
Indented Assembly Cost Analysis .....	274
Function—Form Diagrams .....	275
Trend Analysis .....	278
Proposal on Opportunities for Re-design .....	279
Thoughts on Benchmarking the Competition .....	280
7.5 Setting Product Specifications .....	283
Specification Process .....	284
Basic Method: The House of Quality .....	289
Advanced Method: Value Analysis .....	297
7.6 Summary and “Golden Nuggets” .....	302
References .....	302

## Chapter 8: Product Portfolios and Portfolio Architecture

303

---

8.1 Chapter Roadmap .....	304
8.2 Product Portfolio Architecture .....	304
Background .....	304
Portfolio Architecture Types .....	306
8.3 Choosing an Architecture Type .....	315
Theory .....	316
Market Basis for Architecture Decisions .....	318
8.4 Platform Architecture .....	331
Negotiating a Modular Family Platform .....	332
Basic Method: Charts .....	334
Advanced Method: Functional Architecting .....	339
Advanced Method: Optimization Selection .....	345
8.5 Summary and “Golden Nuggets” .....	354
References .....	355

## Chapter 9: Product Architecture

357

*Chapter written in collaboration with Robert B. Stone, University of Missouri*

---

9.1 Chapter Roadmap .....	358
9.2 Product Architectures .....	359
Introduction .....	359
Architecture Types .....	360
Architecture Examples .....	361
9.3 Product Modularity: Background .....	362

---

## TABLE OF CONTENTS

---

Types of Modularity . . . . .	363
9.4 Modular Design: Basic Clustering Method . . . . .	370
Step 1: Create a Function Structure of the Product . . . . .	370
Step 2: Cluster the Elements into Module Chunks . . . . .	371
Step 3: Create a Rough Geometric Layout(s) . . . . .	374
Step 4: Define Interactions and Detail Performance Characteristics . . . . .	376
9.5 Modular Design: An Advanced Functional Method . . . . .	378
Function Dependencies . . . . .	378
Module Heuristics . . . . .	379
Process: Application of the Module Heuristics . . . . .	391
Summary . . . . .	398
9.6 Architecture-Based Development Teams . . . . .	399
A Method of Forming Module Based Development Teams . . . . .	400
Application of Module-Based Development Teams . . . . .	401
Summary of the Development Team Method . . . . .	408
9.7 Summary and "Golden Nuggets" . . . . .	408
References . . . . .	409

---

## Chapter 10: Generating Concepts

411

---

10.1 Chapter Roadmap . . . . .	413
10.2 Concept Generation Process . . . . .	414
10.3 Basic Methods: Information Gathering and Brainstorming . . . . .	416
Information Gathering: Conventional Aids . . . . .	417
Traditional Brainstorming . . . . .	419
Brain-Ball . . . . .	424
C-Sketch/6-3-5 Method . . . . .	425
Idea Generators for Intuitive Techniques . . . . .	432
10.4 Advanced Methods: Directed Search . . . . .	433
Systematic Search with Physical Principles . . . . .	433
Systematic Search with Classifying Schemes . . . . .	435
Theory of Inventive Problem Solving . . . . .	443
10.5 Morphological Analysis . . . . .	454
Develop Concepts for Each Product Function . . . . .	455
10.6 Combining Solution Principles (Concept Variants) . . . . .	456
Digression/Caution: Function Sharing . . . . .	459
Product Application: Fingernail Clipper . . . . .	460
Product Application: Bilge Water Removal Product . . . . .	461
Product Application: Smart Spoon to Assist Persons with Disabilities . . . . .	464
10.7 Summary and "Golden Nuggets" . . . . .	475
References . . . . .	476

---

## Chapter 11: Concept Selection

477

11.1 Chapter Roadmap .....	478
11.2 Introduction.....	478
Factors that Determine Effective Decision Making.....	479
Design Evaluations .....	480
Information Quality.....	480
11.3 Estimating Technical Feasibility.....	482
Estimation.....	483
Example: Air Conditioning for an Electric Vehicle.....	484
Estimating Hints.....	486
11.4 A Concept Selection Process .....	487
Forming Consensus on the Criteria.....	489
Forming Consensus on the Alternatives.....	491
Ranking.....	492
Assessment .....	492
Attacking the Negatives.....	493
11.5 A Basic Method: Pugh Concept Selection Charts.....	493
Establish the Criteria and Alternatives.....	494
Select a Datum .....	494
Ranking and Assessment .....	495
Alternative Rank Ordering .....	496
Attacking the Negatives.....	496
Iteration and Solution.....	497
Example: Coffee Mill.....	497
11.6 Advanced Discussion: Measurement Theory .....	500
Set Structure of Evaluation.....	500
Ordinal Scales .....	501
Interval Scales .....	506
Ratio Scales .....	511
Extensively Measurable Scales .....	513
11.7 Advanced Method: Numerical Concept Scoring.....	513
Scoring with Interval Scales .....	513
Selection Error Analysis .....	517
Concept Selection with Error Analysis:	
Design of a Cat Litter Box Product.....	527
11.8 A Critique of Design Evaluation Schemes .....	532
11.9 Chapter Summary and "Golden Nuggets" .....	533
References .....	533



---

## Chapter 12: Concept Embodiment535

---

12.1 Chapter Roadmap .....	536
12.2 Overview and Context .....	537
12.3 Basic Methods: Refining Geometry and Layout .....	542
General Process of Product Embodiment .....	543
Embodiment Checklist .....	546
12.4 Advanced Methods: Systems Modeling .....	550
Systems Modeling .....	550
Mechanical Embodiment Principles .....	555
FMEA Method: Linking Fault States to Systems Modeling .....	565
12.5 Case Study: Computer Monitor Stand for a Docking Station .....	571
Summary .....	595
12.6 Summary and “Golden Nuggets” .....	596
References .....	600

---

## Chapter 13: Modeling of Product Metrics603

---

13.1 Chapter Roadmap .....	604
13.2 Introduction: Model Selection by Performance Specifications .....	604
Model Preparation and Selection Method .....	606
Product Application: Model Preparation and Selection .....	607
13.3 Mathematical Modeling versus Physical Prototyping .....	610
Example .....	610
13.4 Advanced Topic: What is a Product Model? .....	614
Informal Models .....	614
Formal Models .....	615
13.5 Constructing Product Models: basic Method .....	622
A Basic Modeling Approach .....	623
A Product Application in Constructing Basic Models: Iced Tea Maker .....	632
13.6 Constructing Product Models: Advanced Method .....	644
Approach .....	645
Method .....	645
13.7. Product Models: Cases .....	648
Electric Wok Product .....	648
Handle Temperature .....	654
Other Metrics to Integrate a Complete Model .....	658
Comments on Design Model Validation .....	660
13.8 Summary and “Golden Nuggets” .....	661
References .....	662

---

## Chapter 14: Design for Manufacture and Assembly663

---

14.1 Chapter Roadmap .....	664
14.2 Overview and Motivation .....	665
14.3 Basic Method: Design Guidelines .....	666
Design for Assembly .....	667
Design for Piece Part Production .....	675
14.4 Advanced Method: Manufacturing Cost Analysis .....	685
Cost Driver Modeling .....	686
Manufacturing Cost Analysis .....	690
14.5 Critique of Design for Assembly Methods .....	709
14.6 Chapter Summary and Golden Nuggets .....	716
References .....	716

---

## Chapter 15: Design for the Environment719

---

15.1 Chapter Roadmap .....	721
15.2 Why DFE? .....	722
15.3 Environmental Objectives .....	722
Global Issues .....	723
Regional and Local Issues .....	724
15.4 Basic DFE Methods: Design Guidelines .....	725
Application: Paper Carrier Design .....	725
15.5 Life Cycle Assessment .....	733
Overview .....	733
Basic Method: AT&T's Environmentally Responsible Product Assessment .....	738
Weighted Sum Assessment Method .....	744
Life Cycle Assessment Method .....	752
15.6 Techniques to Reduce Environmental Impact .....	753
Design to Minimize Material Usage .....	754
Design for Disassembly .....	756
Design for Recyclability .....	764
Design for Remanufacturing .....	767
Design for High-Impact Material Reduction .....	769
Design for Energy Efficiency .....	771
Design to Regulations and Standards .....	771
15.7 Chapter Summary and "Golden Nuggets" .....	777
References .....	778

---

## Chapter 16: Analytical and Numerical Model Solutions 781

---

16.1 Chapter Roadmap .....	782
16.2 Overview and Strategy .....	783
Solution Definition .....	786
Pareto Optimality .....	787
16.3 Basic Method: Spreadsheet Search .....	789
Product Application: Spreadsheet Search for a Toy Rocket Product .....	792
Summary .....	800
16.4 Fundamental Concepts in Optimization .....	801
Constraints .....	801
Objective Functions .....	803
Standard Null Form .....	803
16.5 Advanced Topic: A Discussion of Analytical Formulations .....	805
Unconstrained Problems .....	805
Lagrangians .....	806
16.6 Practical Optimization .....	811
Numerical Search .....	812
Stopping Criteria .....	813
Sensitivity Analysis .....	814
Global Optimality .....	815
Solution Method: Matlab .....	815
Solution Method: Spreadsheet Solvers .....	817
16.7 Product Applications .....	822
Application: Redesign of a TOMY "Push-n-Go" Train .....	822
Application: Electric Wok Product .....	828
16.8 Summary and "Golden Nuggets" .....	830
References .....	831

---

## 17 Physical Prototypes 833

---

17.1 Chapter Roadmap .....	834
17.2 Prototyping Essentials .....	836
What Are Physical Models/Prototypes .....	838
17.3 Types of Prototypes .....	839
Prototypes Goals .....	845
17.4 Uses of Prototypes .....	846
Mock-up Materials and Processes .....	848
Prototyping Processes .....	852
17.5 Rapid Prototyping Techniques .....	854
Rapid Prototyping: A Historical Perspective .....	856

---