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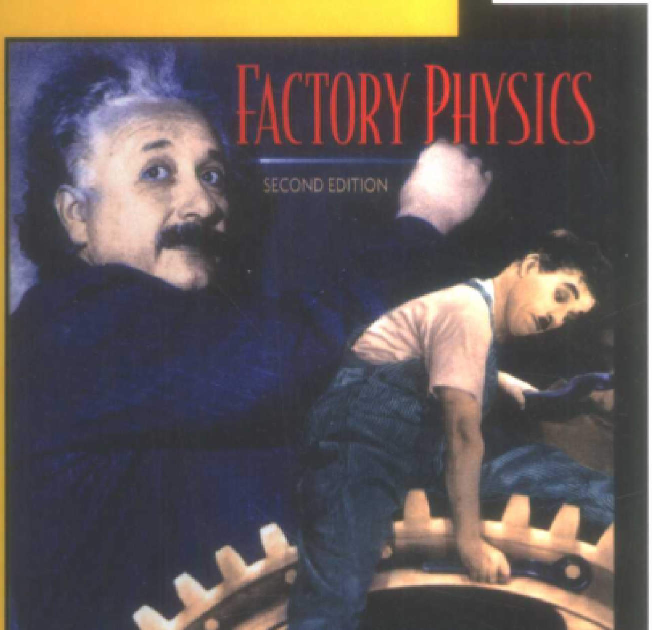
国外大学优秀教材——工业工程系列（影印版）

Wallace J. Hopp　Mark L. Spearman

工厂物理学

——制造企业管理基础

（第2版）



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该书的作者是美国西北大学的Wallace J.Hopp教授和佐治亚理工学院的Mark L.Spearman教授，是生产运作管理领域的知名学者，他们运用自己深厚的物理学中方法论的背景，在多年实践经验和理论研究的基础上，深刻分析与阐述了作业管理中的内在规律，以独特的视角与思维方式对发生在制造企业中的现象和本质进行了透彻的分析和系统的总结，以类似于物理学中定律定理的方式给出了准确的定性描述或定量计算公式。书中不仅对生产管理的发展历史和现状、取得的成就和问题等进行了精辟的总结和分析，而且紧密跟踪当前最先进的方法和技术，并预测了今后的发展趋势。该书不同于一般的教科书，一方面涉猎范围极宽，广泛介绍了生产领域的概念、方法、技术及实践效果；另一方面对重点问题进行了极为深入细致的研究，探究了事物的本质，提出了独到的见解。

该书的起点较高，适合作为“生产系统”和“运作管理”方面的研究生课程的主教材。对本科生教学，可以作为“生产运作管理”、“生产计划与控制”、“设施规划与物流分析”、“质量管理”等课程的主要参考书。

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Factory Physics
Foundations of Manufacturing Management

SECOND EDITION

工厂物理学
——制造企业管理基础

（第2版）

Wallace J. Hopp
Northwestern University
Mark L. Spearman
Georgia Institute of Technology

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Forward

This textbook series is published at a very opportunity time when the discipline of industrial engineering is experiencing a phenomenal growth in China academia and with its increased interests in the utilization of the concepts, methods and tools of industrial engineering in the workplace. Effective utilization of these industrial engineering approaches in the workplace should result in increased productivity, quality of work, satisfaction and profitability to the cooperation.

The books in this series should be most suitable to junior and senior undergraduate students and first year graduate students, and to those in industry who need to solve problems on the design, operation and management of industrial systems.

Gavriel Salvendy

Department of Industrial Engineering, Tsinghua University
School of Industrial Engineering, Purdue University
April, 2002

前　　言

本教材系列的出版正值中国学术界工业工程学科经历巨大发展、实际工作中对工业工程的概念、方法和工具的使用兴趣日渐浓厚之时。在实际工作中有效地应用工业工程的手段将无疑会提高生产率、工作质量、合作的满意度和效果。

该系列中的书籍对工业工程的本科生、研究生和工业界中需要解决工程系统设计、运作和管理诸方面问题的人士最为适用。

加弗瑞尔·沙尔文迪
清华大学工业工程系
普渡大学工业工程学院（美国）
2002 年 4 月

PREFACE

Origins of Factory Physics

In 1988 we were working as consultants at the IBM raw card plant in Austin, Texas, helping to devise more effective production control procedures. Each time we suggested a particular course of action, our clients would, quite reasonably, ask us to explain *why* such a thing would work. Being professors, we responded by immediately launching into theoretical lectures, replete with outlandish metaphors and impromptu graphs. After several semicoherent presentations, our sponsor, Jack Fisher, suggested we organize the essentials of what we were saying into a formal one-day course.

We did our best to put together a structured description of basic plant behavior. While doing this, we realized that certain very fundamental relations—for example, the relation between throughput and WIP, and several other basic results of Part II of this book—were not well known and were not covered in any standard operations management text. Our six offerings of the course at IBM were well received by audiences ranging from machine operators to mid-level managers. During one class, a participant observed, "Why, this is like physics of the factory!" Since both of us have bachelor's degrees in physics and keep a soft spot in our hearts for the subject, the name stuck. Factory physics was born.

Buoyed by the success of the IBM course, we developed a two-day industry course on short-cycle manufacturing, using factory physics as the organizing framework. Our focus on cycle time reduction forced us to strengthen the link between fundamental relations and practical improvement policies. Teaching to managers and engineers from a variety of industries helped us extend our coverage to more general production environments.

In 1990, Northwestern University launched the Master of Management in Manufacturing (MMM) program, for which we were asked to design and teach courses in management science and operations management. By this time we had enough confidence in factory physics to forgo traditional problem-based and anecdote-based approaches to these subjects. Instead, we concentrated on building intuition about basic manufacturing behavior as a means for identifying areas of leverage and comparing alternate control policies. For completeness and historical perspective, we added coverage of conventional topics, which became the basis for Part I of this book. We received enthusiastic support from the MMM students for the factory physics approach. Also, because they had substantial and varied industry experience, they constructively challenged our ideas and helped us sharpen our presentation.

In 1993, after having taught the MMM courses and the industry short course several times, we began writing out our approach in book form. This proved to be a slow process because it revealed a number of gaps between our presentation of concepts and their implementation in practice. Several times we had to step back and draw upon our own research and that of many others, to develop practical discussions of key manufacturing management problem areas. This became Part III of this book.

Factory physics has grown a great deal since the days of our terse tutorials at IBM and will undoubtedly continue to expand and mature. Indeed, this second edition contains several new developments and changes of presentation from the first edition. But while details will change, we are confident that the fundamental insight behind factory physics—that there are principles governing the behavior of manufacturing systems, and understanding them can improve management practice—will remain the same.

Intended Audience

Factory Physics is intended for three principal academic audiences:

1. *Manufacturing management students* in a core manufacturing operations course.
2. *MBA students* in a second operations management course following a general survey course.
3. *BS and MS industrial engineering students* in a production control course.

We also hope that practicing manufacturing managers will find this book a useful training reference and source of practical ideas.

How to Use this Book

After a brief introductory chapter, the book is organized into three parts: Part I, The Lessons of History; Part II, Factory Physics; and Part III, Principles in Practice. In our own teaching, we generally cover Parts I, II, and III in order, but vary the selection of specific topics depending on the course. Regardless of the audience, we try to cover Part II completely, as it represents the core of the factory physics approach. Because it makes extensive use of pull production systems, we make sure to cover Chapter 4 on "The JIT Revolution" prior to beginning Part II. Finally, to provide an integrated framework for carrying the factory physics concepts into the real world, we regard Chapter 13, "A Pull Planning Framework," as extremely important. Beyond this, the individual instructor can select historical topics from Part I, applied topics from Part III, or additional topics from supplementary readings to meet the needs of a specific audience.

The instructor is also faced with the choice of how much mathematical depth to use. To assist readers who want general concepts with minimal mathematics, we have set off certain sections as *Technical Notes*. These sections, which are labeled and indented in the text, present justification, examples, or methodologies that rely on mathematics (although nothing higher than simple calculus). These sections can be skipped completely without loss of continuity.

In teaching this material to both engineering and management students, we have found, not surprisingly, that management students are less interested in the mathematical aspects of factory physics than are engineering students. However, we have not found management students to be averse to mathematics; it is math without a concrete purpose to which they object. When faced with quantitative developments of core manufacturing ideas, these students not only are capable of grasping the math, but also are able to appreciate the practical consequences of the theory.

New to the Second Edition

The basic structure of the second edition is the same as that of the first. Aside from moving Chapter 12 on Total Quality Manufacturing from Part III to Part II, where it has been adapted to highlight the importance of quality to the science of factory physics, the basic content and placement of the chapters are unchanged. However, a number of enhancements have been made, including the following:

- *More problems.* The number of exercises at the end of each chapter has been increased to offer the reader a wider range of practice problems.
- *More examples.* Almost all models are motivated with a practical application before the development of any mathematics. Frequently, these applications are then used as examples to illustrate how the model is used.
- *Web support.* Powerpoint presentations, case materials, spreadsheets, derivations, and a solutions manual are now available on the Web. These are constantly being updated as more material becomes available. Go to http://www.mhhe.com/pom under Text Support for our web site.
- *Inventory management.* The development of inventory models in Chapter 2 has been enhanced to frame historical results in terms of modern theory and to provide the reader with the most sophisticated tools available. Excel spreadsheets and inventory function add-ins are available over the Web to facilitate the more complex inventory calculations.
- *Enterprise resources planning.* Chapters 3 and 5 describe how materials requirements planning (MRP) has evolved into enterprise resources planning (ERP) and gives an outline of a typical ERP structure. We also describe why ERP is not the final solution to the production planning problem.
- *People in production systems.* Chapter 7 now includes some laws concerning the behavior of production lines in which personnel capacity is an important constraint along with equipment capacity.
- *Variability pooling.* Chapter 8 introduces the fundamental idea that variability from independent sources can be reduced by combining the sources. This basic idea is used throughout the book to understand disparate practices, such as how safety stock can be reduced by stocking generic parts, how finished goods inventories can be reduced by "assembling to order," and how elements of push and pull can be combined in the same system.
- *Systems with blocking.* Chapter 8 now includes analytic models for evaluating performance of lines with finite, as well as infinite, buffers between stations. Such models can be used to represent kanban systems or systems with physical limitations of interstation inventory. A spreadsheet for examining the tradeoffs of additional WIP buffers, decreasing variability, and increasing capacity is available on the Web.
- *Sharper variability results.* Several of the laws in Chapter 9, The Corrupting Influence of Variability, have been restated in clearer terms; and some important new laws, corollaries, and definitions have been introduced. The result is a more complete science of how variability degrades performance in a production system.
- *Optimal batch sizes.* Chapters 9 and 15 extend the factory physics analysis of the effects of batching to a normative method for setting batch sizes to minimize cycle times in multiproduct systems with setups and discuss implications for production scheduling.

- *General CONWIP line models.* Chapter 10 now includes an analytic procedure for computing the throughput of a CONWIP line with general processing times. Previously, only the case with balanced exponential stations (the practical worst case) was analyzed explicitly. These new models are easy to implement in a spreadsheet (available on the Web) and are useful for examining inventory, capacity, and variability tradeoffs in CONWIP lines.
- *Quality control charts.* The quality discussion of Chapter 12 now includes an overview of statistical process control (SPC).
- *Forecasting.* The section on forecasting has been expanded into a separate section of Chapter 13. The treatment of time series models has been moved into this section from an appendix and now includes discussion of forecasting under conditions of seasonal demand.
- *Capacitated material requirements planning.* The MRP-C methodology for scheduling production releases with explicit consideration of capacity constraints has been extended to consider material availability constraints as well.
- *Supply chain management.* The treatment of inventory management is extended to the contemporary subject of supply chain management. Chapter 17 now deals with this important subject from the perspective of multiechelon inventory systems. It also discusses the "bullwhip effect" as a means for understanding some of the complexities involved in managing and designing supply chains.

W.J.H.
M.L.S.

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Since our thinking has been influenced by too many people to allow us to mention them all by name, we offer our gratitude (and apologies) to all those with whom we have discussed factory physics over the years. In addition, we acknowledge the following specific contributions.

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Factory Physics Principles

Law (Little's Law):

$$\text{WIP} = \text{TH} \times \text{CT}$$

Law (Best-Case Performance): *The minimum cycle time for a given WIP level w is given by*

$$\text{CT}_{\text{best}} = \begin{cases} T_0 & \text{if } w \leq W_0 \\ \dfrac{w}{r_b} & \text{otherwise} \end{cases}$$

The maximum throughput for a given WIP level w is given by

$$\text{TH}_{\text{best}} = \begin{cases} \dfrac{w}{T_0} & \text{if } w \leq W_0 \\ r_b & \text{otherwise} \end{cases}$$

Law (Worst-Case Performance): *The worst-case cycle time for a given WIP level w is given by*

$$\text{CT}_{\text{worst}} = wT_0$$

The worst-case throughput for a given WIP level w is given by

$$\text{TH}_{\text{worst}} = \frac{1}{T_0}$$

Definition (Practical Worst-Case Performance): *The practical worst-case (PWC) cycle time for a given WIP level w is given by*

$$\text{CT}_{\text{PWC}} = T_0 + \frac{w-1}{r_b}$$

The PWC throughput for a given WIP level w is given by

$$\text{TH}_{\text{PWC}} = \frac{w}{W_0 + w - 1} r_b$$

Law (Labor Capacity): *The maximum capacity of a line staffed by n cross-trained operators with identical work rates is*

$$\text{TH}_{\max} = \frac{n}{T_0}$$

Law (CONWIP with Flexible Labor): *In a CONWIP line with n identical workers and w jobs, where $w \geq n$, any policy that never idles workers when unblocked jobs are available will achieve a throughput level* $\text{TH}(w)$ *bounded by*

$$\text{TH}_{\text{CW}}(n) \leq \text{TH}(w) \leq \text{TH}_{\text{CW}}(w)$$

where $\text{TH}_{\text{CW}}(x)$ *represents the throughput of a CONWIP line with all machines staffed by workers and x jobs in the system.*

Law (Variability): *Increasing variability always degrades the performance of a production system.*

Corollary (Variability Placement): *In a line where releases are independent of completions, variability early in a routing increases cycle time more than equivalent variability later in the routing.*

Law (Variability Buffering): *Variability in a production system* will *be buffered by some combination of*

1. *Inventory*
2. *Capacity*
3. *Time*

Corollary (Buffer Flexibility): *Flexibility reduces the amount of variability buffering required in a production system.*

Law (Conservation of Material): *In a stable system, over the long run, the rate out of a system will equal the rate in, less any yield loss, plus any parts production within the system.*

Law (Capacity): *In steady state, all plants* will *release work at an average rate that is strictly less than the average capacity.*

Law (Utilization): *If a station increases utilization without making any other changes, average WIP and cycle time will increase in a highly nonlinear fashion.*

Law (Process Batching): *In stations with batch operations or with significant changeover times:*

1. *The minimum process batch size that yields a stable system may be greater than one.*
2. *As process batch size becomes large, cycle time grows proportionally with batch size.*
3. *Cycle time at the station will be minimized for some process batch size, which may be greater than one.*

Law (Move Batching): *Cycle times over a segment of a routing are roughly proportional to the transfer batch sizes used over that segment, provided there is no waiting for the conveyance device.*

Law (Assembly Operations): *The performance of an assembly station is degraded by increasing any of the following:*

1. *Number of components being assembled.*
2. *Variability of component arrivals.*
3. *Lack of coordination between component arrivals.*

Definition (Station Cycle Time): *The average cycle time at a station is made up of the following components:*

$$\begin{aligned}\text{Cycle time} &= \text{move time} + \text{queue time} + \text{setup time} + \text{process time}\\ &\quad + \text{wait-to-batch time} + \text{wait-in-batch time}\\ &\quad + \text{wait-to-match time}\end{aligned}$$

Definition (Line Cycle Time): *The average cycle time in a line is equal to the sum of the cycle times at the individual stations, less any time that overlaps two or more stations.*

Law (Rework): *For a given throughput level, rework increases both the mean and standard deviation of the cycle time of a process.*

Law (Lead Time): *The manufacturing lead time for a routing that yields a given service level is an increasing function of both the mean and standard deviation of the cycle time of the routing.*

Law (CONWIP Efficiency): *For a given level of throughput, a push system will have more WIP on average than an equivalent CONWIP system.*

Law (CONWIP Robustness): *A CONWIP system is more robust to errors in WIP level than a pure push system is to errors in release rate.*

Law (Self-Interest): *People, not organizations, are self-optimizing.*

Law (Individuality): *People are different.*

Law (Advocacy): *For almost any program, there exists a champion who can make it work—at least for a while.*

Law (Burnout): *People get burned out.*

Law (Responsibility): *Responsibility without commensurate authority is demoralizing and counterproductive.*

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