SIXTH EDITION

PRODUCT DESIGN AND DEVELOPMENT

Karl T. Ulrich | Steven D. Eppinger

Mc Graw Hill Education

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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

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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.

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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.

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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 Weisshappel, 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.

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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).

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Karl T. Ulrich

Steven D. Eppinger

Brief Contents

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CHAPTER ONE

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

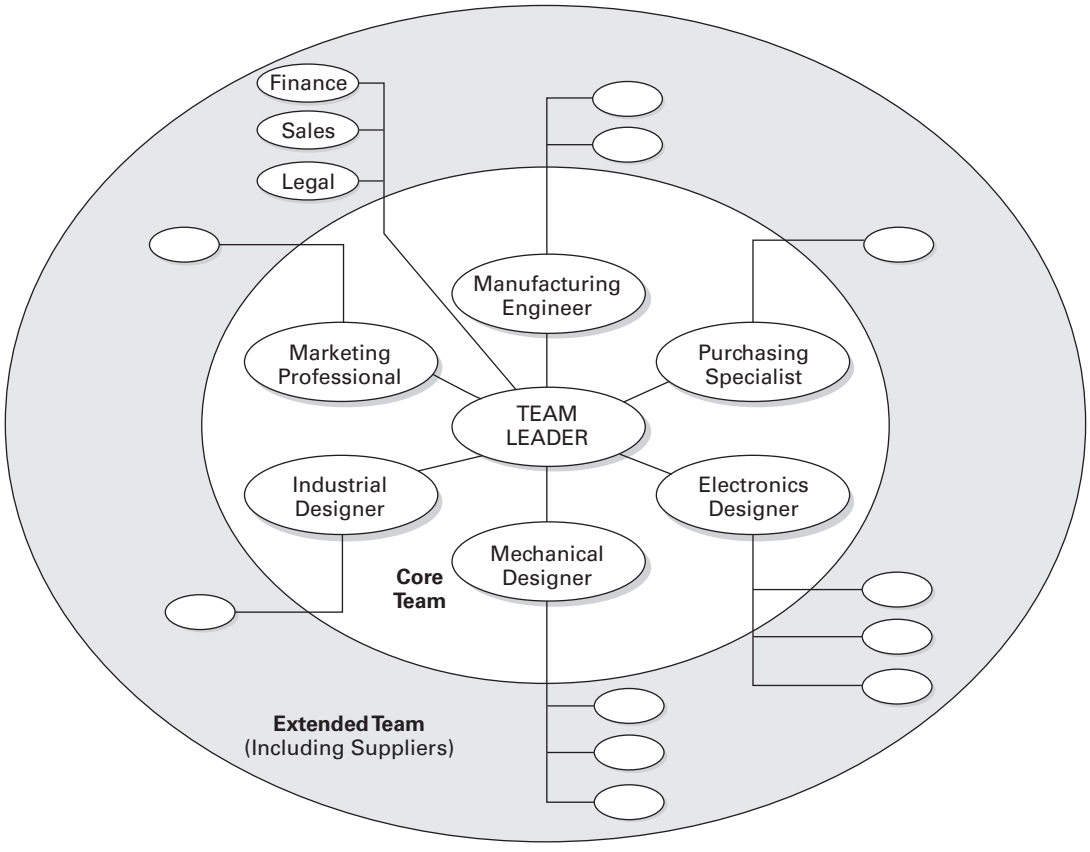

EXHIBIT 1-2 The composition of a product development team for an electromechanical product of modest complexity.

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.

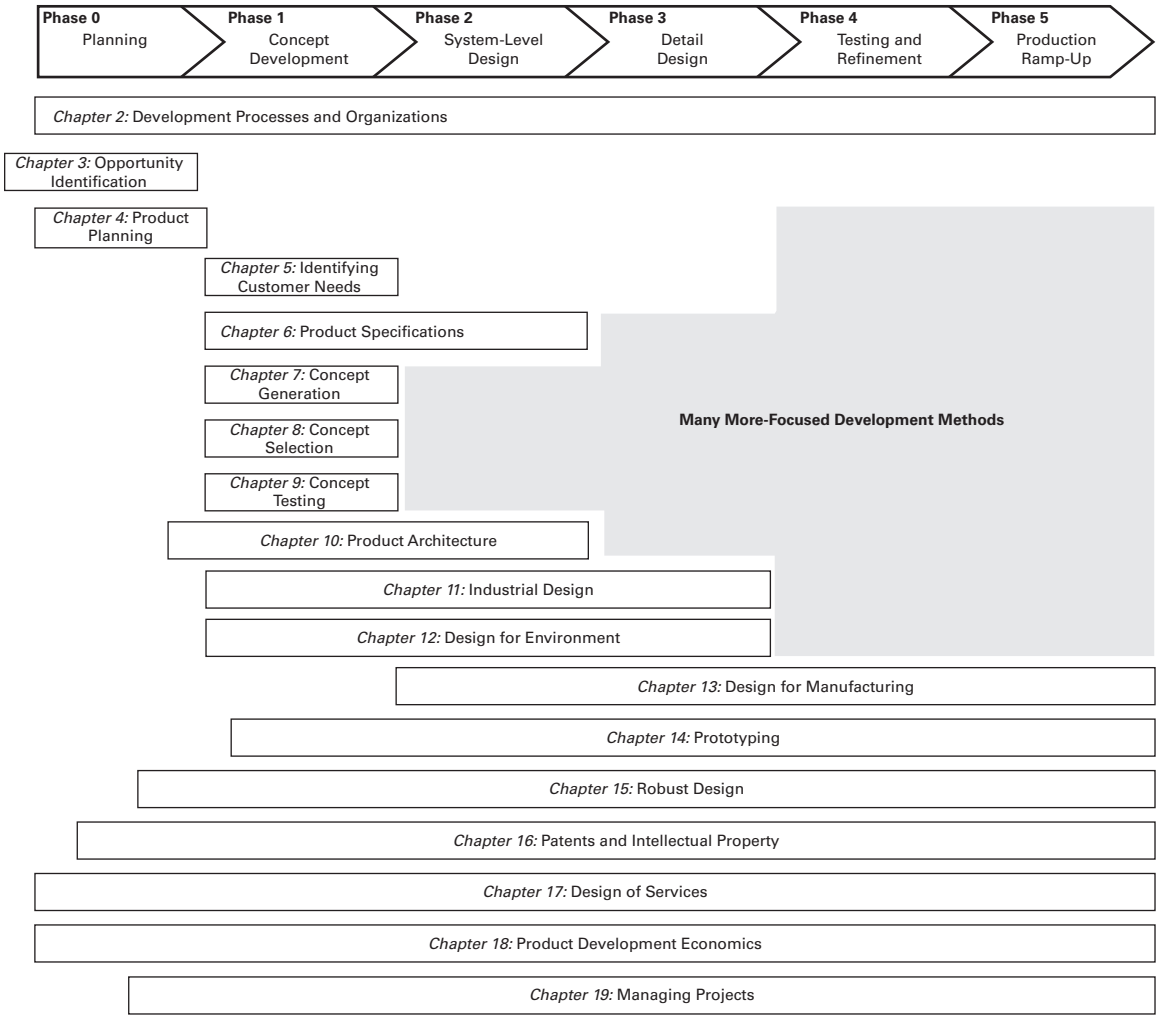

EXHIBIT 1-4 The product development process. The diagram shows where each of the integrative methods presented in the remaining chapters is most applicable.

- 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.