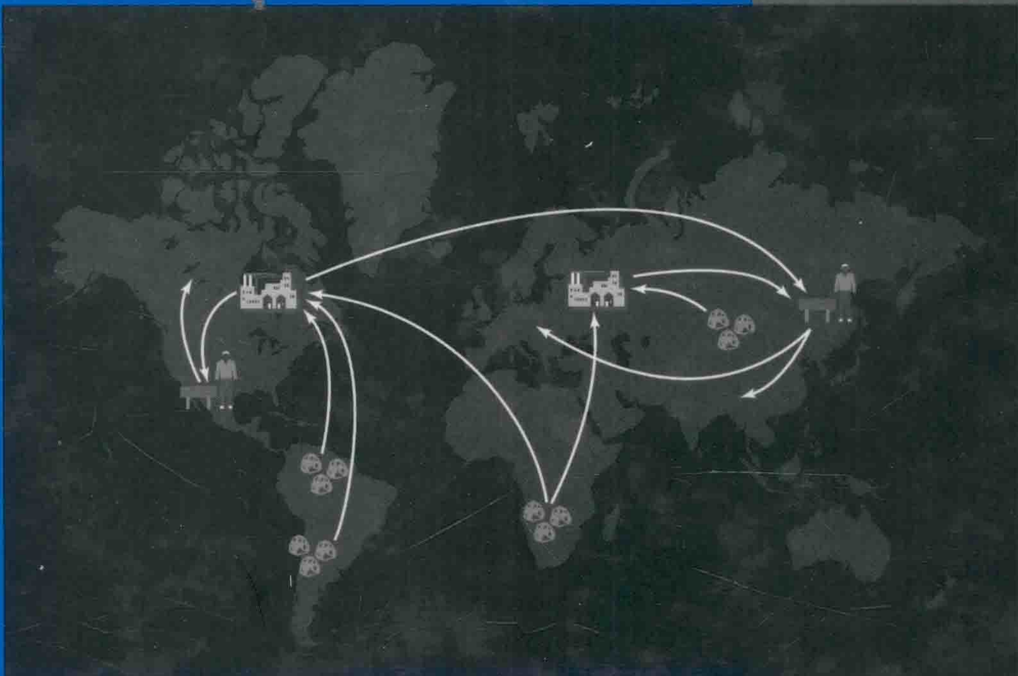
DESIGN AND ANALYSIS OF LEAN PRODUCTION SYSTEMS



Ronald G. Askin

Jeffrey B. Goldberg

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Ronald G. Askin
and
Jeffrey B. Goldberg
The University of Arizona

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To science, engineering, and industry,
for building such a wondrous world;
To family and friends,
for making my world wonderful.

Ron Askin

This book is dedicated to my wife Donna, my children Jessica, Emily, Ben and Brandon, and my mother Bettemae, who love me despite my faults and who gave me the time and space to complete this work.

Jeff Goldberg

Preface

Manufacturing companies are in the business of making, selling, and delivering goods. Considering resource availability, technological feasibility, and customer desires, a corporate strategy guides the design, manufacture, distribution, and service of products. Marketing provides input on what customers want. Engineering converts the data into product designs, and process planners convert those designs into instructions detailing how to manufacture the item. Manufacturing actually produces the products. Supporting these activities are many service functions such as logistics, which procures parts and manages distribution of finished products to customers. This is an ongoing process as products and technologies pass through their normal life cycles. Production planners are responsible for planning the production quantities and timing for each product and for controlling the material, equipment, human, and information resources used in production on a recurring basis.

Understanding the basics of production systems for planning, scheduling, and controlling production quantities and timing has long been a fundamental curricular goal in both industrial engineering and management programs. In business schools, this topic is typically included as part of a broader course in operations management. Industrial engineering programs, on the other hand, tend to delve more deeply into the analytical aspects of production systems, often devoting an entire course to this topic. The related operations management topics of facility layout and location, materials handling, and quality engineering are each presented in their own course. There are many excellent operations management texts designed for undergraduate business students but few texts designed for upper division industrial engineering students and quantitative business programs. Moreover, recent trends such as globalization, lean manufacturing, and integrated supply chain modeling have created new issues and models calling for a new generation of educational resources. This, then, is the motivation for this text. Our objective is to present a current view of production system design and modeling at a level appropriate for upper division undergraduates and beginning graduate students in industrial engineering. The book should also be of interest to graduate students in business schools and to practicing production planners and managers looking for an explanation of new production philosophies. The text fits between the nontechnical conceptual descriptions found in popular publications and the mathematically rigorous presentations found in archival research journals. We present a mix of traditional and modern models, philosophies, and tools. In discussing production systems, we attempt to go beyond the basic *what* questions and provide guidance on *how, when,* and *why* as well. While we emphasize planning models, at times we delve into more hands-on engineering topics such as methods for setup time reduction and fool-proofing of production operations. We attempt to integrate modern philosophies such as time-based competition, lean manufacturing, and supply chain integration into the presentation.

The flow of the book follows the standard production system decision hierarchy. After two introductory chapters, we present three chapters covering the characterization of market demand, long-range strategic planning and partnering, and medium-term aggregate planning. This is followed by a series of chapters describing alternative production-control systems. Separate chapters cover traditional inventory theory, pull control systems, and MRP push systems. A more advanced chapter on multistage planning models concludes this section. This chapter is intended for graduate students. The final section addresses lower-level shop-floor design and operation. We begin with an integration chapter on lean manufacturing concepts. This is followed by a more traditional chapter on shop-scheduling. The final chapter discusses general shop-floor control issues and several special environments. The following describes the book's outline in more detail.

Chapter 1 introduces the student to the business firm. It provides a view of how the various functional areas fit together to conduct the firm's business, explains the scope and role of the production system within the firm, and presents the usefulness and limitations of accounting data as a source for model parameters.

Chapter 2 provides a framework for future study. It provides important definitions and functions and components of production systems. We introduce the basic tradeoffs among inventory, setup cost, and shortages. Many of the basic principles and laws that govern the behavior of production systems, from Little's Law to learning curves, are introduced and illustrated in the context of production operations.

Chapter 3 covers the process of identifying market opportunities. We concentrate on mathematical models for forecasting demand, but we also cover nonquantitative methods and the design and monitoring of forecasting systems. This is a stand-alone chapter and can be skipped without loss of continuity. It is included at this early stage in the text to reinforce the notion that customer demand both empowers and constrains production.

Chapter 4 covers long-range strategic planning and the importance of coordinating information across the supply chain. It discusses key factors for specifying manufacturing strategy, and problems, such as the bull-whip effect, that can occur when information is not freely exchanged. Globalization has led to large-scale, long-term production system design problems that incorporate transportation and cultural considerations. We present a discussion of these issues and an introduction to building decision models in this environment.

Chapter 5 returns to the more traditional set of medium-term aggregate planning models. We emphasize the use of network models where appropriate and the general applicability of linear programming. We discuss the difficulty in explicitly modeling setup considerations. The chapter concludes with a discussion of disaggregation of medium-term family production schedules into a time-phased master production schedule for end items.

Chapter 6 covers reorder point inventory models. The EOQ is explored and extended for time-based criteria, internal manufacturing, constraints, price breaks, and stochastic demand. The chapter presents multiple product and newsvendor problems. The chapter then addresses dynamic demand with uncapacitated and capacitated problems, and illustrates affiliated managerial topics such as ABC classification systems for prioritizing items and exchange curves.

Chapter 7 begins with an explanation of the basic requirements of a production authorization mechanism and poses several alternative approaches, including pull and push. The chapter then emphasizes pull control strategies. It describes various kanban systems and discusses the impact of variance and dynamic behavior. It includes an evaluation and description of CONWIP systems.

Chapter 8 covers push systems, namely, materials requirements planning. It covers the mechanics of the system, along with the advantages and practical limitations. We show how a conceptually simple idea can become complex and break down quickly in a random, continuous environment. The chapter also addresses extensions of MRP to include capacity requirements planning and enterprise integration.

Chapter 9 presents more advanced models for multi-item, multistage planning. It introduces decomposition strategies and modifications to cost structures. We model coordination of batch sizes between stages and competition for capacity. This chapter is intentionally, and probably necessarily, more mathematically sophisticated than the other chapters. As such, it is intended for graduate students.

Chapter 10 discusses recent developments and consolidation of ideas into a lean manufacturing paradigm for eliminating waste and rationalizing procedures in manufacturing. It promotes fool-proofing of processes, setup time reduction, efficient facility layout, reduction of variability, and statistical process control. It also discusses the role of preventive maintenance and the usefulness of flow-charting processes.

Chapter 11 presents shop-floor sequencing and scheduling tools. We progress from single-machine to two-machine to flow-shop to job-shop procedures and discuss makespan, flowtime, and tardiness objectives. The shifting bottleneck procedure is shown to integrate previous modeling approaches. We conclude with an acknowledgment that these traditional, quantitative scheduling approaches often make simplistic assumptions. This leads to a discussion of knowledge-based approaches that attempt to be more realistic.

Chapter 12 ends the text with a collection of relevant scheduling topics. The chapter begins with hierarchical vs. heterarchical control and requirements for manufacturing execution systems, followed by special topics for flow systems, including line-balancing, lot-streaming, and re-entrant flow scheduling. It also covers the importance of tool management and issues that arise in flexible manufacturing systems.

The text may be used in several ways. There is more than enough material for a one-semester course at either the undergraduate or the beginning graduate level. We assume the reader has an understanding of basic operations research and statistics. (An Appendix summarizing linear programming is provided for those students needing a refresher. However, the text emphasizes system design and modeling concepts; it is not a primer on solving mathematical models.) For a first course in production systems for upper division industrial engineering students, we recommend covering the major topics in Chapters 1 through 8 and 10 through 12. At the instructor's discretion, some of the more quantitative topics in the later sections of Chapters 3 through 7 and 11 may be omitted without a loss of continuity. Indeed, it is in this manner that the authors have piloted the text. For undergraduates, we strongly recommend that the topics in Chapter 10 be covered, either in this course or in a related course. However, we would not consider covering topics such as the bottleneck scheduling heuristic in Chapter 11. Many undergraduates will find the bullwhip effect and multifacility models in Chapter 4 rather challenging as well. Several minicase studies are provided in the end of chapter exercises, and we do recommend using these or similar exercises for in-class discussions or group projects.

For graduate courses we recommend including the more sophisticated planning models in the later sections of Chapters 4 through 6 and 11 and in the multistage models of Chapter 9. The instructor may even wish to augment Chapter 4 of the text with the latest readings on supply chain management system design and supply contracts and Chapter 9 with advanced results on multiechelon inventory theory. To do so, however, will require the prerequisite of a solid operations research background. Chapters 10 and 12 may be omitted for students with a background in industrial engineering. Chapter 11 may also be omitted for graduate students if a separate course in scheduling theory will be taken.

Practicing production managers may choose topics based on their specific needs and background. An engineer with responsibility for operations may find that reading the text helps explain the aggregate planning and production-control information systems with which they currently interact. This background will allow them to select pieces from the text for implementing improvements while understanding the ramifications throughout the rest of the system. For the less technically oriented production manager, an understanding of the concepts and underlying principles of lean manufacturing can be gained without digesting all of the mathematical models. For within-plant operations, a review of Chapters 2, 7, and 10 will provide a relatively thorough yet readable description of how to create a lean production system. Details appropriate to the particular site can then be gleaned from study of the relevant topics in Chapters 6, 8, 11, and 12.

The reader may notice some redundancy between chapters. Certain key concepts reappear to reinforce their importance and applicability. Certain equations are reproduced to increase independence between chapters and permit flexibility in how one chooses to sequence the topics.

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Ron Askin
Jeff Goldberg

Contents

Chapter 1

The Industrial Enterprise

Automobiles, telephones, furniture, clothes, and games. These and all the other products we use in our daily lives are designed, manufactured, and delivered with the intention of making a profit for the producer by enhancing the quality of life of the customer. To achieve this result, entrepreneurs must arrange to bring together the necessary financial, technological, information, and human resources to design, implement, and operate the complete manufacturing system. In this text, we concentrate on one aspect of that total manufacturing spectrum, the production planning and control system. For the most part, we will assume the products have already been designed, and the technologies to be used to make these products have been selected. We will focus on the questions of what to make, how much to make, and when to make it. The associated issues of acquiring raw materials, selecting the most efficient production methods, and deciding how to distribute products (get them to the customers) will also be discussed.

Production system design and operation involve managing production resources to meet customer demand. Managing the system requires the development and execution of production schedules detailing how to use resources to convert raw materials into finished products. In addition to employees, machines, tools, and materials, relevant resources include utilities, information, and established procedures. The physical items used and produced by the system are referred to as **inventory.** Inventories are created during the production process and held in the form of raw materials, component parts, subassemblies, and finished products. The scope of the production system includes long-term **planning,** medium-term production **scheduling,** and short-term **control** (dispatching) decisions. The acquisition of new capacity and development of productive employees require planning months in advance of actual usage of these resources. The interface between long-term planning and medium-term scheduling involves setting production goals for each product over the next several weeks. With these objectives set, short-term schedules must detail the sequence of activities for each worker and machine resource for the current day or week. We may be able to develop a plan for these activities, but the stochastic nature of the world as evidenced by machine breakdowns, late deliveries, defective parts, and changes in customer orders requires that we be able to react quickly to changing conditions. If we plan wisely, we will have the flexibility to adapt to the random events of the everyday world.

The reader should keep in mind that many steps are involved in converting raw materials into delivered products. We must typically fabricate many component parts, assemble these parts into the final product, and deliver the product to the point of sale. Fabrication and assembly may occur at a single location or may involve facilities spread around the world. Some companies choose to keep as many activities "in-house" as possible, whereas other companies are little more than production managers, subcontracting out most activities. The first approach allows tighter control, but the latter approach allows groups to focus on what they do best and permits the company to remain flexible and constantly seek the best supplier for each activity. The latter situation has become increasingly more common for complex products as companies seek to cope in a dynamic world.

Throughout the system we must ensure conformance to product quality requirements, and execute the necessary administrative support functions. This becomes increasingly complex when dealing with multiple cultures, measurement systems, languages, and standards. Figure 1.1 illustrates the overall production process from "ore to door" for a large product such as an automobile or computer. At each stage of this process, we incur cost and add value to the product. However, the valid criteria deal not with the individual steps, but with the total cost of the system and state of the final de-

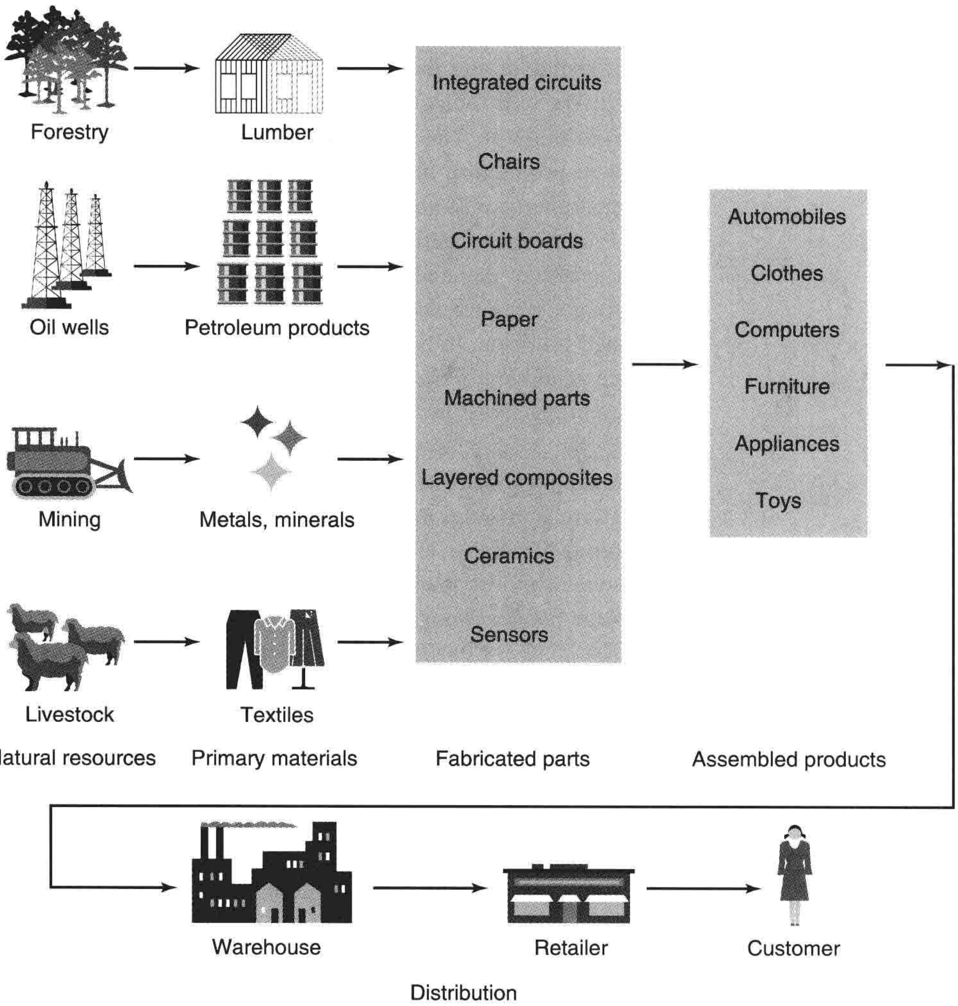

Figure 1.1 The Supply Chain from "Ore to Door"