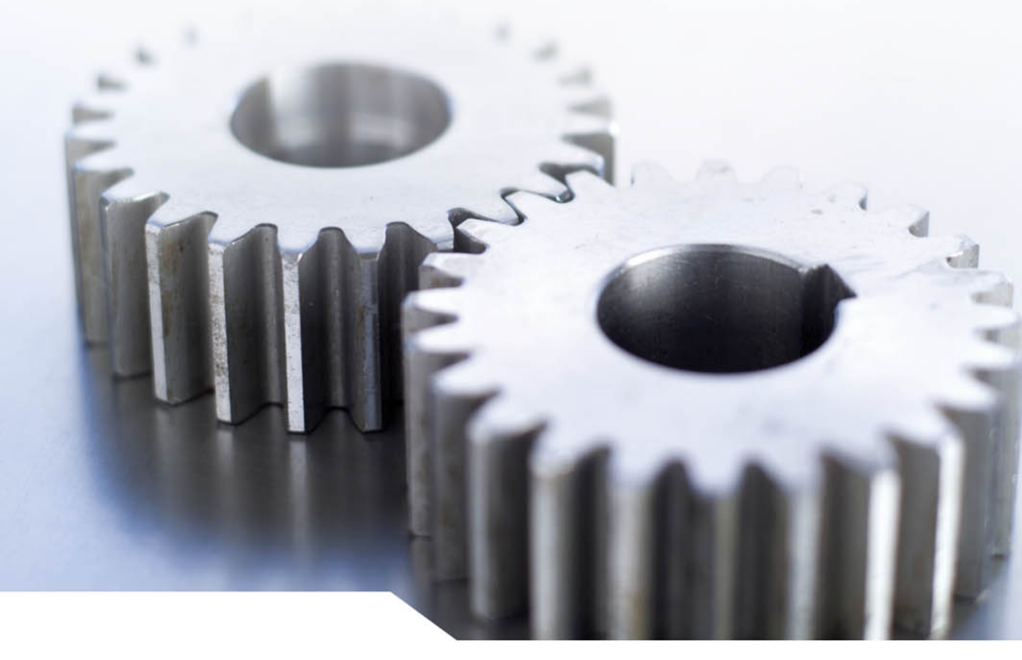
INTRODUCING MANUFACTURING'S
THIRD DIMENSION

OPTIMIZING FACTORY PERFORMANCE

Cost-Effective Ways to Achieve Significant and Sustainable Improvement



JAMES P. IGNIZIO, Ph.D.

OPTIMIZING FACTORY PERFORMANCE

This page intentionally left blank

OPTIMIZING FACTORY PERFORMANCE

Cost-Effective Ways to Achieve Significant and Sustainable Improvement

JAMES P. IGNIZIO, PH.D.

New York Chicago San Francisco Lisbon London
Madrid Mexico City Milan New Delhi San Juan
Seoul Singapore Sydney Toronto

The McGraw-Hill Companies

Copyright © 2009 by The McGraw-Hill Companies, Inc. All rights reserved. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

ISBN: 978-0-07-163286-7

MHID: 0-07-163286-7

The material in this eBook also appears in the print version of this title: ISBN: 978-0-07-163285-0, MHID: 0-07-163285-9.

All trademarks are trademarks of their respective owners. Rather than put a trademark symbol after every occurrence of a trademarked name, we use names in an editorial fashion only, and to the benefit of the trademark owner, with no intention of infringement of the trademark. Where such designations appear in this book, they have been printed with initial caps.

McGraw-Hill eBooks are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. To contact a representative please e-mail us at bulksales@mcgraw-hill.com.

Disclaimer

The 15 case studies in this book represent a work of fiction. Names, characters, places, and incidents are either the product of the author's imagination or are used fictitiously, and any resemblance to actual persons, living or dead, business establishments, events, or locales is entirely coincidental.

TERMS OF USE

This is a copyrighted work and The McGraw-Hill Companies, Inc. ("McGraw-Hill") and its licensors reserve all rights in and to the work. Use of this work is subject to these terms. Except as permitted under the Copyright Act of 1976 and the right to store and retrieve one copy of the work, you may not decompile, disassemble, reverse engineer, reproduce, modify, create derivative works based upon, transmit, distribute, disseminate, sell, publish or sublicense the work or any part of it without McGraw-Hill's prior consent. You may use the work for your own noncommercial and personal use; any other use of the work is strictly prohibited. Your right to use the work may be terminated if you fail to comply with these terms.

THE WORK IS PROVIDED "AS IS." McGRAW-HILL AND ITS LICENSORS MAKE NO GUARANTEES OR WARRANTIES AS TO THE ACCURACY, ADEQUACY OR COMPLETENESS OF OR RESULTS TO BE OBTAINED FROM USING THE WORK, INCLUDING ANY INFORMATION THAT CAN BE ACCESSED THROUGH THE WORK VIA HYPERLINK OR OTHERWISE, AND EXPRESSLY DISCLAIM ANY WARRANTY, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. McGraw-Hill and its licensors do not warrant or guarantee that the functions contained in the work will meet your requirements or that its operation will be uninterrupted or error free. Neither McGraw-Hill nor its licensors shall be liable to you or anyone else for any inaccuracy, error or omission, regardless of cause, in the work or for any damages resulting therefrom. McGraw-Hill has no responsibility for the content of any information accessed through the work. Under no circumstances shall McGraw-Hill and/or its licensors be liable for any indirect, incidental, special, punitive, consequential or similar damages that result from the use of or inability to use the work, even if any of them has been advised of the possibility of such damages. This limitation of liability shall apply to any claim or cause whatsoever whether such claim or cause arises in contract, tort or otherwise.

Downloaded by [Bank for Agriculture and Agricultural Cooperatives 202.94.73.131] at [11/05/15]. Copyright © McGraw-Hill Global Education Holdings, LLC. Not to be redistributed or modified in any way without permission.

The author dedicates this book to
the memory of his mother:
Nora Ignizio

This page intentionally left blank

Après moi,
le déluge.

motto of the Royal Air Force
617 Squadron: "The Dambusters"

This page intentionally left blank

Contents

Foreword

This book takes a major step forward in establishing a science of manufacturing systems. Dr. Ignizio begins the book by citing three principal causes of poor performance of manufacturing systems; namely, complexity, variability, and lackluster leadership. He then proceeds to lay out a prescription for overcoming these obstacles based on the three dimensions of manufacturing: (1) the *first dimension of manufacturing,* which focuses on the physical dimensions of the factory itself, including its location, size, layout, the processes it employs, and the products it manufactures; (2) the *second dimension of manufacturing,* which addresses the physical components housed within the factory; and (3) the *third dimension of manufacturing,* which encompasses the protocols used to manage the factory, with the objective of increasing productive capacity, reducing cycle time, and eliminating uncertainty. In his own words, Ignizio seeks to "fill the gap between the theory and practice of factory performance improvement." In filling that gap, the author advances the science of manufacturing systems in ways no other author has even attempted. This book is replete with developments that would, in themselves, merit a series of archival journal articles.

The material presented in this book describes, discusses, and illustrates the politics, art and science of manufacturing. It identifies the factors that hamper optimum performance—the aforementioned complexity, variability, and lackluster leadership—and describes methods by which the debilitating influences of these factors can be reduced or eliminated. Another purpose of the book is to introduce previously unpublished methods and concepts for the improvement of factory performance, as well as that for supply chain, business processes, and organizational performance.

It is these newly introduced methods and techniques that represent the core concepts of this book. They include such topics as:

- Improved metrics for the measurement and comparison of factory performance
- Optimal allocation of the maintenance function to factory workstations
- Methods for the de-clustering of factory starts or preventive maintenance activities
- Contrasting “workstation-centric and process step-centric” perspectives of factory performance
- The so-called “Waddington Analysis,” a methodology for improving both operations and maintenance performance

These are novel concepts developed by the author over the last two decades, and they represent a significant departure from any of the other prominent texts in the field of manufacturing systems.

A brief summary of this book will uncover its uniqueness. Chapters 1 and 2 introduce the reader to the purposes and terminology of the book. Chapter 3 gives two very useful definitions of a factory:

1. A factory is a processing network through which jobs and information flow and within which events take place.
2. A factory is a nonlinear, dynamic, stochastic system with feedback.

It is these two definitions that tell the reader the perspective from which the author proposes to develop an entire science of manufacturing. In Chapter 4 Ignizio introduces the use of a simple spreadsheet simulation model of a 12-workstation factory for the purpose of evaluating the performance of a factory in two dimensions; i.e., the first two dimensions of manufacturing given above. He demonstrates that it is more effective, and far less costly, to balance the production line than to acquire additional machines (the second dimension) or expand the factory (the first dimension). In Chapter 5 the author introduces the three fundamental equations of manufacturing performance that are applied to running a factory. He demonstrates how variability in process step cycle time affects overall factory performance. Chapter 6 focuses on running a factory in three dimensions. Here the author demonstrates that it is easier and far less costly to invoke the third dimension of manufacturing (i.e., increasing the effective process rates of the several workstations, reducing the variability of factory starts, or reducing the variability of process times for one or more workstations) than to increase the physical capacity of the factory or any workstation. Chapter 7 introduces three factory performance curves that afford the opportunity to evaluate factory performance, while Chapter 8 describes a variety of factory performance metrics, including some that are widely used but nonetheless flawed. In summary, the first eight chapters serve to describe the fundamental methodology for analyzing manufacturing systems.

Chapter 9 sets the stage for the remainder of the book. Chapters 10 through 15 illustrate how the application of the science-based principles discussed in Chapters 1 through 8 can lead to improved production line performance. These principles are dedicated to mitigating complexity, reducing variability, and gaining a more accurate determination of workstation and factory capacity. Chapter 10 focuses on reducing the complexity of the protocols employed within the factory. Chapter 11 discusses ways to reduce variability. Chapter 12 presents a simple example—using a modification of the 12-workstation factory model introduced in Chapter 4—to illustrate how applying the methodology introduced in earlier chapters will substantially improve factory performance. Chapter 13 shows how to determine a true upper bound on workstation and factory capacity. Chapter 14 fashions a systematic approach for developing a vision, a plan, a work organization, and the leadership necessary for implementing all of these elements.

Little has been made here of the third demon of manufacturing systems management, that of "lackluster leadership." Dr. Ignizio employs an interesting and highly effective device to portray the disastrous influence of lackluster leadership on factory performance by using a series of chapter-ending case studies. Actually, these 15 case studies are themselves chapters in the continuing saga of several figures in various levels of management in a fictional manufacturing enterprise, "Muddle, Inc" (the very name speaks to the many tawdry management practices that inhibit effective factory performance in this company). I gave these case studies to my class in a graduate course in engineering management, with the assignment to write a series of four essays on how the managers and engineers of Muddle, Inc. would benefit from a basic understanding of the management concepts in my course. Reading four essays from each of the 60 students was an onerous task, but I was gratified that my students were able to quickly identify the flaws in Muddle's management practices and recommend appropriate organizational and policy changes.

Widespread adoption of Dr. Ignizio's book would do much to improve factory management in the United States and around the world. More than a century ago, Frederick W. Taylor—the father of scientific management—wrote that three groups of people should, ideally, share in the financial benefits derived from improved productivity; namely, workers, management, and owners. The industrial world would be a better place if twenty-first century managers were adherents of Ignizio's philosophy of manufacturing management and practiced the precepts that Taylor advanced so long ago.

Professor William E. Biles, Ph.D.
Department of Industrial Engineering University of Louisville

Preface

Nations with the resolve and skill to produce high-quality goods, and which do so efficiently, prosper and grow. Manufacturing is a crucial component of the foundation that maintains the security, health, and wealth of any country. One of the most important measures of manufacturing performance is that of factory cycle time—the time between the introduction of a job into the factory and its completion. Firms whose factories deliver the right product to the right customer at the right time ultimately dominate those that are merely runner-ups. Manufacturers that are fast and agile will be the survivors in the highly competitive world of making "things."

Over the past 50 years, more than 50 management and manufacturing fads and fashions have been proposed for the achievement of improved organizational and factory performance. Almost all have failed to live up to their hype. Today, in fact, the principal performance measure of a factory—load-adjusted cycle-time efficiency—is either the same or marginally better than that of factories of a half-century ago. While the goods produced by factories have grown in sophistication and have, in general, improved in terms of reliability, the time spent in their actual production continues to represent but a small fraction (on the order of 5 to 20 percent) of the total time they are in the factory. Consequently, there is enormous room for improvement in the running of almost any factory—in any country.

While methods such as *lean manufacturing, reengineering, theory of constraints,* and *Six Sigma* may—*when and if applied properly*—improve factory performance, they represent just one part of the solution. To achieve significant and, in particular, sustainable performance improvement, an approach that balances the art and science of manufacturing while taking into account the culture and politics of the organization must be employed. The attainment of this balanced approach will require more than lean, more than Six Sigma and—when implemented—will result in much more than what was once considered an acceptable level of factory performance. It will necessitate, however, a paradigm shift—a shift akin to that which occurred when the third dimension of warfare was realized by means of exploitation of the airplane.

In this book I examine the importance of manufacturing, its history, and its terminology. I show that to improve factory performance cost-effectively, one must venture beyond the traditional first and second dimensions of manufacturing—the dimensions that rely almost exclusively on physical changes to the factory or its components. Instead, the most effective approach to improved factory performance may be achieved by means of the third dimension of manufacturing—the dimension involving changes to factory operating and maintenance protocols (i.e., the strategies and tactics employed to actually run a factory).

I introduce the operating and maintenance protocols best suited for effectively dealing with the three main enemies of factory performance, that is, the obstacles of complexity, variability, and lackluster leadership. While the approaches illustrated have a scientific basis and rely on the three fundamental equations and one fundamental model of manufacturing, the material is presented in such a way as to minimize the need for expertise in mathematics beyond that of a high school student. However, those who wish to avoid virtually all mathematics may do so by covering just Chapters 1 and 2, Chapters 7 through 12, and Chapters 14 and 15.

Finally, as a means to indicate the impact of organizational politics and dysfunctional cultures, case studies (of a strictly fictional nature) appear at the end of each chapter. In these vignettes, the trials and tribulations of employees of the fictional Muddle Corporation are observed.

James P. Ignizio
Placitas, New Mexico

Acknowledgments

The author wishes to acknowledge the reviewing efforts and subsequent input provided by Laura Burke and Bill Biles. He also wants to express his appreciation to Judy Bass, senior editor, and Daina Penikas, senior editing supervisor, of McGraw-Hill for their faith in and assistance with the production of the book you hold in your hands. Finally, thanks are given to all those who helped to educate me in the complexities and politics of real world manufacturing. Most prominently figuring in that endeavor were Gene Minder, Ben Niebel, Inyong Ham, Katsundo Hitomi, Ken Knott, Jonathan Matthews, Peter Tag, Mike Gannon, and Sam Mouck.

This page intentionally left blank

OPTIMIZING
FACTORY
PERFORMANCE

This page intentionally left blank

CHAPTER 1

Introduction

MANUFACTURING AND ITS IMPORTANCE

At one time in America's history, manufacturing was considered the nation's primary mission. The period from 1800 until 1932 was, in fact, denoted as the time of the "American system of manufacturing" (Hounshell, 1984). Industrial tourists from all over the world (and particularly Japan) traveled to America in an attempt to learn and copy the methods employed.

Beginning in the latter half of the twentieth century, the emphasis in America on making things was seemingly changed to that of making deals. Students who would, in the past, have sought degrees in science and engineering shifted their attention to careers in business, banking, politics, venture capital, law, finance, and other components of the service sector. American manufacturing firms, mostly in an attempt to reduce their costs—and mitigate the impact of regulations—either outsourced much of their production or moved entire factories to other nations. Included among the U.S. firms that have either (1) moved all or the majority of their production elsewhere, or (2) are considering such a move, or (3) actually have closed operations in the United States are Ford, Chrysler, Levi-Strauss, Bethlehem Steel, Boeing Commercial Aircraft, IBM's Personal Computers, RCA, Schwinn Bicycles, Maytag, OshKosh, Carrier Air Conditioning, several semiconductor manufacturing firms, approximately 96 percent of all clothing producers, and many of this nation's manufacturers of wood furniture, lighting fixtures, batteries, and household appliances.

Not only did the manufacturers of items for household consumption move elsewhere, so did much of the production critical to national defense. Just a few of those vital products that are now wholly or primarily outsourced include

- *Bearings.* These are key components to everything from automobiles to spy satellites.
- *Metal castings.* China and other countries are now the major suppliers to the U.S. military.
- *Roller cutters.* Only one firm is left in the United States that produces roller cutters for armored plate or heavy steel.
- *Chemicals.* The United States now must depend on a foreign company's facilities to supply the chemicals used for binding windows and aluminum panels to aircraft.
- *Military clothing.* As one example, an order actually was placed with Chinese manufacturers to produce the U.S. military's black berets (this order was later recalled after protests were raised).

Until quite recently, conventional wisdom held that the "smart thing to do" was for a firm to either outsource a portion of its operations or move entire factories to lower-cost developing nations. Management gurus recommended such measures, and Wall Street analysts quickly upgraded the ratings of the firms that followed this advice. The long-term impact of such decisions, however, was either ignored or not comprehended. More specifically, plans apparently were made in the naive belief that "tomorrow will be exactly like today." The illusion under which decisions were made was that in the developing nations to which factories were being moved

- Labor costs would remain low.
- Regulations (e.g., construction, financial reporting, and environmental) would remain loose to nonexistent.
- The value of the dollar would remain stable.
- Shipping costs would remain constant.
- The cost of oil, natural gas, and other commodities would not increase appreciably.
- The economy would remain constant (e.g., inflation would remain low and there would be no economic meltdown).

Beginning in 2008, manufacturing firms discovered that the premises for many of their decisions as to outsourcing and relocation of factories were no longer valid. As developing nations became wealthier—mostly by means of increasing their manufacturing sector—labor costs rose, regulations were imposed or strengthened, and the cost of production increased. The impact of these changes on the economics of outsourcing was magnified by the decrease in the value of the U.S. dollar coupled with an increase in the cost of oil (along with most other basic resources).

Suddenly, the benefits of outsourcing and moving factories to developing nations were either substantially reduced or simply vanished. As just one reason for this change, the cost of shipping a 40-foot container from Shanghai to San Diego increased by 150 percent from 2000 to 2008.

The developing nations to which much of America's manufacturing was outsourced now have their own problems. With a rise in *their* standard of living and subsequent increase in *their* cost of labor and a tightening of *their* regulations, they have begun to outsource their own manufacturing efforts to even less expensive countries. One can only wonder when the outsourcing cycle will end.

In the United States, some of the firms that have maintained at least some manufacturing capacity and capability are now busy reactivating moth-balled factories and rehiring production personnel. Some of the advantages of maintaining manufacturing capabilities in one's home country, wherever that may be, include

- Reduced transportation costs for shipment to home-country customers
- Mitigation of the risk of the unauthorized transfer of intellectual property
- Maintenance of a trained, experienced home-country workforce
- Maintenance of state-of-the-art factories within the home country
- Reduction of the threat to national security if a need arises to produce critical products locally

There's yet another reason to maintain, to whatever degree possible, manufacturing within one's own country—economics. There are only four economic sectors that generate material wealth:

- Agriculture
- Mining
- Manufacturing
- Construction

Other sectors, such as service and trade, only distribute wealth. It has been estimated, in fact, that manufacturing within the United States generates $1.37 of additional economic activity for every $1 of goods produced. This is more than any other economic sector. Manufacturing is also a country's source—often its primary source—of innovation. In the United States, for example, nearly 60 percent of all private-sector research and development is conducted by manufacturers (Popkin and Kobe, 2006).

Despite the advantages of manufacturing in one's home country, there remains a belief that outsourcing will always reduce costs. This is simply not the case. Factories in America, as well as elsewhere, are, for the most part, not nearly as efficient as they could be—and should be. While a massive amount of money is spent on development of new products, facilities, and machines, little regard is given to the importance of manufacturing protocols—the policies and procedures employed to actually run a factory. While this deficiency has been mitigated in part by the introduction of such concepts as lean manufacturing, far more improvement in factory performance is possible by means of taking an even broader view of factory protocols and, in particular, the crucial importance of fast cycle time.

Unfortunately, in both the United States and elsewhere neither the art nor the science of manufacturing is fully exploited or appreciated. Consequently, when faced with the need to improve factory performance, the typical reaction is to build bigger, more expensive factories and purchase bigger, more expensive, and more complex machines—and perhaps do so somewhere else than in one's home country. As we shall see, there is a better way. First, however, it may be of benefit to provide some background and details that should serve to explain the motivation for this book.

BACKGROUND AND MOTIVATION

By way of introduction and as a means to explain the rationale behind certain opinions expressed in the text (some of which may be viewed, in some quarters, as controversial), allow me to provide a brief overview of my background and experience. This may serve as both an explanation and a warning.

I was a university professor for 30 years. During that time, I also served as a consultant to more than 100 firms and governmental agencies—mostly for assistance with or direction of the improvement of factory, supply-chain, business process, and organizational performance. Prior to and following my academic career, I was employed in industry as a senior-level manager (five years) and internal consultant and scientific advisor (six years). While I don't claim to have seen it all, I've seen a lot.

Over that period (i.e., of more than four decades), I came to the conclusion that courses in manufacturing and management (including those in production management, operations management, management science, manufacturing engineering, industrial engineering, and MBA programs), as taught in universities or via the training programs offered to industry and government by management gurus and motivational speakers, do not necessarily provide an adequate, comprehensive, or even accurate portrait of the environment faced in industry, government, or any real-world organization. In too many cases, the picture presented is naive, overly simplistic, and subsequently limited in scope and value. Even the case studies presented in most courses and textbooks fail to reflect the complexity, confusion, and outright chaos one typically faces in the real world.

Students in engineering, science, and business programs receive an education that often ignores the most important aspects of real-world problems. But those are the factors that must be understood and dealt with effectively if the full potential of the organization is to be achieved. If not, any remedies that are implemented most likely will achieve, at best, only transient improvements—akin to the counterintuitive effect observed in the famous Hawthorne experiments (Roethlisberger and Dickson, 1939).

The most important finding in the Hawthorne experiments was identification of the *Hawthorne effect*. In brief, it was observed that the behavior of people changes when they recognize—consciously or subconsciously—they are part of an "experiment." This may explain why so many pilot studies or full-blown implementations of management fads and fashions result in a transient improvement in performance, only to be followed (weeks, months, or even a year or more afterward) by a disappointing return to the status quo. The Hawthorne effect points out the danger in relying on the short-term impact of any method implemented for the purpose of any type of performance improvement. Even a seriously flawed concept may, when first introduced into the organization or factory, produce a short-lived improvement in performance.

Ignorance of the Hawthorne effect, as well as a failure to recognize other symptoms of a dysfunctional culture (and its accompanying dysfunctional policies, procedures, and values), is exhibited in those organizations in which one management fad after another is embraced, implemented, and ultimately, abandoned. Such routine failures are in part a consequence of deficiencies in both the classes taught in universities and the training courses provided within business and government. When these shortcomings are combined with a short-term planning horizon and a desire for quick and easy solutions by management (particularly, alas, American management), the result is depressingly predictable—disappointing results and lowered morale.

To illustrate the point, consider the skills required to achieve a significant and sustainable improvement in the operation of a real-world factory. Industrial and manufacturing engineering students, for example, are schooled in a number of topics, some of which serve as an important and necessary basis for a (limited) understanding of the science of manufacturing. Rarely, however, is time devoted to two other equally important (and, in some cases, more important) aspects of manufacturing. Yet these factors can make or break any plan for factory performance improvement.

The missing ingredients are the politics and art that must be considered, understood, and dealt with if any method for improved factory, supply-chain, business process, or organizational performance is to be accepted, implemented, and (equally if not more important) sustained. More specifically, without adequate appreciation of the politics and art associated with performance improvement, it is doubtful that the student, on entering the workforce, will have the positive influence on either organizational or factory performance that one would (and should) expect.

It is also my belief that the typical science, engineering, or business school graduate may not have an adequate appreciation of certain of the unique features of the fundamentals required to obtain significant and sustainable improvement in factories, supply chains, business processes, or the organization as a whole. This is particularly true with regard to an understanding and appreciation of the role played by complexity and variability, two of the three primary enemies of performance that must be dealt with if measurable and sustainable improvement is to be ensured.

Complexity, for example, is rarely discussed to the degree it deserves in either academia or industry despite its pervasive negative impact on performance. Variability has received limited attention [mainly owing to its exposition in such texts as Gross and Harris (1998) and Hopp and Spearman (2001)], but the crucial importance of the reduction of variability has, for the most part, failed to reach the middle to upper levels of management.

Furthermore, only a limited number of methods for the mitigation of variability, in either the organization or its factories, have been considered (e.g., the variability induced by reentrancy—a phenomenon prevalent in high-tech factories such as semiconductor manufacturing—has not received nearly the attention it is due).

The third enemy of performance improvement—and often the most damaging—is lackluster leadership or even the virtual absence of leadership coupled with a lack of vision. The recent college graduate ultimately will discover that in most any organization there is an abundance, if not overabundance, of managers. The typical manager in the typical organization busies himself or herself with scheduling and holding meetings, attending meetings, overseeing employee performance evaluations, replying to a never-ending stream of (mostly unimportant) e-mails, listening to complaints, presenting PowerPoint presentations to his or her superiors, serving as a conduit between senior management and the individuals who report to him or her, and endorsing the organization's formal mission plan.

But those are tasks that merely support the perpetuation of the status quo. Leaders and visionaries, on the other hand, are rare and unappreciated commodities.

THE THREE DIMENSIONS OF MANUFACTURING

Hand in hand with a lack of appreciation of complexity, variability, and lackluster leadership is the failure to recognize the fact that there are three dimensions to manufacturing (Ignizio, 1980). As a consequence, factory engineers and managers are likely to consider only the first two dimensions and overlook the third in their decision making. To clarify this point, each of the three dimensions of manufacturing is summarized briefly.

The first dimension of manufacturing addresses the attributes of and decisions made with regard to the physical features of the factory itself, for example,

- Factory location
- Factory size
- Factory layout
- Factory processes and products selection

The second dimension of manufacturing is focused on the physical components housed within the factory, including

- Factory workstations and their machines
- Factory floor operations and maintenance personnel
- Factory support personnel
- Material handling systems
- Inventory storage of in-process jobs
- Spare parts and supplies storage
- Pass-through and dispatch stations
- Maintenance equipment and replacement parts
- Inspection/testing equipment
- Emergency response centers
- The equipment dedicated to the automation of operations

The third dimension of manufacturing encompasses the protocols (e.g., policies, practices, and procedures) employed to actually manage and run the factory. The emphasis in this dimension is on changes in strategies and tactics as opposed to physical changes. Included among these protocols are

- Factory starts protocol (e.g., how many jobs to introduce into the factory and when to schedule these starts)
- Preventive maintenance event protocols (e.g., both the scheduling and content of such events)
- Declustering[1] protocols (e.g., the declustering of jobs started into a factory, the declustering of preventive maintenance events)
- Batching protocols (e.g., the determination of batch sizes supported by the machines that employ batching)
- Development and validation of operation and maintenance specifications
- Establishment of run rules (e.g., which job to run on a machine at any given time, i.e., "WIP management") for each of the factory's workstations

---

[1] The term *declustering* is used to represent the "smoothing out" of events. For example, rather than clustering preventive maintenance events at the beginning of a work shift, they should be evenly spread out over the entire shift if factory variability is to be reduced.

- Protocols for minimization of wait time (e.g., time spent waiting for a technician to conduct a maintenance event, or waiting for a spare part to be delivered to a workstation, or waiting for an operator to introduce a job into a machine, or waiting for a decision to be made, or filling out forms, or waiting for committees to reach a consensus)
- Protocols for determining how to best allocate personnel (either operations or maintenance personnel) to workstations
- Protocols for identifying and reducing excessive complexity (e.g., unnecessary process steps, unnecessary maintenance steps, or unnecessarily complex run rules)
- Protocols employed in the ordering, location, and dispatch of spare parts and factory supplies

Note again that the first two dimensions of manufacturing are those that deal mainly, if not exclusively, with the physical elements of the factory. The primary emphasis of these first two dimensions is that of the achievement of changes to factory capacity—where any changes in capacity are confined to those accomplished by physical means (e.g., adding or deleting machines, adding or deleting personnel, or adding or deleting factory floor space).

As mentioned, most factory managers confine their interest and decisions to just these first two dimensions. One reason for this self-imposed affliction is that physical alterations to the factory are changes the manager can easily see, count, and even touch. As a consequence, managers who restrict their decision space to just the first two dimensions of manufacturing will, for example, purchase expensive machines in an attempt to increase factory capacity when a far less costly and more effective alternative may exist (and likely does exist) within the third dimension of manufacturing (Ignizio, 1998).

The third dimension of manufacturing employs changes to protocols not only to improve capacity (i.e., the main emphasis of the first two dimensions) but also—and chiefly—to reduce factory cycle time and the uncertainty about that time. Perhaps the main reason the third dimension is overlooked so routinely is that changes in protocols are difficult to discern.

While you can see, touch, and count machines (or tool bins, supplies, or people), a change in protocols is virtually invisible—at least to the untrained eye. The fact that changes to protocols are not nearly as transparent as physical changes makes life difficult for those who wish to extend decision making in the factory to the third dimension. But it is this dimension that usually enables one to achieve faster, cheaper, and more sustainable improvements to factory performance.

Ignoring the third dimension of manufacturing is analogous to—and as foolish as—trying to fight a modern-day war within just two dimensions—land and sea—while ignoring the third—the air. It is for this reason that the coverage of this book will focus on all three dimensions of manufacturing—and particularly the third.

PURPOSE OF THIS BOOK

My primary purpose in writing this book is to attempt to fill the gap between the theory and practice of factory performance improvement—and in doing so to reveal crucial aspects of the world of manufacturing rarely touched on in classrooms, textbooks, and training courses. More specifically, my purpose is to provide readers with the concepts, techniques, and understanding necessary to achieve significant and sustainable improvement in the complex, confusing, and perplexing environment of a real-world factory, an atmosphere clouded with and influenced by interpersonal relationships, oversized egos, turf battles, in-house politics, resistance to change, and—often—a resistance even to listening. While my focus will be on the factory, it should be understood that the concepts presented apply as well to supply chains, business processes, and the organization as a whole.

The material presented will describe, discuss, and illustrate the politics, art, and science of manufacturing. In support of this, the three enemies of factory performance—complexity, variability, and lackluster leadership—will be identified, discussed, and illustrated. Methods for most effectively eliminating or at least mitigating their negative impact will be presented. Avoidance of these three enemies should diminish the need to consider a move of a firm's production facilities to other, seemingly lower-cost countries.

In keeping with the goal of reducing unnecessary complexity, the mathematical prerequisites of readers are minimal. In fact, as readers will discover, the only mathematics employed within the text are addition, subtraction, multiplication, and division. Even the discussions that involve mathematics are illuminated by means of straightforward numerical illustrations.

If, however, a reader insists on avoiding any level of mathematical and technical detail, this is possible by restricting his or her focus to Chapters 1 and 2, 7 through 12, and 14 and 15. Hopefully, however, you will decide to read the chapters in order because, once again, the level of mathematics employed (with the possible exception of Chapter 13) has been reduced to that which a high school student should be able to follow.

A secondary purpose of the book is to introduce a number of original and previously unpublished methods and concepts for the improvement of factory, supply-chain, business process, and organizational performance. While many of these methods have been presented via short courses to my clients, I have refrained—until now—from disseminating most of these ideas in a public forum. Among these are such topics as

- New, holistic, and robust metrics for the measurement and comparison of factory performance
- Optimized allocation of maintenance or operations personnel to factory workstations
- Methods for the declustering of either factory starts or preventive maintenance events
- The Waddington analysis, an effective and practical methodology for improving both operations and maintenance
- An improved method for the estimate of workstation or factory capacity
- Achievement of C^4U-compliant specifications (i.e., complete, correct, concise, clear, and unambiguous specifications) for the conduct of operations or maintenance events
- Process-step decoupling (a method for dealing with the variability and complexity induced by reentrant process steps, e.g., workstations that must support multiple operations as fed back from downstream processing)
- A process-step-centric perspective of factories as opposed to the conventional workstation view presented in the literature[2]

Finally, case studies, in the form of an ongoing novelette, accompany each chapter. These serve to accompany and illustrate the concepts introduced, particularly their political and interpersonal

---

[2] The use of a process-step-centric perspective is vital when dealing with real-world factories, particularly those that are reentrant and/or use machine-to-operation (i.e., machine-to-process-step) assignments. This will be made clear in the chapters to follow.

aspects. These yarns center around incidents that occur within a strictly fictional—but, alas, representative—company.

The firm in question manufactures a high-tech product and has belatedly come to recognize that its upstart competitors are eating into the firm's profits and market share. Each case study reveals how good ideas can be torpedoed while flawed concepts are embraced. By means of these stories, readers, hopefully, should learn how to avoid the same mistakes this unfortunate firm makes.

The name of the fictional firm is Muddle, Inc. While the firm and all the characters discussed in these case studies are purely fictional, the situations and politics are, unfortunately, representative of those found in many real-world situations. A detailed introduction to the Muddle Corporation is provided in the next section.

INTRODUCTION TO MUDDLE, INC.

The Muddle Corporation is a large multinational manufacturing firm. The company is replete with examples of mediocre to poor to simply atrocious business practices and decision making—factors that induce waste and diminish the firm's profit and market share. The problems Muddle must cope with, as well as the mistakes it makes, are—unfortunately—typical of those that may be observed in many real-world manufacturing firms. These problems and mistakes will, however, provide lessons that readers may learn from and hopefully avoid repeating.

The present CEO of Muddle is Marvin Muddle, the son of Peter Muddle. Peter, in turn, was one of the firm's founders, its previous CEO, and now serves as chairman of the board.

Marvin, sporting an MBA from a prestigious Ivy League university and 10 years' experience with the firm, is faced with a company whose profits, market share, and stock price are in decline. Since the tech bubble burst in 2001, Muddle's stock price has plummeted a whopping 80 percent. The morale of Muddle's employees, most of who rely on their stock options to augment an unimpressive level of compensation, has plunged even lower.

One of the most pressing problems facing the Muddle Corporation is that of poor factory performance. This problem is, in fact, much worse than comprehended by the firm's senior management—managers far more interested in the development of an improved or more "jazzy" product than the mundane matter of improved factory performance.

At one time, the firm virtually owned the market for its high-tech product despite its outdated, mostly intuitive, and thoroughly substandard manufacturing practices. That product, however, has now become more or less a commodity, and a number of firms have surfaced with equal or even superior versions of the artifact, along with manufacturing processes, policies, and procedures that allow them to often beat Muddle to the market. As a consequence, customers for Muddle's product have, of late, been shifting their business to Muddle's competitors.

Marvin Muddle is convinced that the glory days of the firm can be recaptured if he can just reduce costs. Cost reduction is and always has been, in fact, his main, if not only, concern. Certainly, thinks Marvin, reductions in manufacturing costs coupled with introduction of the latest and greatest management and motivational methods will enable Muddle to crush its competition.

If that doesn't work, Marvin simply will engage in a cutthroat price war that should drive the competition out of business. This approach may reduce the firm's profit margin significantly, but considering the deep pockets of the company, it is bound to be effective. In fact, one of his father's favorite sayings is: "If you can't compete, destroy." Satisfied that he has an answer to the firm's predicament, Marvin returns to the business at hand—consideration of yet another change in the company's logo.

In the meantime, while Muddle's costs have indeed been reduced—mostly via layoffs of employees, shutting down of domestic factories, transfer of manufacturing facilities to offshore (and lower labor cost) countries, and the sale of a plethora of poorly performing companies purchased during the ill-fated tech bubble—the firm's market share hasn't improved appreciably. Just as disappointing, the introduction of a long line of management fads and fashions launched over the past several decades hasn't produced the results promised by a series of glib and high-priced management consultants. In fact, despite Muddle's embrace of reengineering, one-minute management, total quality control, quality circles, management by objectives, management by walking around, management by positive thinking, management by the Ouija board, management practices of Hannibal Lecter, management via blind faith, management by intimidation, theories A through Z, and a host of other celebrated concepts, matters have only gotten worse. In particular, average product cycle time actually has increased—substantially.

Some weeks ago, the perky and persuasive Sally Swindel, the very same management consultant who previously sold the firm on reengineering (promising that it would be the answer to all the firm's problems), returned with what she guaranteed to be an even better approach: lean manufacturing.[3] Sally assured the members of Muddle's Management Review Committee (MRC) that lean manufacturing—a concept she claimed originated in Japan with the Toyota Company—will "turn the fortunes of the firm around." All it will take to get started, she insisted, is a two-week training course. Sally added that if Muddle sends enough people to that course, the fee will be dropped from the normal $40,000 down to $30,000 per attendee. She even guaranteed a discount in the room rates of the plush seaside resort hotel in which the attendees will be housed.

Desperate for a quick and easy solution to Muddle's problems, Marvin Muddle ignored his Management Review Committee's timid recommendation for "further investigation" as well as a "proof of concept." One member of the MRC actually had the temerity to remind Marvin of the drastic consequences the firm endured—and is still trying to recover from—after implementing reengineering, the previous "final solution" recommended by Sally Swindel.

Brushing those concerns aside, Marvin demanded the MRC make plans to introduce lean manufacturing into the firm's factories—and do so ASAP. He concluded the meeting with a warning that he expects results within 6 to at most 12 months.

We'll see how that works out.

OVERVIEW OF THE MATERIAL TO FOLLOW

Chapter 2 provides a brief summary of the history of manufacturing, focusing on some of the most important concepts and developments that have been introduced over the decades (and even centuries) to improve factory performance. While an impatient reader may be tempted to skip this chapter (e.g., "Who cares about history?" or "I already know this"), please read it. You may discover that the history of manufacturing you were taught in school has some serious deficiencies and oversights. (As just one example, the first moving assembly line for the assembly of vehicles was

---

[3] Before drawing the *erroneous* conclusion that I'm bashing such concepts as lean manufacturing, do take the time to read the rest of the book. In the chapters that follow, both the scope and the limitations of lean manufacturing will be covered.

developed long before Henry Ford or Ransom Olds was born—several centuries before to be exact.) More important, if you are acquainted with the history of manufacturing, you'll reduce your chances of falling victim to those who would try to sell you one fad after another—and who, in most instances, are actually marketing some very old ideas under different and more clever names.

Perhaps most important of all, Chapter 2 concludes with a preliminary analysis of why some firms succeed in attaining improved performance while others quickly or ultimately fail to achieve any lasting benefits. Why, for example, has Toyota managed to so successfully implement and exploit its production system while, at the same time, scores upon scores of firms that have tried desperately to emulate Toyota's practices have either failed to do so or have experienced only transient improvement? To answer this question, one must have some familiarity with the history of manufacturing.

Chapter 2, as well as all the chapters that follow, concludes with a case study that deals with the situation at the Muddle Corporation. Will the Muddle Corporation change its ways? Will lean manufacturing be implemented properly, and will it make a significant and lasting difference? Will Marvin Muddle lose weight? Will Sally Swindel change her last name? You'll find out the answer to at least some of these cliff-hangers in the end-of-chapter case studies.

In Chapter 3, certain crucial notation, terminology, and definitions are presented. In addition, two approaches for constructing a factory flowchart (e.g., value-stream process flow and process flowchart) are presented and illustrated. This chapter serves to introduce readers to the important difference between a workstation-centric perspective and a process-step-centric view of a factory. While I can't promise you that this chapter will be a riveting read, the material covered is essential to an understanding of the notions that form a basis for an appreciation of the technical factors that determine factory performance.

Chapter 4 provides you with an opportunity to test out your own theories or intuition with regard to running a factory. You are presented with a simulation model of an exceptionally simple factory and are invited to expend a limited budget for adding machines, improving machine availability, or increasing machine process rates (e.g., run rates). Your goal is to improve a particularly important aspect of factory performance, the average product factory cycle time (i.e., the average time between the introduction of a job into the factory and its exit, in finished form, from the factory). Those of you with some familiarity with the theory of constraints (Goldratt and Cox, 1984; Hitomi, 1996) or lean manufacturing (Arthur, 2007; Bodek, 2004; George, 2002; Hirano and Furuya, 2006; Ignizio, 2008b, 2008c; Levinson, 2002; Liker, 2004; Standard and Davis, 1999; Womack and Jones, 2003; Womack, Jones, and Roos, 1991) may find this chapter to be of particular interest.

About 99.9 percent of those who attempt to improve this factory ultimately will discover that their intuition and what they have been taught may be insufficient, ineffective, or even inappropriate when it comes to dealing with a very typical factory situation. For example, how many readers would believe that you can inadvertently increase overall factory cycle time simply as a consequence of balancing the workload (i.e., the so-called fundamental premise of lean manufacturing) across factory workstations? Or that adding machines and/or increasing their availability can, under certain circumstances, degrade overall factory performance? Or that any effort that focuses on the components of the factory rather than on the factory as a whole may cause more problems than it cures?

Moving on, it is essential to appreciate that there are three fundamental equations and a single fundamental model that together serve to determine factory performance. In informal surveys conducted over the past two decades, I found that fewer than 10 percent of factory engineers or factory managers are familiar with these three equations—and none were aware of the fundamental model. This is not entirely their fault because most university programs do not cover the three fundamental equations, and none, until recently, have taught (or been aware of) the fundamental model.

Unfortunately, a failure to cover these equations and model serves to severely diminish an engineer's or manager's ability to either understand or most cost-effectively solve problems that exist within the factory. Instead of correcting the real source of problems, what is too often done is to focus on the symptoms—leading to an ineffective, counterproductive, and wasteful "Band-Aid approach" to problem solving.

It is odd that while one would never consider hiring a physicist who is unaware of the equation relating force, mass, and acceleration ($f = m \cdot a$) or an electrical engineer who is ignorant of the equation relating voltage, current, and resistance ($V = I \cdot R$), it is standard practice to run a factory without any acquaintance whatsoever with the fundamentals that dictate its performance. As such, it is no wonder that so few factories achieve anywhere near the level of performance of which they are capable.

In Chapter 5, the omission with respect to the three fundamental equations of manufacturing is corrected (in a later chapter, the fundamental model of manufacturing is presented and illustrated). Once this is accomplished, readers will be prepared to reconsider the factory demonstration of Chapter 4. One of the most important matters covered in Chapter 5 is that of the adaptation of the three fundamental equations to a process-step-centric view of the factory.

Chapter 6 provides readers with a second opportunity to improve the performance of the simulated factory of Chapter 4. You will discover that when armed with some appreciation of the three fundamental equations of manufacturing—and by means of exploiting the third dimension of manufacturing—you can improve factory performance at a fraction of the cost (and time) necessary under the conditions set forth in Chapter 4.

Chapter 7 reflects on the findings produced in the factory demonstration model of Chapters 4 and 6. Three important plots of factory performance are introduced and illustrated. These are the factory operating curve, the load-adjusted cycle-time efficiency curve, and the profit versus factory loading curve. These curves provide the three most valuable indications of overall factory performance available. Each curve is illustrated by means of generating it from the factory demonstration models of Chapters 4 and 6.

Chapter 8 deals with the metrics that should be employed to evaluate the performance of a factory—and/or to compare the performances of two or more facilities fairly and objectively. In addition to the three curves covered in Chapter 7, you will be introduced to the Waddington effect plot, the M-ratio (the ratio of scheduled to unscheduled downtime), the availability profile plot, the cycle-time contribution factor, and the degree-of-reentrancy (DoR) metric.

Equally important, metrics commonly used but actually of little or no value—or even counterproductive—will be identified. Among these (and this discussion may be disconcerting to some readers) are such widely employed performance measures as moves, utilization, and inventory turnover (or WIP turns). This material, as well as the three curves presented in Chapter 7, will provide the factory engineer or factory manager—or, in particular, senior management—with useful and valid measures of factory performance.

To quote Lord Kelvin, “If you cannot measure it, you cannot improve it.” A restatement of this quote serves to succinctly summarize the purpose of Chapter 8; that is, “If you don’t employ a meaningful metric, you not only can’t improve factory performance, but you are likely to only worsen it.”

Chapter 9 serves to summarize the material presented in the previous eight chapters. More specifically, the scope and limitations of the methods and models that have been introduced are discussed. This allows us to focus our attention on practical, pragmatic, and cost-effective methods for improving factory performance, that is, the material to be presented in the remaining chapters of this book. In short, Chapter 9 permits us to transition from history, concepts, and equations to a straightforward and practical approach to factory performance improvement.

The material in Chapter 10 addresses the matter of the reduction of complexity in the factory. Some of the usual sources of unnecessary complexity (e.g., batching, excessive and/or unnecessary inspection steps, disorganized and cluttered work areas, excessive steps in the conduct of a preventive maintenance or repair event, and unclear and ambiguous specifications) are discussed, and means for reducing complexity are presented and illustrated. As a side benefit, you’ll even learn how to properly perform the musket drills used in the Napoleonic War period. As you will discover, effectively firing a musket during the heat of battle involves many of the same protocols necessary to run a factory. You can learn a lot from some odd and seemingly ancient practices.

Chapter 11 addresses the reduction of variability within a factory. Typical sources of variability and their symptoms are discussed. Practical methods for dealing with variability cost-effectively then are introduced and illustrated. The typical obstacles imposed on the introduction of measures for variability reduction are also discussed. Since variability reduction is usually the fastest, cheapest, most effective, and most sustainable means for improving performance, this is a particularly critical topic and chapter.

The guidelines listed in the previous chapters, particularly those of Chapter 10 and 11, are employed in Chapter 12 to deal with a revised version of the 12-workstation factory. Here, your objective will be to maximize profit and reduce factory cycle time. In other words, Chapter 12 serves as a means of both summarizing and illustrating the art and science of manufacturing.

The fundamental model of manufacturing is the subject of Chapter 13. This model allows the factory engineer or manager to compute the capacity of each factory workstation more accurately (even in the face of reentrancy and multiple product types) as well as more precisely predict factory bottlenecks. When the fundamental model is combined with the material of Chapter 11 (i.e., variability), a reasonably accurate estimate of workstation or factory performance is possible. The painful fact is that most factory engineers and managers have no idea as to their facility's true capacity and, as a consequence, cannot determine whether or not they are under- or overloading their factory.

Chapter 14 provides recommendations for the establishment of an effective approach for the implementation of methods for the achievement of significant and sustainable factory performance improvement. The crucial role of management, at all levels up to and including the firm's CEO, is discussed. Of particular importance is the need for management, at every level, to be involved in performance improvement. This chapter continues and elaborates on the discussion initiated in Chapter 2, an analysis of why a few firms (e.g., Toyota) manage to achieve significant and sustainable improvement in factory performance, whereas most others, apparently using the same approach, fail. Among the other topics covered are

- Leaders versus managers
- The selection of factory performance-improvement personnel
- The education and training of factory performance-improvement personnel
- The need for and establishment and role of a "center for factory performance improvement"
- An overview of decisions and actions that can make or break any factory performance-improvement effort
- A list of dos and don'ts

A summary, conclusions, and recommendations form the material covered in Chapter 15, the final chapter of the book. In this chapter, the attributes of the ideal factory are cited, along with a succinct summary of the most promising methods that may be used to strive for that goal. For those who may wonder if the concepts outlined in this book actually work, a brief discussion of a Spanish firm, Inditex, is provided in this chapter. Inditex, an apparel manufacturing firm (its most well-known retail outlet is Zara, a women's clothing store chain), has demonstrated that by overcoming the three enemies of factory (and corporate) performance, you can become the biggest, fastest growing, and most profitable clothing manufacturing firm in the world—without outsourcing production, chasing fads, or having a fixation on cost cutting. Also included in this chapter is the final installment of the case studies involving the Muddle Corporation.

CHAPTER SUMMARY

In this chapter, the three primary enemies of factory (or supply-chain or organizational) performance were identified. These are

- Complexity
- Variability
- Lackluster leadership

It also was noted that significant and sustainable factory performance improvement can only be obtained by means of a proper balance between the art and science of manufacturing—along with an appreciation of the office politics and corporate culture that must be overcome so as to achieve acceptance of any method or methods proposed for improvement. In this book, I address the art and science of manufacturing within the main sections of each chapter. The corporate politics and culture are covered by means of the case studies presented at the conclusions of the chapters. Given an appreciation of all three elements (i.e., politics, art, and science) of manufacturing, the likelihood of success in factory performance-improvement efforts is vastly increased. This, in turn, should lead to the achievement of our primary goal: *greater and sustainable factory performance improvement*.

Again, for the sake of readers who may wish to skip over material dealing with technical details, the recommended reading assignment consists of Chapters 1 and 2, 7 through 12, and 14 and 15. The Muddle case studies are meant, however, to be read sequentially from Chapters 1 through 15.

CASE STUDY 1: LITTLE THINGS MEAN (AND INDICATE) A LOT

With apologies to the songwriters, Edith Lindeman and Carl Stuz, I've made a few revisions to the lyrics of "Little Things Mean a Lot" to fit a typical factory scenario:

Bring me a spare part from across the room
And don't say it's been inspected if it's not
Sign the release form as you pass my desk
Little things mean a lot

The case study to accompany these lyrics may seem too bizarre to be real, but they do say that truth is stranger than fiction. I'll let the reader decide whether or not any real-world firm could have such an extraordinarily poor system for the delivery of parts and supplies to its factory floor or such a dysfunctional culture. Perhaps the most important point made, however, is that deficiencies in even the most seemingly minor aspect of manufacturing may have grave consequences on both performance and morale.

As indicated earlier, the Muddle Corporation has several multibillion-dollar factories located in sites scattered across the globe—wherever labor is cheap and regulations are loose. The performance of these factories, when compared with Muddle's competitors, is, however, definitely subpar. Marvin Muddle, the firm's reclusive and extremely well-compensated CEO, demands that something be done about this. "No way," warns Marvin in a Webcast to his employees, "is my company content with being second best."

Actually, Marvin exaggerates his firm's standing. The performances of its factories are in reality worst in class. Marvin has "tried everything" to improve the situation, from bringing in high-paid motivational speakers, to holding pep rallies, to instituting challenge goals, to issuing edicts, to embracing every management and manufacturing fad conceivable. Last month he even went so far as to change the firm's logo and slogan—for the fifth time in seven years.

The most recent attempt by Marvin to improve his firm's standing and bottom line has been the adoption of lean manufacturing. Marvin has been informed that lean manufacturing is the hottest and most fashionable management technique since reengineering and business process reengineering.

Ignoring or oblivious to the harmful impact that the latter two concepts had on the firm a few years back, and despite the fact that Marvin hasn't taken the time necessary to actually understand what lean manufacturing is all about and (in particular) what is required for a successful implementation, he issues an edict that states that all of Muddle's middle and lower-level managers must attend Sally Swindel's two-week lean manufacturing training courses (of course, he sees no reason why he or the members of the

MRC should spend their valuable time in such a course) and that lean must and will become the focus of the firm—at least until something better comes along.

Marvin's most recent change in the firm's slogan is *"LEAN* Forward." The change is intended to reflect the firm's new emphasis on lean manufacturing. Despite his edict, change in slogan, change in company logo, and millions of dollars and thousands of personnel hours spent on training in lean, the situation only gets worse.

When, however, one takes a close look at just one (apparently) small part of the operations of Muddle's factories, one reason for the firm's last-place position becomes clearer. Not only is maintenance an afterthought at Muddle, but the role played in dispatching replacement parts and supplies to its multimillion-dollar machines is hardly given any thought.

Let's consider one brief observation of life on the factory floor. We'll limit our focus to a few hours of the trials and tribulations of Dan Ryan, a recently hired day-shift factory floor supervisor. Dan is responsible for operation of the machines in a single workstation (workstation 107) within one of Muddle's largest and most important factories, designated by the firm as "Factory 7." Unfortunately for Muddle and its shareholders, it is also the firm's poorest performing factory in terms of such matters as getting the product to the customer on time and the predictability of product lead time.

Today, two of the dozen or so (complex and extremely expensive) machines in Dan's workstation suddenly and without warning break down. Dan's of the opinion that the frequency and magnitude of the unscheduled downtimes of the machines in his workstation have something to do with the way in which preventive maintenance (PM) events are performed. Following his review of some of the major PM event documents for his machines, he's not convinced that the PM specifications are written properly.

Dan is even beginning to believe that the misconduct of PM events is causing the majority of the unscheduled downtimes, more so than any shortcomings in the design or operation of the machines themselves. Last week, Dan even complained, to no avail, to his department head about the ambiguity and lack of clarity of the PM specifications.

That meeting didn't go well. Donna Garcia, Factory 7's assertive factory floor operations department head, advised Dan to shut up and just follow the darn specifications. After all, she hissed, the same PM specifications are being used across all of Muddle's factories. This is part of a program designated "NO DEVIATIONS" (i.e., based on a belief that every factory should follow precisely the same factory layout, selection of machines, policies, procedures, and processes). Donna emphasized that the effort required to obtain approval for even the slightest change in any specification would be enormous and generate some mighty unfavorable feedback from William "Wild Bill" Barlow, Muddle's director of manufacturing. And the possibility of everyone in every factory reaching a consensus on a specification change was nigh on to impossible. Furthermore, with Wild Bill's latest edict on cost cutting, there would be zero chance of spending any funds on the improvement of PM specifications.

"Besides," Donna added, "I've been out of the office for a two-week training course on lean manufacturing, and tons of work have piled up during my absence. Do run along, Danny Boy, I'm already late for Muddle's refresher course on employee motivation. So, case closed; get back to your workstation."

But let's get back to Dan's immediate problem. Two of his machines have broken down, and the impact of those failures will soon be felt across the factory—and firm. Dan and his crew quickly identify the failed parts in each machine. Repairs can be made if Dan is able to acquire two screws for one machine and a vacuum pump for the other. Dan's sure those parts must be on hand—somewhere in the bowels of one of the two parts and supply warehouses that serve the factory.

Dan hurries to the computer terminal that supports his workstation. A few agonizing minutes later, the parts and supplies order software package, code named *Broken Arrow,* is finally up and apparently running. Dan initiates a search for the vacuum pump by typing in "vacuum pump" in the program's search engine.

But nothing happens!

Sorry, change that to nothing happens except that Dan is unceremoniously kicked out of the *Broken Arrow* program. Three more times Dan tries to run a search on "vacuum pump," and three more times he fails. Perhaps, thinks Dan, I should be typing in "vacuum pumps." But this too results in a string of time-consuming failures.

Brad Simmons, one of Dan's coworkers and the factory floor supervisor for the adjacent workstation, has been observing Dan's desperate attempts to place an order and the even more desperate look on the poor man's face. "Dan, old boy," says Brad, "what's the problem?"

Dan, sweating profusely, explains his predicament. “Brad, what the heck is wrong? I know how to spell ‘vacuum pump,’ yet every time I type in those words, I get kicked out of *Broken Arrow* and have to bring the program up again. The same thing happens when I type in ‘vacuum pumps.’ Am I losing my mind?”

“No,” says Brad, “you aren’t losing your mind, old boy, and you’re definitely using the correct spelling. The problem is that the sad little lunatics who created *Broken Arrow* may have been fair to decent programmers, but they weren’t all that hot at spelling. If you want to search for vacuum pump, you’ll need to type in ‘vacum pump’! That’s v-a-c-u-m. Just type in one ‘u’ instead of two.”

Dan shakes his head and types in “vacum pump” rather than “vacuum pump.” Sure enough, just as Brad promised, he is taken to the portion of *Broken Arrow*’s database that stores information on the availability of the various vacuum pumps used by the factory’s machines. He manages to locate the particular one he needs and types in the order—despite the program’s incessant demands for unnecessary and redundant entries (e.g., he has to type his workstation location in five different places on the order form, his employee identification number in three other slots, and then complete a survey to determine his satisfaction with the process).

Finished with the vacuum pump order, Dan is ready to search for the specialty screws needed for repair of the other failed machine. After a few unsuccessful attempts, he discovers that he can’t just change the search word and hit the ENTER key. Instead, he has to close *Broken Arrow,* reopen the program, wait a few minutes for the start screen to appear, and then begin the entire search process over.

Dan types “Type 107X” screws in the search menu. This brings up what should be a photograph of the screws—a means to visually check the screw type shown on the screen with the one that is needed. Instead of showing the screws, however, the photo that appears is of a paper bag. A handwritten note on the bag reads, “Type 107X screws.” Shaking his head, Dan can only assume that the team who designed *Broken Arrow* had taken a photo of a bag containing the screws rather than of the screws themselves.

Growing ever more frustrated, Dan places a request for 10 Type 107X screws. Even though he has been on the factory floor just a few weeks, he has learned to always request more of anything than is actually needed. If he just orders two screws, he reasons, the maintenance tech might lose, misplace, or strip the threads on one or two. And if he ever needs the miserable Type

107X screws again, he can hide the excess in one of his technicians' tool boxes and avoid the need to order them via *Broken Arrow.*

Pressing the ENTER key, Dan is dismayed to discover that the screen reads, "REQUIRED ITEM NOT AVAILABLE." Dan's cursing and frantic hand waving attract the attention of Brad, who hurries over to see if he can help.

"Brad, *Broken Arrow* is telling me that there aren't any Type 107X screws in-house for the repair of Machine 107. We can't get Machine 107 up and running until we get those screws from the vendor, and that could take a day or more. Is it really possible that there are none of those screws in stock? It's my understanding that they are constantly failing. I thought we had tons of those screws."

"Sorry, Dan, someone must have forgotten to tell you about another quirk of *Broken Arrow*. You can't just type in "10" for the number of screws. Some screws come in packages of two, six, a dozen, or some other number. I'm guessing that Type 107X screws simply don't come in packages of 10."

"Good grief," Dan replies, "so how do I order 10 screws?"

"You're going to have to try ordering one, two, three, and so on. Sooner or later, the number you enter will—hopefully—coincide with the number in the packaging of Type 107X screws as originally entered in *Broken Arrow*'s database. I know it's crazy, but *Broken Arrow* is, according to management, a 'finalized, tested, tried and true' software support package. Heck, it even won a corporate award. So, if you're thinking about it, I'd forget trying to escalate the issue. Believe me, it will only cause grief. Take it from a guy who knows first hand. Besides, management claims to have saved $200,000 a year by terminating all support for revisions to the program. Welcome to Muddle, Incorporated, old boy. Here, cost savings overrides everything, including common sense."

Dan follows Brad's advice and finally determines that Type 107X screws come in packages of four each. To accomplish an order for the 10 screws, he has to place three separate orders for four screws each. Based on the throbbing in his head, Dan is beginning to wonder if he is experiencing a migraine—or a stroke.

* * *

Two hours later, Dan receives a visit from Ben Arnold, the universally despised technical assistant for Factory 7's senior plant manager. Even though Dan has been on the job only a few weeks (having previously endured three agonizing and seemingly pointless weeks of new employee indoctrination), he has heard about Ben—and had hoped and prayed never to meet the man.

Ben, eyes narrowed and a permanent sneer imprinted on his face, informs Dan that his workstation has become the factory constraint. Jobs are piling up in front of the workstation, and it won't be long until they will have to decommit factory starts. That, Ben advises, is something that simply will not be tolerated. A decommit of factory starts is, according to Ben, the absolute worst thing that can happen in a Muddle factory. "Why," Ben demands, his face now just inches from Dan's, "haven't you ordered the replacement parts?"

Dan explains his situation and stresses that the parts have been ordered, but he has yet to be paged with a confirmation that the parts are located and available for pickup. "Procedures dictate," pleads Dan, pointing to the parts ordering policy prominently posted next to the workstation, "that no one is to attempt to retrieve any parts order until they have been paged. The penalty for that offense is immediate termination."

"Idiot," says Ben through clenched teeth, "our pagers only work about half the time on the factory floor. They probably sent you a communication you didn't receive. That happens all the time. So move your butt to the dispatch station and see if the parts are there!"

Dan decides that it may be best not to mention the fact that company policy also dictates that he, as a factory floor supervisor, must not leave his workstation except for lunch breaks, bathroom breaks, training sessions, and scheduled meetings. Instead, he rapidly walks (company policy prohibits running on the factory floor, another cause for immediate termination) to the nearest parts dispatch station, the one to which he had transmitted the parts order.

Reaching the station, Dan is shocked to see that its customer window is closed. A small, handwritten sign is taped to the window. It states that, as a part of the lean manufacturing program and in support of the *LEAN* Forward effort, the station has been "decommissioned," and its staff "redeployed" (the latter term being the firm's code word for being laid off). A ceremony recognizing the lean *kaizen* team that recommended the closing is to be held in the company cafeteria later that day. Attendance is mandatory.

Muttering a particularly inappropriate obscenity, Dan turns on his heel and speed walks to the one remaining dispatch station, located a 20-minute hike from the closed station. Reaching the station, he is relieved to learn that the parts he ordered, some three hours ago, are there. The dispatcher, a crusty old fellow with bad teeth, informs Dan that he had paged him over two hours ago, and it wasn't his responsibility to make sure that the page was received.

Deciding not to argue the point, Dan reaches over the desk to take the box containing the screws and vacuum pump. The dispatcher, displaying the swift reflexes of a wild west gunslinger, moves to block his path.

"No you don't," says the dispatcher, grasping Dan's arm. "Those parts were ordered under the name of John Wilson. The name on your badge is Dan Ryan. We only allow the person who ordered the parts to pick them up. And Pard, you ain't that person!"

"But I'm the floor supervisor who replaced John Wilson. They haven't changed the auto-population program on my computer, the one Wilson used to use. So, naturally, everything I've been sending out has been under the name of John Wilson. Don't you understand? I ordered those parts, and I'm picking them up. This nonsense is impacting factory performance. I'm begging you, please, just give me the parts."

"Sorry, Pard, that would be a serious violation of company policy. You need to escalate this matter to the senior plant manager. If he says you can have the parts, then they're yours. Otherwise, they stay right here. And by the way, the escalation procedure takes—on average—about a week. Good luck, Pard."

* * *

We'll conclude this case study with a brief discussion and a few observations. The situation Dan Ryan experienced reflects all three major obstacles to improved factory—or organizational—performance. You may recall that these are (1) lackluster leadership, (2) complexity, and (3) variability.

Muddle's lackluster leadership is reflected in its impact on company politics, specifically the politics characterized by the firm's actual (as opposed to its formal) culture. This culture serves to dissuade any change to the status quo. For example, the "NO DEVIATIONS" program may have been well intended but only places a roadblock in front of any proposal for a change in existing policies, procedures, or processes. Those who have attempted, despite this obstacle, to propose changes have been branded as heretics and accused of trying to "rock the boat." The message transmitted to all Muddle personnel is to live with "NO DEVIATIONS" rather than stick one's neck out. This "shoot the messenger" attitude permeates the firm and cripples its effectiveness.

Marvin Muddle confides in and takes advice from a small, closed circle of subordinates. Jealous of their position and influence, these individuals—members of the firm's Management Review Committee—do everything possible to shelter Marvin from any complaints or criticism (constructive or not) from the firm's employees and lower-level managers. Thus, even though the "NO DEVIATIONS" program has seriously degraded both factory performance and morale, word of this is kept from Marvin.

Real-world illustrations of this type of behavior have been exhibited by the manner in which bad news was kept from such infamous "CEOs" as Saddam Hussein, Adolf Hitler, and Joseph Stalin. The subordinates of those men quickly learned that even if it required lies and deception, any revelations of bad news to their leader just might result in worse news for them. The members of Muddle's MRC, as well as most of those in a management position at the firm, would rather run their tongue through a paper shredder than mention anything that might conflict with the comfortable and limited view of the world held by Marvin Muddle.

Further evidence of the negative impact of the firm's lackluster leadership, although not explicitly cited in the case study, exists in the atmosphere of fear and intimidation that permeates the entire company. Proclamations such as the "NO DEVIATIONS" program and "*LEAN* Forward" slogan only motivate the firm's managers and employees to cut costs—even when such cost cutting actually results in significantly degraded factory performance (as in the instance of closure of the dispatch station and the redeployment of its personnel). However, when a firm's managers are only interested in reducing the expenditures that appear on their accounting sheets, and ignore the hidden costs of inefficient operations (and the subsequent reduction in a firm's profit and share of market), cost reductions will be rewarded, whatever the true consequences.

Lackluster leadership and the company politics engendered also play a role in the metrics employed by Marvin Muddle and his Management Review Committee. Marvin and the MRC are presented each week with charts and plots that allegedly indicate the performance of each factory in the firm. Those plots focus mainly on costs per unit of product produced, factory floor personnel utilization, machine utilization, factory starts, and factory cycle time. They are also used (again, allegedly) to compare the performance of Muddle's factories. A few of the firm's more courageous senior engineers have sent e-mails to Marvin noting that none of these plots or metrics are useful and, in fact, that they present a flawed and misleading picture of performance. Since, however, all e-mail to Marvin is routed through his technical assistant, those concerns never reach the CEO.

Another aspect of the impact of the company politics that result as a consequence of poor leadership may be observed by Donna Garcia's (Factory 7's factory floor operations department head) reaction to Dan's recommendation to improve PM specifications. Donna has recognized that a particularly effective road to promotion and salary increases at Muddle is to simply fill her outlook calendar with as many meetings as humanly possible—not a hard thing to do with a firm afflicted with "obsessive-compulsive meeting disorder" (OCMD). Donna's discovered that the thankless task of dealing with problems on the factory floor just gets in the way of attending meetings.

Next, let's examine the issue of complexity. The unnecessary extent and degree of complexity imposed on Dan and his coworkers simply for ordering spare parts should be evident in the story. Not only are the policies, procedures, and processes overly and unnecessarily complex, there is no clear picture of if and when they can be ignored. The "NO DEVIATIONS" program is but one example of unnecessary complexity—and inflexibility. While on the surface the program may appear reasonable to higher management, such dictates add many additional—and complex and unnecessary—impediments to the acceptance and implementation of methods that provide for improved efficiency.

At Muddle, as well as at many real-world firms, thousands of good ideas are never put forward simply because of the red tape required for their recommendation. To make matters worse, the practice of rewarding bad ideas (e.g., the recognition being given to the lean *kaizen* group that recommended closing down the spare parts dispatch station in the Muddle factory) is all too prevalent.

Another example of unnecessary complexity is evident in the problems involved in using the *Broken Arrow* parts and supplies ordering system. That system took years and many millions of dollars to develop (even though a far better off-the-shelf program could have been purchased for a fraction of the cost from an outside vendor). The *Broken Arrow* effort was initiated by means of a slick marketing program introduced by Muddle's senior vice president for automation and information technology. He promised that automation, in any aspect of factory procedures, always would lead to reduced costs of operation. *Broken Arrow,* he assured Muddle's MRC, would enable the firm to eliminate the "primitive" job positions of parts and supplies runners. (The runners had been used, prior to *Broken Arrow* and their "redeployment," to dispatch orders from the parts and supplies warehouses directly to the factory floor supervisors. On receipt of the parts or supplies that had been ordered, a runner would deliver them to the appropriate factory floor supervisor. Many of the runners were even capable of assisting in the repair or PM event. Primitive, perhaps, but extremely efficient.)

When the "primitive" runner system was in effect, the average time between requesting and receiving a spare part for an unscheduled machine down event was on the order of 30 minutes. After the introduction of *Broken Arrow,* that time skyrocketed to three or four hours and often more. Even worse, the variability about the wait-for-spares times increased dramatically, resulting in decreased machine availability and increased factory cycle time.

Just one more example of unnecessary complexity will be mentioned. This source of complexity exists within the PM specifications employed by Muddle. These specifications were provided by the machine vendors to Muddle on delivery of the machines. The unspoken intention was that they be used during the first few months of the machines' operation and then revised to adapt to actual factory conditions. The cost-cutting obsession at Muddle serves to ignore that fact. Revising a PM specification takes, after all, time and resources. As a consequence, the specifications are seldom, if ever, changed (any changes, by the way, require numerous approvals and a degree of red tape seldom seen anywhere outside a government agency).

The result is that the PM specifications delivered by the vendor, no matter how poorly written and ambiguous, are accepted as the "best known method" for conducting the PM—even when many of the steps involved are unnecessary and even (and often) serve to cause unscheduled machine down events.

The induction of unscheduled machine down events by unnecessary PMs is, in fact, the reason for the need for replacement of the Type 107X screws cited in the case study. It so happens that PM events are being conducted too frequently. This, in turn, results in the subsequent stripping of the threads on the screws—and the unscheduled downtime required to replace the screws.

Let's turn our attention to evidence of excessive variability indicated by the case study. Look closely and you'll find that this brief case study is replete with examples of excessive variability. There are, for example, clear indications of excessive human-induced variability at the CEO level. Marvin Muddle has changed the firm's logo and slogans five times in seven years. The message transmitted to his employees, as well as to any sharp-eyed business analyst, is that Marvin is indecisive and grasping for straws. A CEO or manager who is indecisive and vacillates between the emphasis of one goal over another—or who frequently changes the metric or metrics by which the firm or factory is measured—is a source of excessive and damaging variability. The practice of flip-flopping—in politics or in business—ultimately leads to a condition known as *decision paralysis* (i.e., the fear of making any decision) among all levels of the workforce.

Another example of variability is the random adherence to company policies. As we noted, even though company policy stated that Dan should not attempt to retrieve an ordered part until after the receipt of a page, the senior plant manager's technical assistant demanded that Dan ignore that dictate, as well as ignore the written policy that floor supervisors should not leave their workstations for other than lunch, training sessions, meetings, and short biobreaks.

When a firm announces that the violation of a policy is enforceable by termination or other serious consequences and then allows (or encourages) infringements to happen, variability and confusion reign supreme. One of the prime written directives of Muddle is to "encourage and embrace change and always challenge the status quo." Any employee naive enough to believe this could receive an unpleasant surprise.

Roughly a third of the time the person proposing any recommendation for a change or a challenge of the status quo will be reprimanded or even punished (as a consequence of the "shoot the messenger" culture) for "rocking the boat." Another third of the time the individual's manager will take credit for the proposal. The final third of the time the recommendation simply will be ignored. The latter response, it should be noted, is possibly the most insulting and demoralizing of all.

The final illustration of variability that will be discussed is one that is—like most variability—not visible to the untrained eye. The practices inherent in Muddle's flawed parts ordering process lead to increased downtime, increased wait for spare parts, and a subsequent increase in the variability of maintenance and repair times. As you will learn in later chapters, the variability induced by the existing parts ordering and delivery practice (and limitations of *Broken Arrow*) serves to increase factory cycle time and uncertainty in job completion dramatically.

By the way, in a situation somewhat similar to the fictional one described in this case study, it was proven (via a detailed simulation model of the factory in question) that overall factory performance could be improved significantly by adding more dispatch stations (rather than closing any) and using the "primitive" runner system. I'll leave it to readers to guess whether or not management accepted that recommendation.

CHAPTER 1 EXERCISES

1. The spare parts ordering process that Dan Ryan has to go through is obviously flawed. Discuss the following matters:
    - Why do you believe the process has been tolerated rather than changed?
    - What revised process (in general, brief terms) would you propose to improve the process?
    - How would you measure any improvement in the revised process—and objectively compare it with the original method?
2. It is the author's observation that high-tech manufacturing firms (e.g., semiconductor manufacturers, solar cell manufacturers, etc.) actually have more primitive and less effective manufacturing protocols than many lower-tech companies (e.g., producers of incandescent light bulbs, manufacturers of crown molding, etc.). Assuming that this is true, what would your explanation be as to why?
3. List the problematic features of the Muddle culture that were identified in the case study. Discuss how these may have originated and why they haven't been addressed.

CHAPTER 2

History—and Implications

DON'T KNOW OR CARE MUCH ABOUT HISTORY?

Some of the remarks I often must endure whenever I begin any discussion of the history of manufacturing in either my university classes or training courses include

- "Let's just get to the meat of things!"
- "Who cares about history? I just want to learn how to improve factory performance!"
- "How long is this going to take?"
- "Gee whiz, Doc! We all know that the Toyota Company invented manufacturing; we're not stupid."
- "Why don't we just copy Toyota's methods and cut to the chase?"

So how does one respond to such complaints? To answer this question, it is necessary to understand why such questions are asked. One reason, I believe, is an almost frenzied desire on the part of some individuals to be provided with a quick and easy solution to their current problem. They have a problem, and they want an "answer" ASAP. It's as simple to them as that. Any discussion other than that which will solve their problem *du jour* immediately is considered irrelevant. Another—even more troubling—reason is that some people simply do not appreciate how a discussion of the history of manufacturing, no matter how brief, could be of any conceivable value to them.

My response to such individuals consists of two parts. The first part addresses the current interest in the Toyota production system, a.k.a. *lean manufacturing.* At the time this book is being written, lean manufacturing is being touted as the answer to improved factory performance (as well as improved health care, accounting, etc.). Tutorials and presentations on lean manufacturing now dominate most conferences held by professional societies having anything to do with manufacturing—much like reengineering tutorials and presentations did a decade or so ago.

The efficiency and effectiveness of the Toyota Company, however, cannot and should not be ignored or underestimated. Toyota became so superior in terms of profit per car, customer satisfaction, product reliability, and almost any other ingredient leading to dominance in an industry that it is now the role model other firms desperately hope to emulate. Such firms typically do so by copying what they see (e.g., via visits to a Toyota factory) and even employing the same Japanese words and phrases that Toyota uses to describe its methods. But these firms remain blissfully unaware of or simply choose to ignore the equally if not more important aspects of the firm that they don't see.

The result is that most firms that attempt to copy the Toyota production system (i.e., implement lean manufacturing) either fail to attain or are ultimately unable to sustain performance improvement. The failure/disillusionment rate of lean manufacturing has been estimated to range from 70 to 90 percent. In fact, even some of the strongest advocates of the methodology go so far as to claim a 95 percent failure/disillusionment rate. (This is, by the way, very much the same failure rate incurred by the firms that adopted reengineering—the alleged answer to either organizational or factory performance improvement in vogue a decade or so ago.)

However, if you are familiar with the history of manufacturing, there is an answer—or at least a partial answer—to why so few firms are able to implement the Toyota production system successfully, whereas most others ultimately fail in their attempt. The question as to why Toyota has been successful and most other firms have not is addressed later in this chapter. Next, however, allow me to continue my response to those who doubt the need for an introduction to the history of manufacturing.

The second part of my answer to the question of a need for an appreciation of the history of manufacturing is to employ an analogy—one dealing with warfare. I ask the skeptics if they would have faith in a general or admiral who had little or no (real, factual) knowledge of the history of warfare, particularly the history of both the successful and failed strategies and tactics that have been employed in battles. If a person's answer to this question is, "Yes" (i.e., he or she has no problem with relying on a military leader who is ignorant of the history of warfare), then such an individual is probably beyond help.

If, on the other hand, one can comprehend the need for a military leader (and his officer corps) to have an appreciation of the history of military strategy and tactics, then that person should be equally receptive to the belief that it is just as vital for the factory engineer or manager to have an appreciation of the history of the strategies and tactics that have been introduced into the "battleground" of the factory. That person should want to know which of these produced successful results and which failed—and, just as important, why.

Despite this argument, I sometimes encounter factory engineers and managers who continue to rely on strategies and tactics that have failed in the past—and who stubbornly resist any argument for change. An ignorance of the history of manufacturing makes you easy prey for the voracious herds of management gurus, management consultants, and motivational speakers who too often want to sell you old ideas under a newer, fancier, and more expensive "wrapper."

Beware, in particular, of consultants and gurus who "dumb down" concepts and methods so as to suggest to factory engineers or managers that performance improvement is possible simply by means of a few clever-sounding rules and guidelines. While certain rules and guidelines are (when understood) useful, they are not sufficient. Management fads and fashions, however, may rely almost totally on slogans, rules, principles, and guidelines while failing to explain the "why" and "how" of their methodology. In a factory, however, that "why" and "how" require an appreciation of the science of manufacturing.

While conducting a survey of management books and articles, I found that more than 50 management fads and fashions have been introduced over the past 50 years.[1] The failure and/or

---

[1] A *fad* or *fashion* is a concept (e.g., a diet plan for the obese) that is enthusiastically embraced by a specific group of individuals (e.g., people concerned about their weight) for a relatively short period of time—followed by waning interest. The typical lifetime of a *management* fad ranges from 5 to 10 years, although a small group of "true believers" may never abandon their faith in a given fad. The similarity between the adoption and abandonment of management fads and diet fads is uncanny.

disillusionment rate of these fads and fashions typically ranges from 70 to 90 percent—or more.

In almost every case, these fads and fashions are based on concepts that originated decades or even centuries ago. In many cases, they actually have a kernel of truth. They disappoint, however, mainly because of

- A failure to provide the support necessary for success—particularly the essential support and engagement of top management.
- A failure to appreciate the limitations of the concepts—that is, there are no magic wands that can easily, quickly, and effectively address or solve every problem.
- A failure to appreciate that the majority of the problems induced by years of bad decisions cannot be rectified in just a few days, weeks, or even months.
- A failure to appreciate that it takes far more than a week or two of "training classes" to become an expert in the politics, art, and science of manufacturing.
- A failure to appreciate that you simply cannot turn just anyone into an expert.[2]
- A focus on the symptoms of the problems within the factory rather than an identification and appreciation of their causes.
- An outright misapplication of the concept embraced—that is, failing to use the right people, having the right training, supported by the right methods, on the right problem.

With this background in mind, let's move on to an abbreviated discussion of the history of manufacturing. This history has been divided into three parts: (1) from ancient times up to and including World War II, (2) post–World War II until now, and (3) the present. After completing these sections, you will be better able to intelligently discuss why the Toyota Company has been so successful and most of its imitators have not.

---

[2] I continue to be dismayed that so many firms have such a disquieting ability to pick possibly the very worst person or persons to lead their factory performance-improvement efforts. This may be yet another example of how politics and personalities sabotage even the best intentions.

HISTORY UP TO AND INCLUDING WORLD WAR II

While the scope and purpose of this text do not allow for in-depth coverage of each and every development in or influence on the evolution of manufacturing, a few of the more important events will be introduced. In reading this material, you will see clearly that there has been and continues to be—like it or not—a significant influence on manufacturing as a consequence of the needs, nature, and evolution of warfare.

Sun Tzu; the Battle of Thermopylae

In 480 BC, the Greek city-states were faced with an invasion by the Persian emperor Xerxes. The Greeks were vastly outnumbered by Xerxes' forces, but a small and determined band of warriors, some 300 Spartans and several hundred Thespians, attempted to hold them off (a delaying action evidently intended to allow other Greek forces time to regroup) at a choke point at Thermopylae. Outnumbered by at least 10 to 1 (some say 50 or even 100 to 1), the small Greek force, led by King Leonidas of Sparta, kept the enemy at bay for three days and even inflicted enormous casualties on the numerically superior Persian invaders.

During those three days, the forces of Xerxes attempted one frontal assault after another—suffering horrific losses each time. The Persian forces were only able to capture the pass after a local resident betrayed the Greeks and showed the Persians a little-known mountain path (i.e., a way to bypass the choke point on the battlefield) that led to a position behind the troops of Leonidas.

Centuries before the battle of Thermopylae, the importance of choke points (termed *bottlenecks* or *constraints* within the environment of a factory) was well known and documented. For example, *Sun Tzu's Art of War* (Barnes & Noble Classics, 2003), a volume written more than 2,000 years ago, cites the use of choke points in both offensive and defensive situations. Military leaders in relatively more recent times (e.g., Henry V of England, Napoleon, Wellington, Mao Zedong, and the British Admiralty in both World War I and World War II) have been equally aware of the crucial importance of choke points.

The lessons learned with regard to choke points in warfare were carried over into the environment of the factory. For example, the existence of choke points in the Model T factory was recognized and dealt with effectively by Henry Ford's advisors roughly 100 years ago.

The technical aspects of choke points within a factory were addressed in the mid-twentieth century by a number of academicians, including Katsundo Hitomi (Hitomi, 1996). Their papers and books, however, were thought to be written at such an esoteric level of mathematics that they received little attention outside academia.

In the 1980s, the existence and importance of choke points within a manufacturing environment were reintroduced by Eliyahu Goldratt and Jeff Cox (Goldratt and Cox, 1984) in their best-selling book, *The Goal*. Rather than employing the off-putting mathematical treatment of academicians on this subject, Goldratt and Cox provided a simple analogy (i.e., a group of Boy Scouts on a hike) and a set of straightforward steps for the identification and "elevation" of choke points (i.e., factory constraints). As a result of the simplicity of their treatment of bottlenecks, coupled with the employment of a simple analogy, a sizable number of factory engineers and managers who had previously overlooked or ignored factory choke points suddenly became true believers in what Goldratt and Cox term the "theory of constraints."[3]

The Arsenal of Venice

One of the most prominent examples of the influence of warfare on manufacturing occurred at the Arsenal of Venice (Wills, 2001). From about the twelfth through the nineteenth century, the most important manufacturing effort of the arsenal was the assembly of ships and cannons, particularly those used for naval warfare.

The Arsenal's most famous warship was the *galea sottile* (a thin or long galley). In addition, the Arsenal produced a variety of other ships, including the *galea grossa* (a large merchant ship).

The first moving assembly line for the production of vehicles (the vehicles being ships in this case) was implemented at the Arsenal of Venice—centuries before the moving automobile assembly lines of Ransom Olds and Henry Ford. Beginning with the keel,

---

[3] It must be noted, however, that the choke points in warfare (e.g., mountain passes and narrow ocean passageways) are *fixed*. Their position is both known and constant. In a factory, on the other hand, there are *multiple and migrating* choke points/constraints. Unfortunately, these aspects of the real-world factory are often overlooked or downplayed—resulting in an overly simplistic treatment of factory constraints. More will be said about this in subsequent chapters.

the work in progress (a.k.a. *WIP*) was floated down a canal. At points along the route, warehouses were strategically located, and a specifically trained subset of Arsenal workers would perform a predetermined set of steps of the assembly process. At the end of this moving assembly line, a completely outfitted and manned ship sailed into the Mediterranean, ready for duty. As is the case of the Toyota assembly line of today (and unlike the less flexible assembly line employed for the Model T), a variety of types of ships could be produced at any given time.

Documentation indicates that by the sixteenth century, the art of manufacturing at the Arsenal of Venice had advanced to the point where it was possible to assemble a warship in as little as an hour (e.g., King Henry III of France is said to have witnessed such a feat of moving-assembly-line manufacturing in 1574). The more typical (but still impressive) production rate, however, was on the order of one to three ships a day. When compared with the several months of assembly time required per vessel by shipbuilders in other countries, the Arsenal of Venice's factory performance was a marvel of its time.

The Arsenal is said to have employed as many as 16,000 workers in its heyday, each housed in publicly owned accommodations close to their work. The Arsenal was considered such a miracle of shipbuilding that "industrial tourists" from all over the world visited the site—very much akin to the manner in which wide-eyed modern-day industrial tourists make their pilgrimages to Toyota factories.

Nor did the methods employed by the Arsenal of Venice escape the eyes of the scientists, mathematicians, and engineers of that time. Galileo (who moved to the Venetian Republic in 1592) credits his visits to the Arsenal and discussions with the workers there with the establishment of his two new sciences: the strength of materials (e.g., as required in the construction of ships) and an understanding of accelerated motion (e.g., as exhibited by the cannons built at the Arsenal) (Galileo, 1638).

Even Dante Alighieri, author of the *Divine Comedy* ("Dante's Inferno") mentions the maintenance activities conducted at the Arsenal in his verses. The excerpt from Canto 21 that describes this follows:

As in the Arsenal of the Venetians
Boils in the winter the tenacious pitch
To smear their unsound vessels o'er again,

For sail they cannot; and instead thereof
One makes his vessel new, and one recaulks
The ribs of that which many a voyage has made;

One hammers at the prow, one at the stern,
This one makes oars, and that one cordage twists,
Another mends the mainsail and the mizzen;

Thus, not by fire, but by the art divine,
Was boiling down below there a dense pitch
Which upon every side the bank belimed.

Based on records that survive, it would appear that such methods and concepts as just-in-time manufacturing, modular manufacturing, flexible manufacturing, preventive maintenance, standardized parts, inventory control, waste control, employment of external setups,[4] establishment of worker pensions, and efficient methods for staffing, training, accounting, and production control were employed. The end result of these developments (of what are now considered to be the basis of modern manufacturing) was a moving-assembly-line process that approached the ideal state, that is, a single-unit continuous-flow assembly process. In fact, it was not until Ford's assembly line for the Model T that any other assembly-line factory came close to the efficiency of the Arsenal.

Despite the advances in manufacturing developed at the Arsenal of Venice, these concepts were not transferred to any significant degree to other types of manufacturing. Possibly it was believed that they only applied to shipbuilding. As a consequence of this limited perspective, these concepts, now so vital to efficient modern-day manufacturing, had to be reinvented decades and even centuries later.

Matthew Boulton and the Soho Factory

Skipping ahead several centuries, let's consider the impact that the Englishman, Matthew Boulton (and his business partner, James Watt—whose refinements served to vastly improve the steam engine), had on manufacturing. Boulton was an inventor, a

---

[4] Externalized setups consist of the conduct of setup activities that may be performed *while a machine is still running* rather than shutting the machine down (a concept developed independently by Frank Gilbreth and termed *SMED* by the Japanese).

businessman, and—most important—a leader and visionary. In 1765, his most advanced factory was completed.

Boulton's Soho factory was three stories high and included workshops, showrooms, offices, and inventory stores. Boulton even provided accommodation for his employees (Encyclopedia Britannica, 2008; Cooke-Taylor, 1886; Usher, 1920).

The Soho factory was a model of manufacturing efficiency and employed (contrary to the bleak images of more typical factory conditions provided by Charles Dickens) a safe and clean work environment. Boulton employed interchangeable components and a variety of advanced manufacturing methods. Accompanying these technical advances was the use of well-lit, clean, orderly, and properly ventilated facilities, as well as an obsession with regard to the reduction of waste. Boulton went so far as to have the walls of the Soho factory painted a clean, bright white—all the better to quickly identify dirt and clutter or any other form of waste.

Boulton even provided his workers with accident and death benefits. Their contributions of 1/60th of their compensation provided benefits of up to 80 percent of their wages. In addition, and unlike the majority of factory owners of the time, Boulton refused to hire young children.

Boulton and his partner, James Watt, had a major influence on the first industrial revolution. With Boulton's encouragement and assistance, Watt's steam engine was converted from its original vertical movement (e.g., as used to pump water from mines) to a rotary-motion machine. This provided factories with a means to run their machines (e.g., an alternative to the use of water wheels). The steam engine in factories led to the first industrial revolution and the (steam-driven) railroads led to the second.

The American System of Manufacturing

The period from 1800 to 1932 has been designated as the time of the American system of manufacturing (Coman, 1930; Hounshell, 1984). The practices that distinguished this system from those used previously or by other countries were the employment of machine tools and templates (a.k.a. *jigs*)[5] in place of hand-crafted production. The machine tools increased the processing speed of the factory,

---

[5] The importance of templates, or jigs, for the achievement of tight tolerances is possibly the least appreciated of the concepts developed for the achievement of mass production.

and the jigs provided the foundation for tighter parts tolerances (which led to the practicality, as opposed to just the theory, of interchangeable parts).

Since parts were interchangeable, it was possible to separate manufacture (e.g., the forming of each individual part of a product) from assembly. The simplified assembly process, in turn, permitted the use of semiskilled (and lower-cost) workers in place of skilled craftsmen.

As with many other advances in manufacturing, the American system came about as a consequence of the needs and funding of the military. America's armories were encouraged to produce muskets with interchangeable parts. While Eli Whitney is erroneously given credit for the development of interchangeable parts, the first practical and successful development of methods for the production of high-precision interchangeable parts (for muskets) was accomplished in 1820 by Captain John H. Hall (Hall served as a contractor to the Armory at Harper's Ferry).[6]

The methods developed in America for the practical and cost-effective introduction of interchangeable parts soon migrated to the factories of that time. Early adopters included firms that produced clocks, sewing machines, bicycles, and woodworking and farm equipment. The most prominent of these adopters was, of course, the Ford Motor Company in the first two decades of the twentieth century (Ford, 1922; Hounshell, 1984; Levinson, 2002).

Scientific Management

Concurrent with the development and refinement of the American system of manufacturing was the advancement of the philosophy, concepts, and methods of scientific management (Alford and Beatty, 1951; Gilbreth, 1909, 1911; Taylor, 1911; Walton, 1986). Some of the pioneers of this field and a very brief sample of the concepts they conceived and introduced are listed in Table 2.1. In the far right-hand side of the table are some alternative words or phrases used to describe some of these notions—words and phrases sometimes

---

[6] As noted in the discussion of the Arsenal of Venice, the use of interchangeable parts was evident there, centuries prior to the accomplishment of Captain Hall. Matthew Boulton also employed interchangeable parts in his Soho factory. The assembly of muskets, however, required levels of parts tolerances beyond those employed in the construction of the ships by the Arsenal of Venice or the variety of artifacts (e.g., buttons and toys) manufactured by Boulton.

TABLE 2.1

Scientific Management pioneers and their contributions

Name of Scientific Management Pioneer	Contributions	Alternative Word or Phrase
Frederick Taylor	Scientific management and industrial engineering Preventive Maintenance Time study Piece-rate incentives	Japanese production system Total productive maintenance
Henry Gantt	Graphic aids (Gantt chart) Extensions of Taylor's work	–
Frank Gilbreth	Process step mapping Externalized setups Motion study "Seventeen basic motions"	Value stream maps SMED
A.K. Erlang	Queuing theory and models	–
Walter Shewhart	Continuous improvement PDSA (plan, do, study, act) or PDCA (plan, do, check, act); a.k.a. the "*Shewhart Cycle*" Total quality management Statistical-based quality control Control charts	*Kaizen* Ishikawa circle
Ford Motor Company and American grocery stores (early twentieth century)	Just-in-time manufacturing Fast cycle time	Taiichi Ohno's JIT
Ford Motor Company (early twentieth century)	Error proofing Assembly line signals/alarms Waste walks "Go and see" CANDO (reduction of clutter in the workspace and factory floor) Machines organized according to the sequence of operations Design for manufacturability Sorenson proxy (the assignment of jobs to machines in a given workstation that must support several process steps)	*Poka-Yoke* Andon Muda elimination Genchi Genbutsu 5S or CANDO

employed by those teaching the topic of lean manufacturing (or the Toyota production system).

The last two segments of Table 2.1 list just a few of the many protocols of scientific management either introduced or developed within the Ford Motor Company by Henry Ford's staff. The lessons learned by Ford's people in automobile production ultimately led to the introduction of analogous concepts into the production of military equipment during World War II.

The impact of these methods on wartime manufacturing is something that should not be forgotten by factory engineers or managers. The implementation that received the most attention, particularly in Japan, was the "bomber an hour" effort directed by Charles Sorenson of the Ford Motor Company (Nolan, 1997).

Bomber an Hour

In World War II, the crucial role of aircraft in warfare was finally recognized. The need for aircraft by the Allies, however, far outstripped existing manufacturing capabilities—at least until techniques originally developed for the manufacture of automobiles were introduced into the assembly lines for aircraft.

One of the most important and effective aircraft of World War II, particularly in the battle against Japan, was the B24 bomber, known as the *Liberator.* At the start of hostilities, the U.S. Army Air Corps had hoped to assemble one B24 a day at the Willow Run factory. In support of this seemingly overly ambitious goal, the assistance of Henry Ford's best and brightest advisors was sought. Charles Sorenson (Ford's production chief) and his team devised a set of manufacturing protocols—based on their success with the rapid assembly of Ford automobiles—that enabled the Willow Run facility to vastly exceed the bomber-a-day goal. Once the bugs were ironed out, the procedure enabled the assembly of a bomber an hour.

Operational Research in World War II

During World War II, the academician C. H. Waddington (a pioneering figure in both operational research and genetic algorithms) maintained a diary that detailed the efforts of an operational research (OR) team in support of the British Air Coastal Command. That command was, in turn, dedicated to the battle against the German U-boat. Waddington's diary was declassified in 1973 and released by Elek Science Publishing under the title, *OR in World War 2: Operational Research Against the U-Boat* (Waddington, 1973).

Waddington's book should be mandatory reading not just for military officers but also for managers, engineers, and scientists of all stripes—including in particular factory managers and engineers. Waddington describes methods employed successfully for the solution of a host of military problems ranging from maintenance to personnel staffing and training to flight assignments to the strategies and tactics employed in actual combat. He also describes the push-back the OR groups received from the military and the political climate that had to be dealt with. Strikingly similar problems—and politics and resistance to change—exist in the factory.

While the scenario (i.e., World War II) may seem like ancient history to some readers, the same problems encountered then are still faced in both the military and industrial sectors of today. Our aircraft may now be jet propelled and our factories might be automated and populated by robots, but the methods employed by OR groups more than six decades ago apply equally well today.

For example, factories that have adopted the methods described in Waddington's journal have experienced improved performance. This has been particularly true in the area of maintenance—one of the most overlooked factors determining factory performance.

Several of the methods described by Waddington will be discussed in detail in subsequent chapters. These include

- *The Waddington effect plot.* This is a means to determine if preventive maintenance events are actually doing more harm than good.
- *Waddington analysis.* A procedure for the development of C⁴U-compliant operating or maintenance specifications[7]—and reduction of complexity.
- *Maintenance personnel staffing and training.* The assignment of maintenance personnel to workstations so as to reduce the "wait for tech" time in the factory.

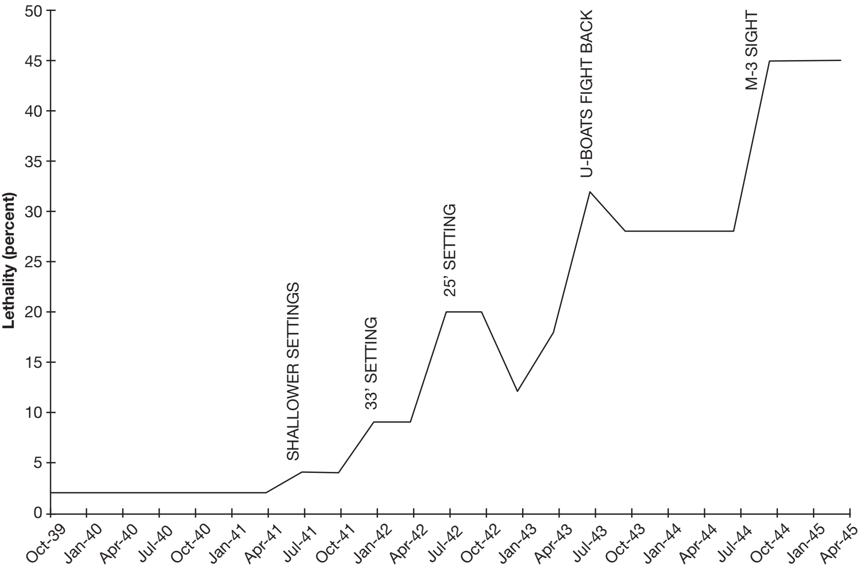
More to the point, Waddington's book illustrates the importance of protocols, the core of the third dimension of manufacturing. This crucial point is made evident in the graph of Figure 2.1

---

[7] Recall that C⁴U-compliant specifications are those that are "complete, clear, concise, correct, and unambiguous."

FIGURE 2.1

Percent lethality of attacks on U-boats.



(based on a plot in Waddington's text). Note that the horizontal axis is in years, whereas the vertical axis represents the percent lethality of attacks on U-boats.

Despite the crucial importance of dealing with the German U-boats, the lethality of air attacks (i.e., probability of sinking or severely damaging a U-boat first detected on the surface) was pathetically small during the first two years of World War II. As may be seen in Figure 2.1, the probability of a lethal air attack on a U-boat was only about 1 or 2 percent—and possibly less (i.e., the claims by some pilots may have exaggerated their successes).

The military brass of the British Air Coastal Command believed that the degree of lethality could be improved most effectively by means of predominantly physical changes, specifically changes involving the manufacture of more aircraft and the development and implementation of improved weapon systems. Just like many factory managers of today, they restricted their focus to changes they could see, count, and touch—matters with which they felt most comfortable.

The members of the British OR group supporting the Air Coastal Command proposed, instead, the adoption of a variety of controversial (to the British Admiralty) protocols (i.e., policies and procedures). Possibly the most important of these was the recommendation that the depth charges (known as *sticks*) dropped from its planes be set to explode at a level of 25 feet below the surface as opposed to the much deeper settings (100 to 200 feet) usually used.

The reaction of the British Admiralty was, in a word, contempt. What, after all, could a bunch of silly academicians teach the military about warfare?

In light of the damage inflicted by the German U-boats, however, the Air Coastal Command ultimately and reluctantly agreed to reduce the depth-charge setting. Rather than the 25-foot setting recommended, though, the charges were set to explode at about 50 feet. The impact of this reduced setting is evident in the increase in lethality beginning in the spring of 1941. This success motivated the Air Coastal Command to implement an additional reduction in the setting to about 33 feet in the summer of 1941.

The impact of this decision is also obvious in Figure 2.1. The original 25-foot setting was finally implemented in the summer of 1942—and resulted in yet an additional increase in lethality.

By the conclusion of the war, the probability of a lethal attack on a German U-boat by an Air Coastal Command aircraft was on the order of 40 to 45 percent (the physical and psychological impact of this attrition rate on German U-boat crews is captured in the movie, *Das Boot*). While not all the improvement in lethality was due to changes in operational protocols, the overall impact of protocols in the battle against the U-boat is unmistakable.

In addition to the OR group's recommendations for reduced depth-charge settings, an investigation of aircraft maintenance events and their scheduling was conducted. It was discovered that the preventive maintenance (PM) events themselves were inducing unscheduled downs. Unscheduled downtime, in turn, significantly reduced the number of hours that a plane could be airborne and searching for a U-boat.

Waddington describes both the impact of these problematic PM events and the approach employed (i.e., a change in protocols) to alleviate the situation. The overall result was an increase in the effective size of the Air Coastal Command's air fleet on the order of 60 percent![8]

---

[8] Think about what such an increase in the effective capacity of the machines in a factory could provide in terms of factory performance improvement. In other words, instead of spending money on buying more machines, a quicker and far less costly alternative may be to simply reduce unscheduled downtime.

Unfortunately, many of the lessons learned with regard to the use of protocols for performance improvement as developed by the OR group were either forgotten or ignored after World War II. Since these can play a major role in factory performance improvement, some of them will be covered and illustrated in subsequent chapters. Next, however, I briefly discuss an important but overlooked methodology for performance improvement (particularly for sustaining improvement) designated *Training Within Industry.*

Training Within Industry (TWI)

The demand for ships by the Allied forces during World War II was enormous, particularly in light of the damage inflicted on them by German U-boats (a matter discussed previously). The same was true for every other weapon or weapon support system. While America had vast natural resources, its capability for producing these essential items was severely limited as a consequence of inefficient manufacturing practices. In response to the need for improved production performance, a training program, labeled *Training Within Industry* (TWI), was developed.

The TWI program, implemented by means of a straightforward set of lessons, served as a catalyst for significant improvements in factory production within the United States. An illustration of this is captured in the plot provided in Figure 2.2 (War Production Board, Bureau of Training, 1945).

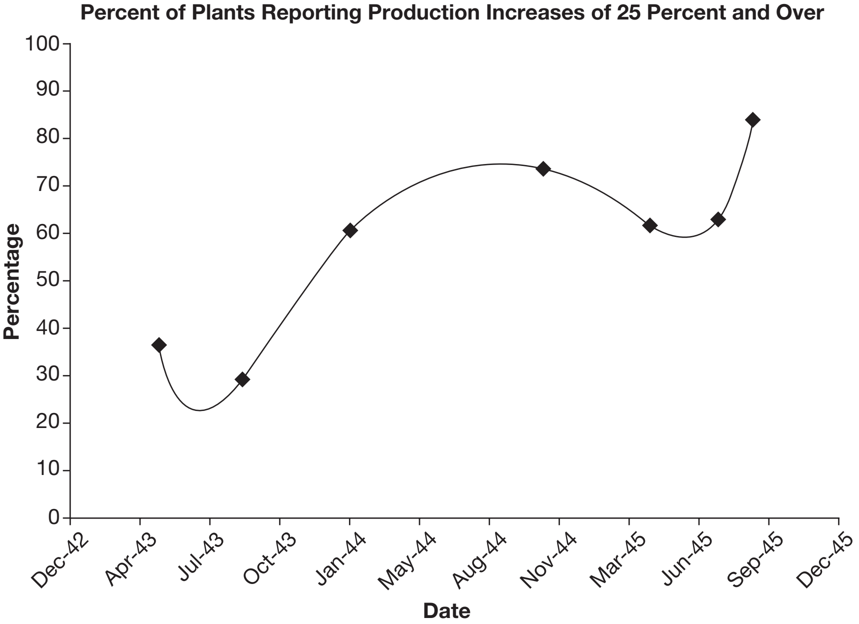
Quite simply, over the period from May 1943 through September 1945, the percentage of American plants reporting increases in production of more than 25 percent rocketed from 37 to 86 percent. Much of this improvement was credited to TWI.

While the reference (War Production Board, Bureau of Training, 1945) fully describes and discusses TWI, the most pertinent point is that TWI was introduced into Japan following World War II. Not only was it introduced there, but it also was eagerly embraced—particularly by the Toyota Company, where it has been credited with forming the "roots of lean manufacturing." Unfortunately and ironically, at almost the same time Toyota adopted TWI, it was virtually abandoned (as well as conveniently forgotten) in the United States.

Manufacturing firms in America saw no need for TWI at the end of the war. Even with inefficient production methods and obsolete factories, they could produce shoddy goods that were eagerly purchased by American consumers. With the rise of a new type of American CEO—focused on short-term results and cost

FIGURE 2.2

Impact of TWI program.



cutting—it was left to the Japanese, particularly the Toyota Company, to adopt and benefit from the TWI lesson plans provided to them by American trainers.

TWI may be considered a missing link between what is termed *lean manufacturing* and its successful and sustainable implementation. The failure to employ or even be aware of TWI might be a key reason for the huge failure rate of lean manufacturing efforts in the United States—and this is yet another illustration of the need to be aware of the history of manufacturing.

HISTORY: POST–WORLD WAR II TO PRESENT

Following World War II, the Japanese economy and industry were in shambles. General Douglas MacArthur, supreme commander of the Allied Powers in Japan from 1945 to 1951, took actions that would forever change both the social structure and manufacturing methods of Japan. One of the most significant of these was to encourage and buttress the rebirth of Japan's manufacturing sector.

In support of MacArthur's goals, the Japanese Union of Scientists and Engineers (JUSE) invited a number of American academicians and consultants to provide educational and training programs in support of the reengineering of Japanese manufacturing. Prominent among these Americans were W. Edwards Deming and Joseph Juran (Walton, 1986), two men who could—and probably should—be called the "fathers of Japanese manufacturing."

In 1950, Deming trained scores of factory engineers and managers in Japan. Among the attendees of Deming's classes were a large number of senior-level managers, including CEOs. Deming remarked that when his classes were offered in the United States, virtually no interest was shown on the part of management. Yet, when offered in Japan, the very same classes attracted Japanese managers at all levels.

Deming's lectures were focused on three primary areas: (1) the employment of Walter Shewhart's PDCA (plan-do-check-act) cycle, (2) an appreciation of the causes of variability, and (3) process control via Shewhart's control charts. At roughly the same time, other Americans were training the Japanese in the methods of TWI.

In 1954, Joseph Juran was invited to lecture the Japanese on management's role in the promotion, support, and implementation of quality control programs. Juran emphasized that managers had the responsibility to lead such efforts (in sharp contrast to most American managers at the time, who took no part—or interest—in leading any type of factory performance-improvement programs). It was emphasized that managers, up to and including the CEO, had to be involved in factory performance improvement—rather than delegate that responsibility to their people.

As a consequence of such lectures and advice, Japanese managers and factory workers became involved in the reincarnation of manufacturing in that country. Henry Ford's book on manufacturing became a Japanese best-seller there (much like books on Japanese management have now become best-sellers in America). There was even a popular weekly radio program that served to train both factory managers and workers in statistics.

In the United States, however, virtually no interest in Deming's and Juran's efforts was exhibited by American management. It was, in fact, not until the unanticipated and unwelcome "invasion" of Japanese automobiles in the 1970s and 1980s that any significant attention was paid to the Japanese production system (Pegals, 1984).

Examining the accomplishments of the Japanese or Toyota production system, readers should note that the foundations of Japanese success rested on the introduction and employment of manufacturing protocols—most of which, ironically, originated in America and were either ignored or abandoned by American management following World War II. Instead, as mentioned, the emphasis of American management was (and, for the most part, still is) focused almost exclusively on cost cutting and short-term performance.

Apollo Manned Moon Landing Program

My own introduction to the importance of protocols came as a consequence of my responsibilities as an engineer and, later, a manager in America's manned moon landing program. The manned moon landing mission required the construction and assembly of an enormous three-stage booster rocket (the Saturn V launch vehicle), the three-person Apollo space capsule, and the Lunar Excursion Module (LEM).

To successfully fulfill President John F. Kennedy's promise to land our astronauts on the moon by the end of the decade (i.e., by 1969), a combination of physical developments (e.g., the design and production of the components of the launch vehicle, spacecraft, and ground support systems) and protocols was required. Ignorant of the methods described in Waddington's book (which was not declassified until 1973), we went about revising, refining, and reinventing protocols for the development and validation of what are now termed *C^4U-compliant specifications*.

In addition to the development of a methodology for C^4U-compliant specifications, protocols were introduced for

- Optimized deployment of antennas on the vehicles (Ignizio, 1962) [which may be used in a factory to locate workstations and parts and supply centers (Ignizio, 2003a)]
- Complexity reduction in the steps of the launch countdown procedure
- Mitigation of the Waddington effect (e.g., although the term *Waddington effect* was not used at the time, we became aware that many of our well-intentioned maintenance, test, and inspection methods actually caused more problems than they solved)

- Improved methods for both the scheduling and declustering of events

While there is little, if any, mention of such protocols in the articles and books on the history of the Saturn/Apollo program, I can assure you that they played a significant role in its success. More important to this text, however, is the fact that lessons learned in that effort are directly transferable to factory performance improvement—as will be illustrated in chapters to follow.

THE PRESENT: LEAN MANUFACTURING

Over the past 50 or so years, numerous concepts (e.g., reengineering, quality circles, total quality management, total productive maintenance, Six Sigma, zero defects, management by objectives, management by walking around, etc.) have been proposed for the improvement of factories and entire organizations and industries. Some of these have shown promise, whereas others have been relegated to the dustbin of history. Lean manufacturing, one of the most recent methodologies (at least in terms of interest), has exhibited—*when employed by the right people, in the right manner, to the right problem*—the potential to fulfill the promises of its advocates. Despite this, lean manufacturing's failure and disillusionment rate, as mentioned, has been extraordinarily high. The primary reason for the 70 to 90 percent failure/disillusionment rate has been mainly due to three problems: (1) the lack of support and involvement by management, (2) the failure to balance the rules and guidelines of lean manufacturing with the science of manufacturing, and (3) employment by the wrong people in the wrong manner on the wrong problem.

One artifact of lean manufacturing that has seemed to have a significant and positive impact on at least some factory managers and engineers has been the citation of the so-called seven wastes (Liker, 2004). This listing, by itself, has made many people more aware of the impact of certain behaviors on factory performance. The seven wastes are

- *Overproduction.* Producing items for which there are no orders or market.
- *Waiting.* Waiting for batches to form or waiting for spare parts.
- *Unnecessary transport.* Excessive transit time and unnecessarily long transport paths.

- *Overprocessing or improper processing.* Employing unnecessary operations (steps) in the processing of jobs or using inefficient processes.
- *Excessive inventory.* Excess raw materials or using inventory as a buffer to mitigate inefficient factory protocols.
- *Unnecessary movement.* Wasted motion or excessive walking.
- *Defects.* Producing an excessive number of defective parts and the possible scrapping of the defects or the corresponding need to correct those defects.

While all of the seven wastes were pointed out previously by the pioneers of scientific management, Toyota compiled these and brought them to the attention of a much more receptive audience. To these seven wastes, I would add five more:

- *Wasted opportunities.* The opportunities to reduce factory cycle time are, in any firm, enormous. Unfortunately, the enormous benefits of fast cycle time are often ignored.
- *Time wasted in meetings.* Anywhere from 50 to 70 percent of the time spent in meetings is wasted. This is particularly true when the meetings are used as a means for some of the attendees simply to gain "face time."
- *Time wasted chasing fads.* Instead of expending time, energy, and resources on every management or manufacturing fad that happens to be in the news, first perform a rigorous assessment of the validity of these notions.
- *Suboptimization.* Suboptimization (e.g., a focus on the attainment of optimal performance at one workstation in the production line while ignoring the impact on the entire factory) is a major source of waste. Rewarding efforts that only serve to suboptimize amplify their negative impact.
- *The waste of human creativity.* The most serious waste of all is that of human creativity, that is, ignoring the concepts, ideas, and enthusiasm of your best and brightest employees.

I might even add a thirteenth waste, that of ignoring the lessons of history. Why, for example, has Toyota been so successful, whereas the bulk of its imitators have not? This question will be dealt with in a later section. First, however, let's discuss a recent concept that is often associated with lean manufacturing—the Six Sigma process.

SIX SIGMA

At this point in time (i.e., 2009), the two approaches receiving the biggest buzz in the manufacturing sector are lean manufacturing and Six Sigma (and a combination known as *Lean Six Sigma*). The preceding section has dealt with lean manufacturing. Here, I provide a brief description and assessment of Six Sigma.

A Google search produced the following definitions of Six Sigma:

- "A method or set of techniques . . . focused on business process improvement."
- ". . . a failure rate of 3.4 parts per million, or 99.9997 percent."
- "A systematic method for improving the operational performance of an organization by eliminating variability and waste."
- "A quality management and process improvement methodology particularly well suited to process-intensive industries like manufacturing."
- "An invention of Motorola in the 1980s . . . ."
- ". . . a management philosophy developed by Motorola that emphasizes setting extremely high objectives, collecting data, and analyzing results to a fine degree as a way to reduce defects."

Other than the fact that Six Sigma cites a very specific goal (3.4 parts per million) for failure rate and its practice of assigning belts of various colors to it advocates, one would be hard pressed to distinguish the concept and its tools from those of the fields of either operations research or industrial engineering. Joseph Juran, one of the handful of people responsible for the rebirth of Japanese manufacturing, stated that "there is nothing new here" when referring to Six Sigma. He went on to say that "they've adopted more flamboyant terms, like belts with different colors" (Paton, 2002).

While, as is the case with lean manufacturing, there is nothing fundamentally wrong with Six Sigma—when applied by the right people to the right problem in the right manner—its early hype has been subdued by recognition that it is not necessarily the answer. This is particularly true when it is implemented by those seeking a quick and easy fix. An article in *Industrial Engineering* (Del Angel and Pritchard, 2008) discusses "the rising concern across industry sectors regarding the failure of many Six Sigma and Lean projects."

A couple of quotes from that article follow:

- "Nearly 60 percent of all corporate Six Sigma initiatives fail to yield desired results."
- ". . . many corporations are pulling back on specific change initiatives realizing that the Six Sigma methodology by itself is not the cure-all for corporate ills."

The authors recommend, as a means to avoid this high failure rate, the use of a "behavior-focused approach."

Unfortunately, the typical approaches employed in the implementation of Six Sigma lead, as noted by Del Angel and Pritchard, to a 60 percent failure rate—close to the 70 percent failure rate of lean manufacturing. Returning, however, to our earlier discussion; why is it that Toyota evidently has managed to avoid this failure rate and disappointment? What exactly is Toyota doing right and its imitators doing wrong? I return to this important matter in the following section.

A QUESTION: WHY TOYOTA?

The preceding discussion indicates that much of what is considered new and original with regard to approaches (particularly protocols) to factory performance improvement is actually just a reinvention or refinement—or renaming—of methods that originated decades or even centuries ago. This should not be surprising. Perhaps it is true that "there is nothing new under the sun."

What is surprising, however, is the fact that so few manufacturing firms have been able to adapt these methods—under whatever name—to achieve significant and (particularly) sustainable improvement in the manufacturing process. In fact, apparently only the Arsenal of Venice (for several centuries), Toyota (for about a half century), and Ford (for less than three decades) have been able to achieve truly noteworthy factory performance improvement over any significant period of time.

Even the Ford Motor Company, where many of the concepts now credited to the Toyota production system or lean manufacturing were developed, was able to sustain its heralded production system for Model T assembly for only a few decades. A host of companies in the United States and elsewhere have recently—or relatively recently—adopted (or claimed to have adopted) the Toyota production system/lean manufacturing, but the jury is out as to whether or not they can sustain, for any appreciable length of time, any real or alleged improvements provided by their implementation of that system. In fact, as has been noted, the failure/disillusionment rate for lean manufacturing is estimated to be in the range of 70 to 90 percent—a failure rate eerily similar to that of earlier performance-improvement attempts such as reengineering, total quality management, management by objectives, and quality circles.

In the introduction to this chapter I stated that an appreciation of the history of manufacturing may provide answers—or at the least some understanding—as to why Toyota has been so successful, whereas the vast majority of firms that seek to copy its approach fail to see significant and, in particular, sustained factory performance improvement. Let's now address, in a preliminary form, this issue.

Consider first those factors that enabled the Arsenal of Venice and Ford and now permit the Toyota Company to achieve their success. The most prominent among these are

- Leadership and vision
- A long-term perspective accompanied by the decision making necessary to support that perspective
- The support and involvement of top management, up to and including the CEO
- The establishment of and adherence to meaningful and realistic goals
- A willingness to listen—even to proposals that may happen to be critical of the existing culture and its protocols
- The support of a society that values and promotes real education, particularly in mathematics and science
- A continuing education in the art and science of manufacturing (i.e., rather than expecting a few weeks of training to turn just anyone into an expert)
- A recognition of the need to change coupled with the will to change
- A recognition that it may take years to see any significant and sustainable improvement—and that the journey to improved performance must never end
- The appointment of performance-improvement team leaders who are the firm's best and brightest—and the avoidance of political appointments
- Allowing the appointment of performance-improvement team members to be selected by the team leaders (see previous bullet)

- An appreciation of the history of manufacturing and a knowledge of what has worked . . . and what has not
- Patience and perseverance
- An emphasis on speed (i.e., fast cycle time)

A more detailed recipe for success in factory performance improvement is provided in Chapter 14. Next, however, the importance of fast factory cycle time is discussed.

THE NEED FOR SPEED

Pausing for a moment, consider one essential point—a point too often overlooked by today's factory engineers, managers, and owners. Whether it is the assembly of ships at the Arsenal of Venice, the manufacture of Model T's at the Ford Motor Company, the production of B24 bombers at Willow Run, the assembly of automobiles at the Toyota Company, or the fabrication of computer chips in the semiconductor industry, there is—or should be—one particular goal in common. That goal is *speed.* The focus on speed (i.e., fast factory cycle time) was—and is—paramount to success (Clason, 2003; Meyer, 1993).

Fast factory cycle time enabled Henry Ford to pay his workers more than twice the wages of his competitors and still capture the majority of the market for automobiles. Fast factory cycle time provided the Arsenal of Venice with the foundation necessary to maintain its position as a powerful city-state for centuries. Fast cycle time wins wars. Fast factory (and supply-chain) cycle time is the foundation on which the success of the Toyota Company has been achieved. The benefits of fast factory cycle time include

- Decreased levels of inventory (and reduced inventory holding costs)
- Decreased time to market (and increased net present value)
- Increased opportunities (e.g., freeing funds tied up in inventory)
- The fact that excursions may be identified and corrected in less time
- Increased knowledge turns
- Increased opportunities to run or expedite priority jobs
- Increased yield—or the ability to run cost-effectively with decreased yields
- Increased burst capacity

- Opportunity to trade off increased velocity for increased capacity
- Increased flexibility (e.g., the ability to change production policies faster and with quicker results)
- Opportunity to establish a disciplined and accountable approach to manufacturing
- Increased customer satisfaction—and a subsequent increase in market share

The fact is that in any competitive situation, only the fast and agile will survive and prosper.

Achievement of the goal of fast factory cycle time can be accomplished only if the factory, its organization, personnel, business processes, and manufacturing protocols are all efficient and effective. Of course, fast factory cycle time must deliver products of high (but not unnecessarily high) quality. [A recent example of how firms can achieve unnecessarily high quality was made evident in a report entitled, "Japanese Computer Chips Made at Too High Quality to be Competitive on World Market." Any reader not convinced that you can overdo an emphasis on quality is invited to read this report (TECHNEWS, 2006).] Thus, in this discussion, it is assumed that achievement of a sufficient level of quality (or level of defects or yield) is a given.

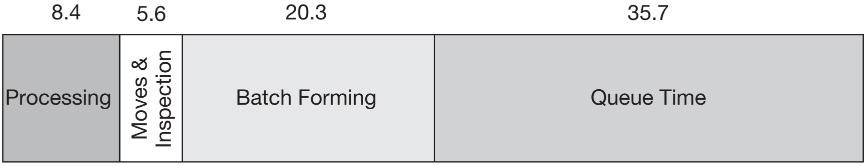
Fast factory cycle time requires the identification and reduction of both visible and hidden waste throughout the entire system. Traditional methods for factory performance improvement, including the bulk of the methods encompassed within lean manufacturing, focus primarily on visible waste (e.g., clutter on the factory floor, unnecessary motion, excessive inventory, and disorganized work areas).

As we shall see, however, it is equally if not more important to develop methods that deal with the hidden waste within a factory. This hidden waste is almost always due to the employment of inferior protocols (e.g., inefficient protocols employed for factory starts, the clustering of starts, the clustering of preventive maintenance events, inappropriate run rules, improper batch sizes, etc.).

The importance of identification and reduction of hidden waste is illustrated by the cycle-time components plot of Figure 2.3. This plot was developed for an actual factory prior to the introduction of improved protocols. The numbers above each block (e.g., "8.4" for "Processing") indicate the average number of days that an average job spends in a given state.

FIGURE 2.3

Components of factory cycle time.



For example, the average time a job spends in transit ("moves") and inspection is 5.6 days. Adding up the numbers in Figure 2.3, we find that the average factory cycle time for this facility is 70 days (i.e., 8.4 + 5.6 + 20.3 + 35.7). This happened to be about twice the cycle time of one of the firm's competitors.

Certain physical limitations (e.g., machine process rates and AMHS [Automated Material Handling System] speed) and quality requirements determine the amount of time spent in processing, moves, and inspection (i.e., for a total of 14 days, on average, per job for the factory of Figure 2.3). The bulk of factory cycle time, however, is consumed by batch forming [i.e., the time required to form a batch of jobs in front of each batching machine (Hopp and Spearman, 2001; Khade and Ignizio, 1990; Sato, Ignizio, and Ham, 1978)] and queue time (i.e., the average time that jobs or batches simply must sit and wait in the queues formed in front of workstations). To be more precise, the two most significant contributors to factory cycle time (i.e., batch forming and queue time) are a consequence primarily of the protocols employed in the running of the factory.

The most important message imparted by Figure 2.3 is that the biggest lever in the reduction of factory cycle time is that of the reduction of batch forming and—*in particular*—queue time. Factory managers who dwell only in the first two dimensions of manufacturing, however, most likely will limit improvement efforts to the reduction of process time, transit time, and possibly inspection time.

Unless you have an effective means to identify and reduce hidden waste, the more traditional methods of factory performance improvement will produce only limited results. This is so because traditional approaches (including lean manufacturing, or the Toyota production system) rely primarily on art and experience and involve only a limited degree of science.

Figure 2.4 depicts the cycle-time components of the same factory illustrated in Figure 2.3. The 70 days of factory cycle time have been reduced to 24.5 days. This was accomplished by means of a combination of the methods to be described in subsequent chapters. The time required to achieve this improvement (which has been sustained for more than five years) was approximately 15 months.

When one realizes that the reduction of just a single day of factory cycle time in certain industries (e.g., semiconductor wafer fabrication) can result in millions of dollars of increase in the firm's bottom line, the need for fast cycle times becomes or should become even clearer. Improvement in factory cycle time is best achieved by combining the best features of the art of manufacturing with the science of manufacturing while maintaining, at all times, an awareness of the political environment.

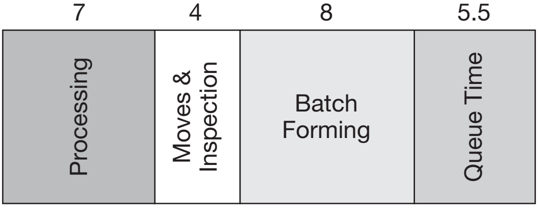
CHAPTER SUMMARY: THE PATH FROM ART TO SCIENCE

This chapter has presented a very brief summary of the history of manufacturing. Taking a closer look, it becomes apparent that the evolution of manufacturing has been achieved primarily via empirical and intuitive means. It has, in fact, been only relatively recently that science—particularly advanced scientific methods and models—has been introduced.

One of the definitions—and the most pertinent for our purposes—found in the *Merriam-Webster OnLine Dictionary* for *empirical* is "relying on experience or observation alone, often without due regard for system and theory." This definition sums up, aptly, the art of manufacturing as well as the evolution of that art. That is, the art of manufacturing has relied on empirical evidence, intuition, and analogies while ignoring, for the most part, science.

FIGURE 2.4

Components of factory cycle time after an improvement effort.



The scientific management movement of the late nineteenth and early twentieth centuries advanced manufacturing by means of the employment of experiments coupled with rather basic descriptive statistics. For example, such people as Frederick Taylor and Frank Gilbreth relied on the statistics (e.g., averages and variances) gleaned from their experiments. These results could be summarized visually by means of histograms and other plots. In this way, one approach to performance improvement could be compared with another.

Such approaches, while advances over purely intuitive efforts, still do not provide a quantitative model of the system (e.g., factory and workstation) that lends itself to an improved and scientifically valid understanding of the actual causes (and the confounding of multiple events) of problems or an indication of the optimal approach to the resolution of problems. A more advanced scientific basis for the evolution of manufacturing requires the development of mathematical models [e.g., queuing theory, stochastic processes, and optimization (Buzacott and Shanthikumar, 1993; Goldberg, 1989; Gross and Harris, 1998; Hillier and Lieberman, 2005; Hopp and Spearman, 2001; Ignizio and Gupta, 1975; Ignizio and Cavalier, 1994; Taha, 2006)] that are specifically adapted to the representation of factories and their production processes.

The Ford production system provided the foundation for the Toyota production system, now popularly designated as *lean manufacturing.* Lean manufacturing, in turn, consists mainly of the art of manufacturing, that is, methods developed empirically and refined over years of experimentation, observation, and statistical analysis. For the most part, however, lean manufacturing does not rely on the models and methods developed via a more advanced scientific approach. This can be—as we shall see—both an advantage (in terms of ease of acceptance) and a disadvantage (in terms of lesser power, robustness, and understanding).

Let's now consider Case Study 2, in which some historical facts with regard to the characters in the Muddle Corporation story are provided.

CASE STUDY 2: A LITTLE BIT OF HISTORY

As mentioned earlier, politics play a major role—sometimes *the* major role—in either the success or failure of factory performance-improvement efforts. Politics, in fact, often represent the most complex human element in such efforts. One way in which to gain a better appreciation of the politics—and culture—of any organization is to learn as much as you can about the background, motivation, beliefs, and experience of its management. So let's first address the background and experience of the managers having the most significant impact on the culture, goals, and values within the Muddle Corporation.

As discussed previously, Peter Muddle was one of the founders of Muddle, its previous CEO, and is presently chairman of its board. His imprint on the culture, goals, and value system of the firm is significant. As such, we'll begin with a brief overview of his history.

Peter Muddle was born, some 70 years ago, in the American Midwest. While he may have been a mediocre student, Peter was clever—sometimes a bit too clever. After his expulsion from college (for plagiarism), Peter teamed up with a former university roommate to establish a firm for the preparation of small-business income tax forms.

Two years later Peter was discovered by the Internal Revenue Service (IRS) to have been submitting bogus income tax forms for several of his clients and splitting the subsequent bogus tax refunds with those clients. A guilty plea and a lenient judge allowed Peter to pay a fine and escape jail time.

Following this misstep, Peter decided to move to California. Shortly thereafter, Peter met a bright young Stanford University student, Harold Smith. Harold had a brilliant idea for the production of what was then a new and novel device. Peter convinced Harold to become his partner, and together they established a firm for the manufacture of the item. Peter was able to obtain venture-capital funding for the firm that became the foundation of what is now the Muddle Corporation—although its original name was S&M (short for Smith and Muddle) Enterprises.

Over the next several years, the unsuspecting Harold allowed Peter to file the patents for his inventions—inventions that moved S&M into the forefront of its field. All the patents, however, were filed under the name of Peter Muddle.

Without any further need for Harold's services, Peter and his carefully selected board of directors pushed the young and gullible Harold out the door. It was then that Peter renamed the firm Muddle, Inc.

Marvin Muddle, Peter's son and present CEO, was a so-so student but did manage (with some considerable help from a large donation to the university by his father) to obtain an MBA degree. Marvin is a chip off the old block in many respects. His motto—written in Latin on his coat of arms—is, in fact, *"Aufero absque dedecus."*[9] This may explain the atmosphere within Muddle that permits and even encourages the co-opting of ideas.

Jack Gibson, whom we have yet to encounter, is a plant manager for Muddle's Factory 2, the firm's smallest facility. Jack is determined to move up the corporate ladder and has his eyes on the position of director of manufacturing—the position presently held by William "Wild Bill" Barlow. What Jack may lack in brains, he more than makes up for in cunning.

Tommy Jenkins, another individual whom we have yet to encounter, is—like Jack Gibson—also a plant manager. Tommy is "three-in-a-box" with two other plant managers for the factory (Factory 7) in which Dan Ryan and Brad Simmons work.[10] He happens to be the senior plant manager (i.e., the top rung of the management ladder at a given factory site).

Tommy takes his job very seriously—so seriously, in fact, that he insists on being involved in virtually every aspect of the factory, no matter how trivial. Tommy is what is known as a *micromanager.* Micromanagers have little or no faith in their subordinates and insist on being involved in each and every decision. Another aspect of Tommy's personality is his disdain for science. He's convinced that as a consequence of his 20 years of experience with Muddle, there is nothing that anyone can teach him about running a factory.

I also should provide some mention of the histories of other characters in these case studies. Sally Swindel, as discussed earlier, has recently convinced Muddle to implement lean manufacturing. Previously, she was responsible for Muddle's unsuccessful attempt at the adoption of reengineering. Sally works for Hyperbola, Ltd., a major consulting firm with a worldwide presence. Although her only previous work experience was that of an order taker at a fast-food franchise, Sally has been able to persuade a long line of CEOs to adopt the methods promoted by Hyperbola.

Hyperbola provided Sally with a two-week training course in lean manufacturing before sending her out to spread the message

---

[9] In English, this means "Steal shamelessly."

[10] The firm has a practice that involves, despite its obsession with cost cutting, the assignment of two or more people to almost every low- to middle-level management position. Thus, "three-in-a-box" means that there are three plant managers at this particular site. Tommy Jenkins is the senior of the three in his "box."

that "Lean is *the answer*." Hyperbola furnishes its clients with books on each of the methods it espouses.

The company's latest text is a slim volume entitled, *Lean Is the Answer.* This book is a revision of an earlier book entitled, *Reengineering Is the Answer* (which, in turn, was a revised version of earlier books such as *Total Quality Management Is the Answer, Quality Circles Are the Answer, Theory of Constraints Is the Answer,* etc.). Most managers at Muddle have at least one copy of every book produced by Hyperbola. The irony of their titles evidently has escaped them.

We also met Dan Ryan in Chapter 1. Dan was employed previously by a small manufacturing firm, ToraXpress. That firm had struggled for years and was on the edge of bankruptcy until a retired professor, Aristotle Leonidas, turned its fortunes around. Professor Leonidas introduced a program and training courses that enabled ToraXpress not only to recover but also to become a leader in its field.

A few years later, ToraXpress was purchased by Muddle. Two years after that the company, then a division of Muddle, was but a shell of its former self and was closed on the orders of Marvin Muddle. Of its 300 employees, only a handful were offered positions in Muddle's other factories. Among this select group was Dan Ryan.

Brad Simmons, the factory floor supervisor for the workstation adjacent to Dan's, has been with Muddle his entire career—some 12 years. Brad is resigned to the fact that the performance of Muddle's factories will never improve without a major change in the practices and procedures employed on the factory floor. When Brad heard about adoption of the lean manufacturing effort, he pulled as many strings as he could to obtain a full-time position with Muddle's *LEAN* Forward team. Based on his recommendation, Dan Ryan also was given—and accepted—a similar position on the team.

Donna Garcia, as you may recall, was (until their appointment to the *LEAN* Forward team) Dan and Brad's department head. Donna is the factory floor operations manager for Factory 7 and is responsible for all operations and maintenance activities in the factory. Donna is a compulsive tattletale and makes it a practice to meet regularly with Tommy Jenkins. As with other characters in this story, Donna wants desperately to climb Muddle's career ladder.

Ben Arnold, whom Dan Ryan had the unfortunate opportunity to meet earlier, is Tommy Jenkins' technical assistant (i.e., technical advisor). Ben previously worked at Muddle's Factory 2, at which time he became friends with Jack Gibson. It's rumored that Ben may have played some role in the promotion of Jack to Factory 2's (junior) plant manager position.

Julia Austen is another person we have yet to meet. Julia is a Muddle Fellow (a position allegedly based on the individual's "world class" technical expertise). Unlike most Muddle Fellows, Julia actually is an expert, albeit in one rather narrow aspect of manufacturing. Julia, like Brad and Dan, is beginning to question the decisions being made with regard to improving factory performance.

Let's now listen in on the conversation between Brad and Dan in the company cafeteria.

* * *

"Dan, old man," says Brad, "before we start the *LEAN* Forward training course, I have a few words of advice."

"No problem, I'm all ears."

"I strongly recommend that you don't let anyone know you've had training in factory performance improvement; you know, the stuff you said that professor guy, Leonidas, taught you when you were at ToraXpress."

"Actually," replies Dan, "I wasn't hired into ToraXpress until after Professor Leonidas had almost finished his training courses. In fact, I was only able to attend two of his lectures. But that was enough to convince me that he was spot on about how to achieve factory performance improvement."

"That doesn't really make any difference," says Brad. "You still need to keep quiet about anything you may have learned."

"Okay," replies Dan, raising his eyebrows, "but why on earth should I keep that a secret?"

"Because, in this company, it can be dangerous to let people know you have any expertise whatsoever in whatever topic may be on the agenda. Unless you're a member of a fairly select group—and trust me, you ain't—just keep your mouth shut and nod your head. Agree with whatever is said in the *LEAN* Forward class, no matter how foolish or misguided you think it might be."

* * *

One can conclude from this case study that the Muddle family has a checkered past and a habit of taking credit for the ideas of others. And if the advice of Brad Simmons is to be believed, it's best to keep your mouth shut unless it is to express agreement.

This page intentionally left blank

CHAPTER 3

Terminology, Notation, and Definitions

A PROPER FOUNDATION

To most fully appreciate and effectively exploit the art and science of manufacturing, you should be familiar with the terminology, notation, and definitions that allow you to intelligently discuss and employ these concepts. It is advisable, therefore, that you read this chapter because much of what follows is based on the material covered here. This recommendation holds true even if you may have had a previous introduction to the art (e.g., lean manufacturing) and/or science (e.g., industrial engineering, manufacturing engineering, operations research, stochastic systems, or production control) of manufacturing because the treatment presented in this text differs, in some cases considerably, from that found in other works.

Once the definitions, terminology, and notation have been covered, these concepts will be further clarified by means of an end-of-chapter numerical illustration. The illustration employed—that of an extremely simple factory—indicates just how to "pull together" and implement the material presented in this chapter.

Our discussion begins, however, with the definition and purpose of a factory—a topic that should not be taken lightly. Factories, as you shall see, are considerably more complex than the stereotypical "noisy, big building with lots of smoke belching out."

THE FACTORY: DEFINITION AND PURPOSE

We've certainly all seen factories, and some readers may have worked or perhaps are presently working on a factory floor or are otherwise employed by a manufacturing firm. A widely held and overly simplistic view of a factory is that of a building that houses machines and people and produces an end product that is delivered to its customers. A considerably more useful definition of a factory is provided below:

> A factory is a processing network through which jobs and information flow and within which events take place.

The jobs (i.e., items requiring processing) within a factory are assembled (e.g., automobile assembly, cell phone assembly, or laptop computer assembly) or otherwise transformed (e.g., the implant of transistors within a silicon wafer or the annealing process employed in the manufacture of metals) from the raw materials entering the factory into the final product that ultimately leaves the factory. These jobs flow through a network of predetermined process steps. Job process steps (a.k.a. *operations*) include

- *Assembly* or *transformation*—an activity resulting in or directly supporting a physical and measurable change to the job
- *Transit* of the job from one machine to the next
- *Inspection* of the job

In addition, a job may have to undergo rework. While this is not part of a predetermined process-step flow, it is a state in which a given job might exist at a specific time.

Concurrent with the flow of jobs through a factory are events that occur within the factory's workstations. These events serve to reduce the availability of the machines that form the workstation and, subsequently, the overall availability of the workstation itself. The degradation imposed by such events on the workstation—and the factory—in turn, will have an impact on factory performance.

Workstation events may occur either randomly, according to a schedule (e.g., perform a maintenance event every week), or according to usage (e.g., perform a maintenance event on the completion of every 500 jobs). Included among the most common workstation events are

- Maintenance of a machine
- Repair of a machine
- Inspection of a machine

- Qualification of a machine
- Setup of a machine

From a more scientific perspective, an alternate and more revealing definition of a factory may be developed, specifically:

> A factory is a nonlinear, dynamic, stochastic system with feedback.

The implication of this definition is that even a seemingly simple factory is a very complex system. It involves all the features (i.e., nonlinear, dynamic, stochastic, and feedback) that serve to define a system so complex as to defy human intuition (Forrester, 1999). A corollary to this finding is that your intuition, when it comes to a factory, is almost always wrong.[1] This may come as a surprise to those who believe that they can manage and run a factory effectively using just their experience and "gut feel." While many factories are indeed managed and run in such a seat-of-the-pants manner, their performance is invariably far below their true potential.

Another insight that may be gained from the second definition of a factory is that a manufacturing facility shares the same features as several other important and related systems. Specifically, the models and methods that may be employed to represent and solve problems within a factory (i.e., within a nonlinear, dynamic, stochastic system with feedback) apply equally as well to supply chains and business processes. In fact, these same models and methods can, with but modest effort, even be adapted to such a seemingly unrelated problem as the design of multicore computer chips (which, like factories, also involve flows and bottlenecks). In short, there are numerous important real-world problems having essentially the same mathematical model as that of a "simple factory."

While mathematical models of a factory play a vital role in factory performance-improvement efforts, process-flow models provide the best means for visualizing the flow of jobs through a factory. These models also serve as a basis for the definitions, terminology, and notation to be covered in the sections that follow. Two versions of these models are described and illustrated below.

---

[1] To quote Francis Bacon, "Beware the fallacies into which undisciplined thinkers most easily fall." Among them is to "assume more order than exists in chaotic nature."

FACTORY PROCESS-FLOW MODELS

Every factory (or supply chain or business process) supports a process flow. There are several ways to represent this flow, but this chapter will deal with only two of these. The first is a representation of the process flow in a factory by means of a workstation-centric model. The second is a representation via a process-step-centric model.

To clarify, a workstation consists of one or more machines that support identical or nearly identical processing functions. For example, there may be workstations that support polishing, those that support etching, those that support photolithography, and those that support a specific inspection step.

A process step, on the other hand, is an operation conducted within a workstation (and, quite possibly, by means of the support of only a subset of the machines in the workstation) or is a transit step between workstations. Some process steps add value to the final product (i.e., from the perspective of the customer), whereas others (such as transit and inspection) are considered non-value-added operations (again, from the perspective of the customer).

The workstation-centric flow model (and its variants) is the most widely employed representation of a factory—and it has its uses. In fact, there may be instances in which the factory under consideration is so simple and straightforward that a workstation-centric model will suffice. The process-step-centric model, however, while not as well known, is more robust, often more useful, and in many cases may be essential if a complete and accurate appreciation of the factory is to be obtained. Our discussion begins, however, with the conventional workstation-centric model.

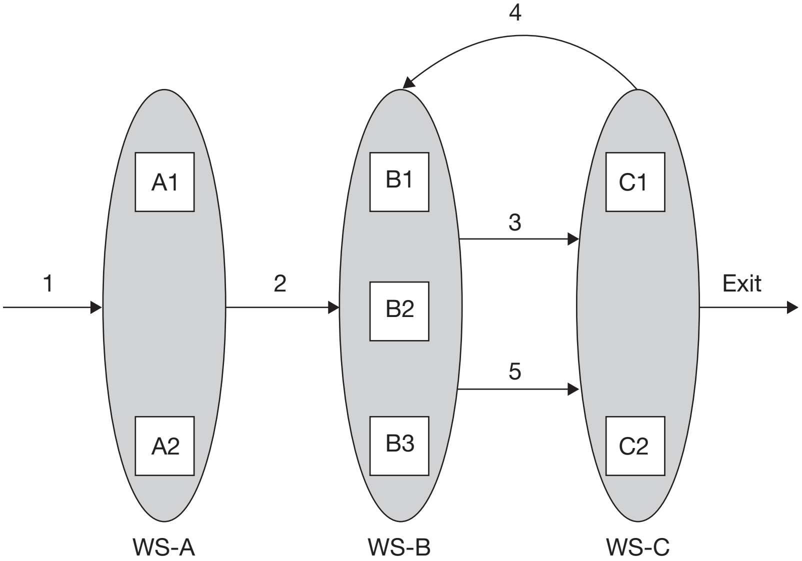
WORKSTATION-CENTRIC MODEL—AND REENTRANCY

The workstation-centric model is best explained by means of an illustration. In so doing, the concept of reentrancy also will be introduced.

Figure 3.1 depicts a simple factory consisting of three workstations (A, B, and C), designated in the drawing as WS-A, WS-B, and WS-C. In a workstation-centric model, workstations (and their devices, e.g., conveyor belts, monorails, carts, etc.) that support transit operations, as well as the transit operations themselves, are not explicitly depicted. Within each workstation are its

FIGURE 3.1

Three-workstation factory with reentrancy.



machines. In workstation A, these machines are designated as A1 and A2; in workstation B, as B1, B2, and B3; and in workstation C, as C1 and C2.

The arrows and arcs in the figure represent the flow of all process steps (a.k.a. *operations*) other than those of the transit type. The arrow emanating from workstation C and labeled as "Exit" serves simply to indicate the departure of the job from the factory.

Since workstations B and C each support more than a single operation and are coupled (the coupling is indicated in the figure by the manner in which operation 4 forms a deterministic feedback loop from WS-C to WS-B), this particular factory is considered to be reentrant.[2] The *degree of reentrancy* (DoR) of a factory is found by dividing the total number of operations (excluding process steps that involve only transit) it supports by the total number of workstations in the factory.

---

[2] If the feedback loop is *probabilistic* (e.g., jobs are, only when necessary, sent back to earlier workstations for rework), the loop is technically not considered reentrant. To be reentrant, the feedback loop must form part of the *predetermined* process flow. If not, the feedback loop is probabilistic.

The factory in Figure 3.1 supports five operations (not counting transit operations), as depicted by the arrows and arcs labeled from 1 to 5, and consists of three workstations. Thus its DoR is given by

$$\text{DoR(factory)} = 5/3 = 1.67$$

It also may be observed that this factory has a single reentrant nest. A *nest,* in turn, is a contiguous series of directly coupled workstations. Workstations B and C are directly coupled (because they are part of the feedback loop formed by operation 4), and the DoR of this nest may be found by dividing the number of nontransit operations supported by the nest by the number of workstations in the nest:

$$\text{DoR(of nest formed by workstations B and C)} = 4/2 = 2$$

For the record, automobile assembly lines have little, if any, reentrancy (the ideal assembly line has none), whereas other, more complex factories (such as semiconductor wafer fabrication facilities, or "fabs") typically have factory DoR values ranging from 3 to 5 or even more—with individual nests that may have DoRs in the double digits. Attempting to treat a reentrant factory with methods developed for nonreentrant systems, by the way, may lead to either overestimates or underestimates of the facility's capability and performance. Furthermore, the ideal factory should not contain any reentrant loops.

We next consider two other, more traditional (in that they do not include reentrancy) workstation-centric models. In Figure 3.2, a flowshop is depicted (again, transit process steps and their associated "machines" are omitted). For simplicity, the machines in each workstation have not been drawn. A *flowshop* is a factory in which each job follows precisely the same pathway, that is, from entry into the first workstation (WS-A in the figure) and movement through all the workstations and exit from the final workstation (WS-F).

Each workstation, in turn, supports just one process step, and every machine in the workstation is assumed to be qualified to support that step. Moreover, it is usually assumed that there is no passing of jobs. That is, if four jobs enter the factory in, say, the job sequence J1, J2, J3, and J4, they must enter and leave each workstation in that same sequence. As you might guess, pure flowshop factories usually are found only in textbooks.

Another type of factory, one somewhat more realistic than a flowshop, is a *jobshop* facility. For sake of discussion, the factory in Figure 3.2 may be converted into a jobshop facility if certain restrictions of the flowshop are relaxed. Figure 3.3 presents one of many possible representations. Notice that in a jobshop, each job that enters the factory may follow a different process flow path. For example, job J1 follows a path (the *dashed line*) from WS-A to WS-B to WS-E to WS-F and then exits the factory. Job J2, on the other hand, follows a path (the *solid line*) from WS-A to WS-C to WS-D to WS-E and then leaves the factory.

An even more general-case factory could be formed by including reentrancy (i.e., deterministic feedback loops) as well as rework (i.e., probabilistic feedback) and allowing job passing (i.e., relaxing the requirement that jobs must proceed through every workstation in the same sequence) in the jobshop factory model. At any rate,

FIGURE 3.2

Flowshop factory in workstation-centric form.

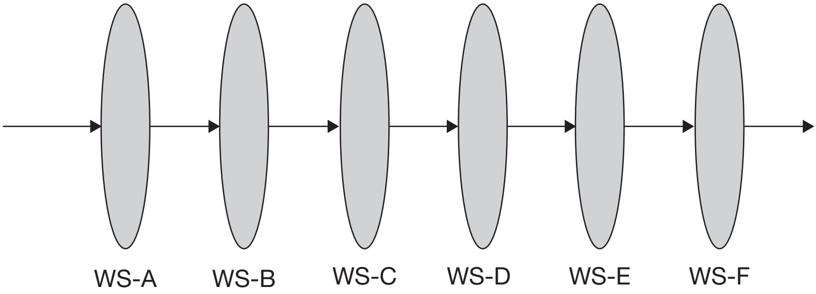
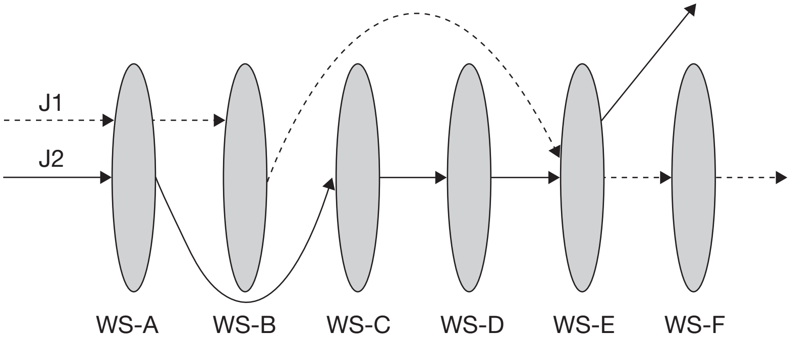


FIGURE 3.3

Jobshop factory in workstation-centric form.



real-world factories are usually more complex than those in these figures. Furthermore, most factories contain many more workstations, machines, job types, process steps, and process flows. As just one example, the typical semiconductor wafer fabrication facility may contain a hundred or more workstations, with possibly up to a thousand or so individual machines, and support hundreds of process steps.

Factories of such size and, in particular, complexity (especially the complexity imposed by reentrancy) are a far cry from the ideal single-unit, continuous-flow factory.[3] This fact alone serves to help explain why so many real-world factories perform so poorly—a fact that is true even if they are assumed by management to be performing "adequately."

PROCESS-STEP-CENTRIC MODELS

The workstation-centric model in Figure 3.1 may be converted into a process-step-centric representation (this is true of any workstation-centric model). To accomplish this, however, we must first know which machines are capable of supporting (e.g., qualified to conduct or be assigned to) each process step. Stated another way, it may be that only a subset of the machines in a workstation are capable of or assigned to a given process step supported by the workstation (e.g., as generally is the case with photolithography or implant machines in a semiconductor wafer fabrication facility).

Therefore, we shall assume that we know the specific process step to machine assignments (a.k.a. *dedications*) for the workstation depicted in Figure 3.1. Specifically, we assume that any machine in workstation A can support process step 1 and that any machine in workstation C can support either process step 3 or process step 5.

On the other hand, we will assume that only machines B1 and B2 are capable of supporting process step 2, whereas only machines B2 and B3 can deal with process step 4. Given these assumptions, the conversion of the workstation-centric model in Figure 3.1 results in the process-step-centric model in Figure 3.4.

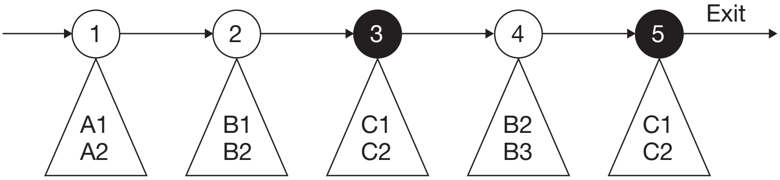
In this figure, the circles represent the operations, or process steps—excluding those that simply support a transit operation. The transit process steps, in turn, are indicated by the arrows leading

---

[3] *Single-unit flow* means that the jobs flow as single units (e.g., in the extreme case, a silicon wafer used to fabricate a computer chip would flow as a single chip rather than as a wafer with hundreds of chips on its surface).

FIGURE 3.4

Process-step-centric representation.



from one (nontransit) process step to another. For our purposes, nontransit process steps that are non-value-added steps are depicted as black circles (i.e., process steps 3 and 5, which may be, for example, inspection steps that every job must endure). As is the case with inspection process steps, the transit steps represented by the arrows are also non-value-added steps. It should be noted that an important goal of either scientific management, classic industrial engineering, or more recently, lean manufacturing is to eliminate or at least reduce the number of non-value-added process steps.

Underneath each process step is a triangle, and within each triangle is a list of the machines that support the given process step. For example, process step 1—based on the assumptions mentioned previously—is supported by machines A1 and A2 (of workstation A).

But (as based on our previous assumptions) notice that process step 2 is supported by only a subset of the machines in workstation B, that is, machines B1 and B2. Further, process step 4 is also supported by only another subset of workstation B's machines, that is, machines B2 and B3.

This is a crucial point and serves to indicate to some degree why a process-step-centric representation, particularly of a reentrant factory, is so important. Specifically, the process-step-centric model indicates not only the process step flow but also the precise support responsibilities of each machine in the factory.

The DoR of a factory also may be determined from the process-step-centric representation. As before, we divide the number of nontransit process steps (five) by the number of workstations (three) to arrive at a factory DoR of $5/3 = 1.67$.

We also may determine the DoR of any nests, just as done previously with the workstation-centric model. From Figure 3.4, it should be clear that operations flow from workstation B to workstation C and then back to workstation B and ultimately return to workstation C. In other words, workstations B and C form a nest. Consequently, two workstations, B and C, support four operations (i.e., 2, 3, 4, and 5), and the DoR of the nest is simply 4/2, or 2.

The importance of the process-step-centric model will be made even more apparent in Chapter 13 when the matter of determining the capacity of workstations and factories is covered. As you shall see, it is often more important to be aware of the capacity of the specific subset of machines that supports each process step than the composite capacity of the entire workstation. With this discussion of factory flow models now behind us, we can move on to other definitions, notation, and terminology.

FACTORY DEFINITIONS AND TERMINOLOGY

A factory possesses certain important features. I begin the list of definitions and terminology with those pertinent to such factory attributes.

Factory Types

The types of factories that one may encounter include

- Flowshops
- Jobshops
- Factories without reentrancy (i.e., DoR = 1)
- Factories with reentrancy (i.e., DoR > 1)
- Synchronous factories (e.g., every job flows through the factory at the same constant speed, such as bottles in a beverage bottling plant)
- Asynchronous factories (e.g., each job—as in semiconductor fabrication—may flow through the factory at different speeds and in addition may remain temporarily held in a queue)
- High-mix factories (e.g., those that process numerous job types)
- Low-mix factories (e.g., those that process only a limited number of job types)
- Low-volume factories (e.g., those that process only a relatively limited number of jobs per time period, such as aircraft manufacturers or research and development factories that produce only prototypes of a product)

- High-volume factories (e.g., those that process a large number of jobs per time period, such as high-volume semiconductor wafer fabrication facilities)
- High-mix, low-volume factories
- High-mix, high-volume factories
- Low-mix, low-volume factories
- Low-mix, high-volume factories
- Factories involving various combinations of the preceding features

Included within a factory are its workstations (and their associated machines), jobs, supplies, spare parts, dispatch centers, operational personnel, maintenance personnel, automation equipment and personnel, transit equipment (e.g., either manual or automated material handling systems), transit support personnel, and all the associated information and documentation believed necessary for the operation of the facility. Accompanying the information and documentation are (or should be) the metrics by which each important aspect of the factory is measured.

I now proceed to list the terminology and definitions employed for the jobs processed and events performed within a factory.

JOBS AND EVENTS

The activities that occur within the factory consist primarily of the processing of jobs and the conduct of workstation-associated events. The processing of jobs (including rework) provides the firm with the potential for profit—assuming that the jobs are not scrapped or otherwise disposed of owing to defects or obsolescence.

Events, on the other hand, consume time in which a workstation or machine otherwise might be available for the processing of jobs. Events also consume resources (e.g., maintenance personnel time) that otherwise might be allocated more effectively.

Job Types and Configurations

Jobs may require either assembly (as in the case of an automobile assembly line), transformation (as in the case of an oil refinery, chemical processing plant, or woodworking facility), or some combination of assembly and transformation (as in the case of the manufacture of computer chips). Furthermore, a job may flow through the factory as a single unit (e.g., as an automobile), as a *lot* (e.g., as a "container" consisting of a number of silicon wafers), or as a *batch* (e.g., a group of either individual jobs or lots).[4]

There are two primary types of batches of interest. The first is a *conventional batch,* sometimes designated as a *parallel batch.* A parallel batch is composed of two or more jobs, and each job (or lot) in the batch is processed simultaneously on the machines that support batching operations. Furthermore, each job in a given parallel batch typically requires the same process time for a given process step. For example, a factory furnace might support batches of 12 jobs each and require six hours of heat treatment.

Once the batch has been processed, six hours later, the jobs within the batch typically move as an ensemble to the machines supporting the next process step (the machines supporting the next operation may or may not use batching). The purpose of parallel batching supposedly is to reduce setup time; that is, each batch undergoes just one setup in front of the batching machine.

Another type of batching is known as *series batching* or *cascading.* The jobs within a cascade are processed sequentially by the cascading machine or workstation. Each job in a cascade must wait for the preceding job in its cascade to finish before entering the machine or workstation. Once a job in a cascade finishes processing, it moves—usually by itself—to the machines supporting the next process step. The purpose of cascading supposedly is to reduce setup time because each cascade undergoes just one setup prior to entry into the cascading machine or workstation.

Other versions of batching may exist, wherein the jobs in a batch might be *split* so as to allow a portion of the batch to be sent to the next process step prior to completion of the entire batch. Whether this is the case or not, batching of any type serves to complicate the process-step flow as well as induce variability into the factory. The ideal (i.e., utopian) factory should not employ batching.

Event Types

As mentioned previously, events are activities that are conducted within a workstation rather than on a job. While conventional wisdom may hold that some of the events to be described are "essential,"

---

[4] The silicon wafers in a semiconductor wafer facility typically are transported in *cassettes* or *front-opening unified pods* (FOUPS). At a particular process step, the entire lot might be processed either simultaneously or as individual wafers. Some process steps, in fact, employ machines that process batches or cascades of lots. Despite this complexity, a *job* in such a facility typically is considered to be a single lot.

the goal of the ideal factory is to eliminate each and every one. First, however, it is useful to distinguish between preemptive and nonpreemptive events.

Preemptive Events A *preemptive event* is one that occurs during the processing of a given job (or batch). The processing of the job must stop and cannot proceed until recovery from the preemptive event. In some cases, the preemptive event even may cause the job to have to restart the interrupted process step. In others, the event could cause the job to be scrapped or require rework. Among the most common types of preemptive events are

- Unscheduled downs
- Power outages or voltage/current spikes
- Unanticipated supply outages and replenishment

Nonpreemptive Events A *nonpreemptive event* is one that occurs (or can be scheduled to occur) during a period in which the machine is not processing a job. Such events include

- Scheduled maintenance [e.g., preventive maintenance (PM) events]
- Unscheduled downs (i.e., those that happen to not occur during processing)
- Inspections and engineering tests
- Qualifications
- Setups
- Scheduled operator breaks (e.g., biobreaks or meetings)

Whether an event is preemptive or nonpreemptive, it still serves to increase the variability and decrease the capacity of the machines within the factory. Consequently, significant improvement in factory performance may be achieved by eliminating or at least mitigating these events.

Job States

During its journey through a factory, a job will exist in one of a finite number of states at any given time. Specifically, it may be engaged in

- Value-added processing, that is, an actual assembly or transformation operation

- Non-value-added processing, including
  - Rework
  - Transit
  - Inspection/test
  - Waiting, including
    - Waiting as an individual job for processing at a nonbatching/noncascading process step
    - Waiting for a batch (or cascade) to form in front of a batching/cascading process step
    - Waiting in a batch (or cascade) as part of the queue formed in front of a batching/cascading process step
    - Waiting in a "set aside" state (e.g., the job is removed temporarily from the production line)

Note that rework has been classified as a non-value-added job state. The rationale for this is that rework increases cycle time and reduces capacity and should not be required unless there is a deficiency in the operators, machines, or process flow. In an ideal factory, there would be no need for rework. Consequently, attempts should be made to avoid circumstances leading to the need to rework a job.

Each of the states in which a job may exist contributes to the average overall job cycle time (i.e., the average factory cycle time for the given job type). Figure 3.5 provides a graphic depiction of the percentage of time spent by an average job within an actual factory in its various job states. In this particular factory, there happened to be no rework (job rework simply was not possible), nor was there any waiting in a set-aside state. Despite this bit of "good news," it should be clear from the figure that there was considerable waste, mostly in terms of wait times, in this factory.

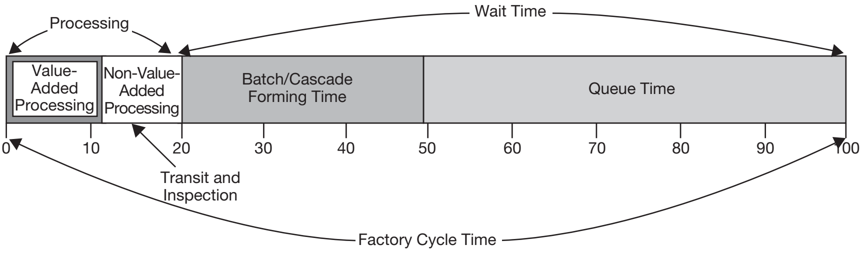
As may be noted from this figure, wait time (of all types) consumed slightly more than 80 percent of factory cycle time! Non-value-added processing consumed about 8 percent of the cycle time. Only 12 percent of the factory cycle time was used for value-added processing. In other words, this factory was operating at just 12 percent efficiency.[5] In short, this factory was performing

---

[5] I've actually encountered real-world factories operating at much lower levels of efficiency. One, in fact, was found to be operating at slightly less than 5 percent efficiency (i.e., non-value-added processing and wait consumed about 95 percent of the average job's cycle time).

FIGURE 3.5

Job states (factory cycle-time components).



extremely poorly. Unfortunately, many real-world factories perform at this level—and some are even less efficient.

A minimally efficient factory (i.e., one involved in assembly operations) should operate at 35 percent or (preferably) more efficiency when running at full capacity (*full capacity* will be defined in a subsequent section). Stated another way, wait times and non-value-added processing should consume no more than 65 percent of the cycle time. When the methods to be discussed in subsequent chapters were implemented in the factory associated with Figure 3.5, its factory cycle time—for the same level of factory loading and without adding machines or personnel—was decreased by 65 percent. (In the five years since then, this reduction in factory cycle time has been sustained.)

WORKSTATIONS, MACHINES, AND PROCESS STEPS

Process steps are supported by the factory's workstations and machines. Events, of the type discussed previously, occur within the workstations and machines. As a consequence, a given machine will find itself in one of a finite number of states. Before listing these states, it is necessary to review and further elaborate on the notions of workstations and machines.

Workstations

A given workstation consists of one or more machines, each dedicated to an identical or nearly identical processing function. For example, a workstation may support the function of polishing, grinding, etching, moving, or inspecting the jobs entering the workstation. Some workstations exist within close proximity (i.e., grouped areas, or *cells*). Others may be geographically distributed in quite possibly an ad hoc manner. Then there are workstations located according to the precise sequence of the functions to be performed (as in an automobile assembly line or as was the case of the moving shipbuilding assembly line at the Arsenal of Venice).

A given workstation may support

- A single process step
- Multiple process steps
- A value-added process step or steps
- A non-value-added process step or steps
- Some combination of the preceding

In addition, a workstation may be a part of a factory nest (i.e., coupled with other workstations via reentrant loops).

Machines

The fundamental physical, nonhuman component of any workstation is its machines. Some of the types of machines that may be found in a workstation include

- Machines dedicated to any and all process steps supported by the workstation
- Machines dedicated to just a portion of the process steps supported by the workstation
- Machines employing batching or cascading
- Machines that are fully or partially automated
- Machines that consist of a "cluster" processing mechanism (e.g., machines that consist of multiple chambers, such as those employed in wet etching in semiconductor wafer manufacturing)

Machines also may be categorized by cost, size, and complexity. It should be noted that a rule of thumb for machine size is that it ideally should not be more than four times the size of the job (or lot or batch) it processes—unless otherwise dictated by the laws of physics. While some factory managers may delight in bragging about the cost and complexity of their machines, the ideal factory should have small, inexpensive, and simple machines.[6]

Machine States

At any given time, a machine will exist in one of a finite number of states. Specifically, the machine may be in the

- *Processing state.* Busy in support of job processing; that is, the machine is engaged in the support of a process step for a potentially marketable job. This includes the time spent in such job process steps as
  - Those involving assembly or transformation
  - Those involving rework
  - Those involving transit
  - Those involving inspection/test (i.e., of a job)

  The average time spent by a machine in these states is termed *processing time*, or *busy time*.

- *Blocked state.* Engaged in the conduct of a machine event; that is, the machine is up and running but engaged in an event that either precludes (i.e., blocks) or could preclude the support of an actual process step. Such events include
  - Those involving inspection/test (i.e., of the machine)
  - Those involving qualification
  - Those involving setup
  - Those machines on hold waiting for the arrival of a priority job

  The average time spent in these states is termed *blocked time*.[7]

---

[6] After being subjected to what seems to have been literally hundreds of factory tours, I never cease to be amazed by the statistics quoted by some plant and factory managers. They brag that their factory and its machines are (1) big, (2) expensive, and (3) complex when the ideal factory and its machines should possess precisely the opposite of these attributes.

[7] Another type of blocked state is termed *warm bagging*. For example, one or more machines in a workstation may be up and running but removed from the process flow.

- *Idle state.* The machine is up, running, and qualified, but there are no jobs either in the machine or waiting for the machine—or alternately, the only jobs in queue in front of the machine cannot be processed until a specific minimum batch size has been formed. The average time spent in this state is *idle time.*
- *Down state.* The machine may be down owing to either a scheduled or unscheduled event. The average time spent in this state is *downtime.*

Note that the primary difference between blocked time and downtime lies in the fact that a machine is actually "up and running" in the blocked state, whereas it is not running in the down state. Be careful to realize that if a machine is in a blocked state, it is not available for the processing of a job.

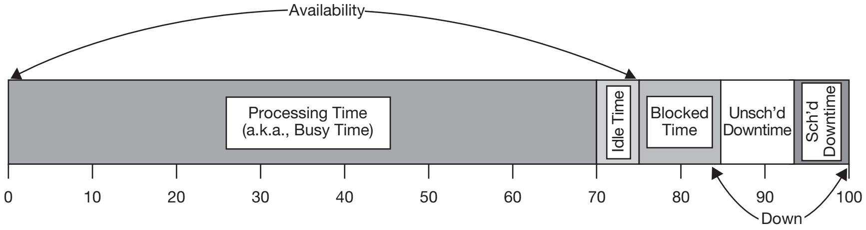
Previously, in Figure 3.5, a plot of factory cycle time from the perspective of the states taken on by the average job was presented. If we assume the perspective of a machine, the states it encounters may be depicted via Figure 3.6.

Again, it must be emphasized that blocked time (e.g., engagement in machine events including test, qualification, and setup) detracts—just as downtimes do—from machine availability. A failure to recognize this (or to not even consider the average amount of machine blocked time) will result in an overestimate of the machine's true capacity.

Despite this, there are firms that fail to factor in blocked time in their determination of availability. As a consequence, they may overestimate (sometimes dramatically) their machine capacity while underestimating its cycle time.

FIGURE 3.6

Machine states (percentages).



Process Steps

Earlier in this chapter we discussed two versions of factory flow models. As mentioned, the process-step-centric flowchart provides more information and generally is the most useful. This focus on the process step is considerably different from the traditional treatment of a factory, where the level of interest may stop at the workstation or machine. However, if we wish to determine the most effective means to improve factory performance, the process step is where our interest should lie. For example, in many factories—and virtually all factories that involve reentrancy—the key attributes of capacity and cycle time are determined by the support provided to each individual process step rather than each functional area. As such, the very notion of the cycle time of a workstation may be meaningless.

More specifically, the cycle time of a factory is found via Equation (3.1):

$$CT_f = \sum_{ps=1}^{P} CT_{ps} \tag{3.1}$$

where CT_f = cycle time of the entire factory
CT_{ps} = cycle time of a given process step (including transit steps)
P = total number of process steps in the factory

Furthermore, the *capacity* (i.e., maximum sustainable throughput) of a factory is determined by the bottleneck (i.e., constraint or choke point) process step, not necessarily a bottleneck workstation. A more general model used to determine the capacity of a process step will be presented in Chapter 13.

PERSONNEL

Factory personnel may be divided into those who work (primarily) on the factory floor and those who otherwise support the firm's manufacturing efforts. The latter are sometimes referred to as *carpet dwellers* or—even less kindly—*cubicle creatures.* For our purposes, discussion will be restricted to factory floor workers.

Factory Worker Assignments

The most typical job assignments found on the factory floor include

- Operations (e.g., forming job queues, performing machine setups, inserting jobs into machines, and removing completed jobs from machines)
- Maintenance and repair (e.g., performance of maintenance and repair events)
- Inspection/test
- Material handling
- Automation support
- Dispatch of spares and supplies
- Safety and emergency response

In some instances, factory floor personnel may be trained to support multiple assignments (e.g., cross-trained). In others, they may be assigned to just a specific task in a specific workstation.

Factory Worker States

At any given time, a specific factory floor worker may be in one of a finite number of states. These include

- Performing assigned duties
- Idle owing to lack of work
- Idle owing to either slacking off or being unaware of the need for his or her services
- In a meeting
- In a training session
- On a break (e.g., biobreak, rest break, or meal break)
- Absent from the factory (e.g., owing to illness, jury duty, vacation, or simply AWOL)

Factory managers too often rely on estimates or nothing more than "educated guesses" as to the *availability* (i.e., for the conduct of assigned duties) of an average factory floor worker. Desired levels (or minimum required levels) of personnel availability often are estimated by assuming a certain average rate of the occurrence of activities requiring worker support and multiplying that by the average time assumed necessary to conduct these activities—and then adding in a buffer of time supposedly (or hopefully) to account for breaks, meetings, absences, etc.

In one factory it was decided that factory floor maintenance personnel should be available to perform their assigned duties for two-thirds of each shift. Or, stated another way, the number of maintenance personnel should be established so that they would, on average, be idle or otherwise unavailable no more than one-third of the time. The decision was made on the basis of the average time required to perform their maintenance (and repair) events and the average rate of occurrence of those events.

Unfortunately, the maintenance and repair specifications used by factory floor personnel (plus an unevenness in skills and training) induced an extremely high degree of variability about the time required to perform a maintenance or repair event. As a consequence, given the subsequent inadequate number of maintenance personnel assigned to the floor, this factory's cycle-time goal was never attained. In fact, average factory cycle time was more than double the cycle-time goal. The factory manager had four choices, either (1) do nothing and suffer the wrath of corporate management, (2) hire enough maintenance personnel to increase their average idle time to 40 percent, (3) take the measures necessary to reduce the variability induced by poor maintenance specifications and training, or (4) purchase additional machines.

Blissfully unaware of the importance of variability, and evidently unable to compute the number of workers actually required to achieve the cycle-time goal, the factory manager chose the worst possible course of action (in terms of time and cost) and purchased a significant number of (large, costly, and complex) machines.

The moral of this story is that the number of factory floor workers required to achieve any particular performance goal is a function of both the average time required and (in particular) the variability about that time.

Another message that should be transmitted is that a reliance on averages is a very dangerous thing. For example, consider a news story that appeared during the housing slump problems of 2008. The story stated that although the sales of preexisting houses in a city had dropped by 40 percent, the average price of homes for sale had increased by 10 percent. The conclusion was that even with the burst of the housing bubble, the prices of homes were rising.

The actual fact was that about the only homes in the area that were selling at that time were those on the lower end of the price range. This left (unsold) much higher-priced houses. Consequently, the composition of the population of houses listed had changed dramatically, resulting in a higher value for the subsequent average house price listing.

PERFORMANCE MEASURES

As mentioned in Chapter 1, I am convinced that if you don't employ a meaningful metric, not only can you not improve factory performance, but you are also likely to worsen it. This section provides a listing and discussion of potential performance measures. Following this is a numerical illustration that pulls together as many as possible of the topics covered in this chapter. (Chapters 7 and 8 provide further coverage of these measures and recommends those that should be used as well as those that should be avoided.)

There are performance measures to gauge the performance of an entire firm, a firm's factories, an individual factory, a workstation, a machine within a workstation, a process step, and personnel and documentation (e.g., maintenance specifications). The discussion here, however, will be limited to factory, workstation, machine, and process-step performance measures. I begin, however, with an explanation of the notation that will be employed.

Notation

To discriminate between performance measures at the process-step, machine, workstation, and factory levels, the notation employed must be clarified. Specifically, in instances in which I am discussing a performance measure for an entity, I will usually employ the following format:

$$\text{Measure}_{\text{entity}}(\text{specific entity designation})$$

In addition, the subscripts that will be used and the limits on each specific entity will be defined as

$$\begin{aligned} ps &= \text{process step, where } ps = 1, \ldots, P \\ m &= \text{machines, where } m = 1, \ldots, M \\ ws &= \text{workstations, where } ws = 1, \ldots, W \\ f &= \text{factory} \end{aligned}$$

For example, if I am discussing the cycle time *CT* of process step *ps* number 9, the notation will be

$$CT_{ps}(9)$$

And should I be referring to the process rate *PR* of machine 3 in workstation B (i.e., B3), I will use

$$PR_m(\text{B3})$$

We begin our discussion of performance measures with those at the process-step level.

Process-Step Performance

Measures associated with the performance of a given process step include

- Process-step average throughput rate TH_{ps}
- Process-step maximum sustainable capacity SC_{ps}
- Process-step maximum theoretical capacity EPR_{ps}
- Process-step cycle time CT_{ps}
- Arrival rate at the process step AR_{ps}
- Departure rate from the process step DR_{ps}

Process-Step Throughput Rate The throughput rate of a process step is the average rate of flow (e.g., jobs per unit time) through the process step over a given time period. For example, if two jobs per hour on average flow through a process step each week and the factory operates 168 hours per week, its weekly throughput rate is 336 jobs, that is,

$$TH_{ps} = 336 \text{ jobs/week}$$

Process-Step Maximum Sustainable Capacity The capacity of a given process step is determined by the capacity (in terms of jobs per unit time) of the machines that support the process step.[8] The maximum sustainable (i.e., practical) capacity of a given process step (i.e., of the machines supporting that step) is determined by the maximum acceptable cycle time permissible as imposed by the associated throughput rate of the process step. I denote the maximum sustainable capacity as SC_{ps}.

---

[8] A model for determination of the capacity of those machines for any general case (e.g., multiple products, reentrancy, job-machine dedications, etc.) is provided in Chapter 13.

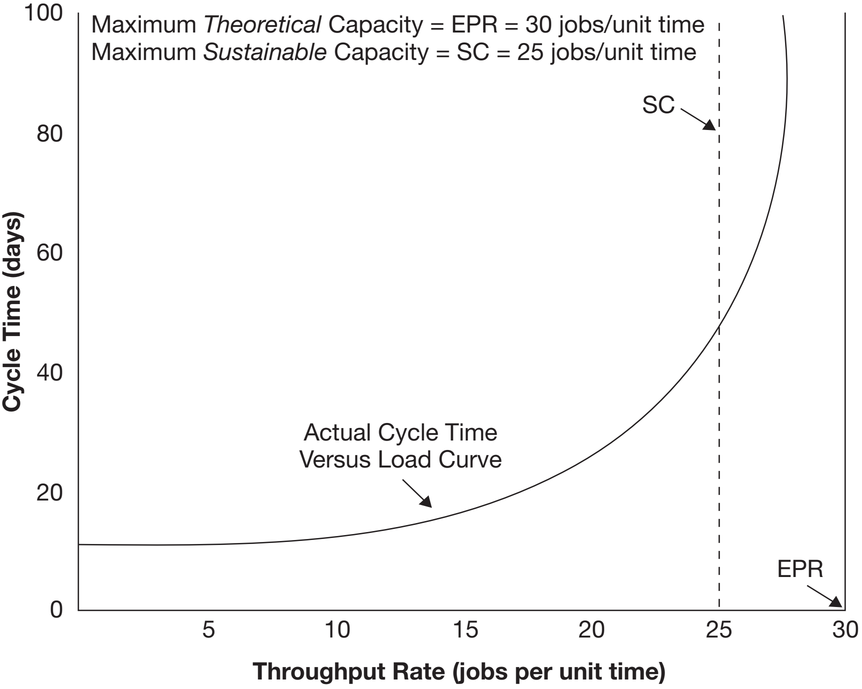
Process-Step Maximum Theoretical Capacity The maximum theoretical capacity of a given process step (i.e., of the machines supporting that step) is the capacity (in terms of jobs per unit time) of the machines supporting that step *in the absence of any variability*. This is also known as the *upper bound of the process-step capacity* as well as the *effective process rate.* I denote this capacity level as EPR_{ps}.

To further clarify the difference between maximum sustainable and maximum theoretical capacity (i.e., SC_{ps} versus EPR_{ps}), consider a process step that, ignoring variability, can (theoretically) support a maximum throughput rate of 30 jobs per day. In this case, by ignoring variability as well as the associated cycle time, EPR_{ps}—the maximum theoretical capacity—is given as 30 jobs per day.

This is the case even though the cycle time for a throughput rate of 30 jobs per day will approach infinity. This may be seen in Figure 3.7, where the maximum theoretical capacity of a process step is depicted (the same discussion also holds true for machines, workstations, or factories).

FIGURE 3.7

Maximum sustainable versus maximum theoretical capacity.



On the other hand, assume that for a throughput rate of 25 jobs per day the actual, real-world cycle time of the process step is 48 days (see Figure 3.7), and further assume that this is the practical limit on the cycle time that may be tolerated for that process step. Thus, in this case, the maximum sustainable capacity is given as $SC_{ps} = 25$ jobs per day.

Process-Step Cycle Time The cycle time of a process step is the average time required to conduct a given operation on a job, that is, the elapsed time between the arrival of the job at the queue (if one exists) in front of the process step (i.e., at the queue in front of the machines supporting the subject process step) and its departure on completion of the operation. If, for example, the average time a job spends in queue or waiting for a batch to form in front of a process step is 1.5 hours and the average time required to process the job is 0.75 hours, then its process-step cycle time is given by the sum of these two times, that is,

$$CT_{ps} = 1.5 + 0.75 = 2.25 \text{ hours}$$

The general form of the equation that will be employed to compute this cycle time is presented in Chapter 5.

Process-Step Arrival Rate The process-step arrival rate is simply the average number of jobs arriving at the queue in front of a process step over a given time period. For example, if five jobs arrive, on average, each hour, then the process-step arrival rate is given as

$$AR_{ps} = 5 \text{ jobs/hour}$$

Process-Step Departure Rate The process-step departure rate is the average number of jobs departing from a process step over a given time period. If the average number of departing jobs is five per hour, then

$$DR_{ps} = 5 \text{ jobs/hour}$$

Machine Performance

Measures associated with the performance of a machine include

- Machine throughput rate TH_m
- Machine maximum sustainable capacity SC_m

- Machine availability A_m
- Machine raw process rate PR_m
- Machine maximum theoretical capacity EPR_m, where EPR_m = effective process rate of the machine
- Machine busy time, busy time rate B_m
- Machine downtime, downtime rate DT_m
- Machine occupancy rate ρ_m
- Machine production control channel width PCC_m
- Mean time between machine down events $MTBE_m$
- Mean time to recover from machine down events $MTTR_m$

Machine Throughput Rate The throughput rate of a machine is the average rate of flow (e.g., jobs per unit time) through the machine over a given time period. For example, if, on average, five jobs per hour flow through a machine each week and the factory operates 80 hours per week, its weekly throughput rate is 80 times 5, or 400 jobs, that is,

$$TH_m = 400 \text{ jobs/week}$$

Machine Maximum Sustainable Capacity The practical (as opposed to theoretical) capacity of a given machine is given by its maximum sustainable capacity and is denoted as SC_m. For example, if it would be irrational (i.e., owing to a subsequent unacceptably high level of machine cycle time) for more than six jobs per hour to flow through a machine and the factory operates 80 hours per week, then its maximum sustainable capacity is given as

$$SC_m = 6 \text{ jobs/hour} \bullet 80 \text{ hours} = 480 \text{ jobs/week}$$

Machine Availability The availability of a machine is denoted as A_m and is found by determining the average amount of time the machine is up, running, and qualified to process jobs per unit of time (e.g., per week). One form of the equation for the determination of machine availability is provided by Equation (3.2):

$$A_m = \frac{T - (DT_m + BT_m)}{T} \tag{3.2}$$

where T = number of hours per week the factory operates

DT_m = total average downtime (scheduled and unscheduled) of the machine per week

BT_m = total average blocked time per week of the machine

For example, if over a 168-hour week a machine is, on average, up, running, and qualified to support jobs for 120 hours (which implies that it is down for blocked time and scheduled or unscheduled down events for a total of 48 hours per week, on average), then

$$A_m = \frac{T - (DT_m + BT_m)}{T} = \frac{168 - 48}{168} = 71.4 \text{ percent}$$

An alternative equation for estimation of the availability of a machine is

$$A_m = \frac{MTBE}{MTBE + MTTR} \tag{3.3}$$

where *MTBE* is the mean time between down and blocked events and *MTTR* is the mean time to recover from down and blocked events.

To illustrate, assume that the average time between either blocked and down events (i.e., scheduled or unscheduled downs) is 90 hours and that the average time required to recover from such events is 10 hours. Using Equation (3.3), the machine's availability is

$$A_m = \frac{90}{90 + 10} = 90 \text{ percent}$$

Machine Raw Process Rate If a machine supports more than a single process step, its process rate may vary according to the specific process step of interest. For the sake of discussion, I shall restrict attention at this point to a machine having a single process rate (a.k.a. *run rate*). The raw process rate is the maximum number of jobs per unit time the machine can process under ideal conditions. By *maximum possible* I mean that there are no preemptive events that occur during processing (e.g., no down events during processing) and that the machine is up, running, and qualified 100 percent of the time. If, under these assumptions, a machine could process five jobs per hour, then its raw process rate is

$$PR_m = 5 \text{ jobs/hour}$$

The inverse of a machine's raw process rate is its raw process time, that is, the time required to process a lot under ideal conditions. Using PT_m to represent a machine's raw process time, we have

$$PT_m = \frac{1}{PR_m} \tag{3.4}$$

and thus

$$PR_m = \frac{1}{PT_m} \tag{3.5}$$

Machine Effective Process Rate Machine effective process rate equals machine maximum theoretical capacity. Again, for sake of discussion, I shall restrict attention to a machine having a single process rate. Its maximum theoretical capacity, that is, its effective process rate, is given by multiplying the machine's raw process rate by its availability. That is,

$$EPR_m = A_m \bullet PR_m \tag{3.6}$$

Consider, for example, a machine with a raw process rate of five jobs per hour and an availability of 80 percent. Its effective process rate is simply

$$EPR_m = 0.8 \bullet 5 = 4 \text{ jobs/hour}$$

The inverse of a machine's effective process rate is its effective process time, that is, the time required to process a lot when availability is considered. Thus, using EPT_m to represent a machine's effective process time, we have

$$EPT_m = \frac{1}{EPR_m} \tag{3.7}$$

and thus

$$EPR_m = \frac{1}{EPT_m} \tag{3.8}$$

Machine Busy Rate Earlier we discussed the various states of an individual machine. One state was that denoted as its *processing*, or *busy, state.* When engaged in the busy state, a machine is actually processing jobs. Recall that the amount of time spent in this state (e.g., over a given period of time) is denoted as *processing,* or *busy, time.* The busy rate of a machine is simply the percent of time, over a given time period, spent in the busy state. For example, if the factory operates 168 hours a week and the machine is busy supporting its process step (or steps), on average, 135 hours, then its busy rate, denoted as B_m, is

$$B_m = \frac{135}{168} = 80.4 \text{ percent}$$

An alternative equation for the busy rate of a machine is given by Equation (3.9):

$$B_m = \frac{AR_m}{PR_m} = AR_m \bullet PT_m \tag{3.9}$$

where AR_m = arrival rate of jobs at the machine
PR_m = raw process rate of the machine
PT_m = raw process time of the machine

Machine Occupancy Rate The occupancy rate of a machine is the percentage of its available time that it is in the busy state. Designated ρ_m, the machine occupancy rate is given by

$$\rho_m = \frac{AR_m}{EPR_m} \tag{3.10}$$

or alternately (by means of Equation 3.9) as

$$\rho_m = \frac{B_m}{A_m} \tag{3.11}$$

Machine Production Control Channel A machine (or workstation or factory) has, associated with it, a production control channel PCC_m.[9] The cycle time of the machine is determined in part by the normalized width of this channel (i.e., the narrower the channel, the longer is the cycle time).

---

[9] The production control channel is sometimes referred to as the *gap* of a machine—the *normalized* gap between its occupancy (utilization) and its capacity. *If the machine's utilization and capacity are computed correctly,* then the production control channel and the gap are equivalent.

Equations for determining PCC_m include

$$PCC_m = 1 - \rho_m \tag{3.12}$$

and

$$PCC_m = \frac{A_m - B_m}{A_m} \tag{3.13}$$

Workstation Performance

Measures associated with the performance of a workstation include

- Workstation throughput rate TH_{ws}
- Workstation maximum sustainable capacity SC_{ws}
- Workstation maximum theoretical capacity EPR_{ws}
- Workstation availability A_{ws}
- Workstation busy rate B_{ws}
- Workstation occupancy rate ρ_{ws}
- Workstation production control channel width PCC_{ws}

A discussion of the performance measures of a workstation will make sense in general only if the workstation supports a single process step and every machine in the workstation is qualified to support that process step and only that process step. If the workstation satisfies these assumptions, then its performance measures follow directly from the measures employed to assess each of its machines. For the cases in which these assumptions do not hold, discussions and illustrations will be provided in later chapters.

Therefore, under the assumption of a workstation that supports just one process step and in which every machine in the workstation supports that step, its performance measures will be described. I begin with workstation throughput.

Workstation Throughput Rate The throughput rate of a workstation, under the assumptions just listed, is the sum of the average throughputs (i.e., rate of flow of jobs) of each of the machines in the workstation. Using TH_{ws} to designate workstation throughput, and assuming M machines in the workstation, we may state that

$$TH_{ws} = \sum_{m=1}^{M} TH_m \tag{3.14}$$

For example, if a workstation has three machines ($M = 3$) and their throughput rates are 3, 3.4, and 4 jobs per hour, on average, respectively, the throughput of the entire workstation is simply $3 + 3.4 + 4 = 10.4$ jobs per hour.

Workstation Maximum Sustainable Capacity The practical capacity of a workstation is given by its maximum sustainable capacity and is denoted as SC_{ws}. For example, consider the case in which it would be irrational (i.e., owing to an unacceptably high level of workstation or factory cycle time) for more than 12 jobs per hour to flow through a workstation. Thus, if the factory operates 80 hours per week, then the workstation's maximum sustainable capacity is given as

$$\begin{aligned} SC_{ws} &= 12 \text{ jobs/hour} \bullet 80 \text{ hours} \\ &= 960 \text{ jobs/week maximum sustainable} \\ &\quad\ \text{workstation capacity} \end{aligned}$$

Workstation Maximum Theoretical Capacity The upper bound on workstation capacity is the absolute maximum workstation capacity possible under strictly theoretical conditions. These conditions would exist if there were no variability whatsoever in the factory. If this were the case, you would be able to increase the flow of jobs through a workstation to its upper bound. The upper bound on workstation capacity (i.e., the effective process rate of the entire workstation under the assumptions cited) is equal to the sum of the effective process rates of its machines. That is,

$$\text{Workstation capacity upper bound} = EPR_{ws} = \sum_{m=1}^{M} EPR_m \tag{3.15}$$

or

$$EPR_{ws} = \sum_{m=1}^{M} \frac{1}{EPT_m} \tag{3.16}$$

Workstation Availability The availability of a workstation is denoted as A_{ws} and is the average amount of time the workstation is up, running, and qualified to process jobs per unit of time (e.g., per week). Given the determination of the availability of each of the workstation's machines, and given M machines, an equation for workstation availability is provided by

$$A_{ws} = \frac{\sum_{m=1}^{M} A_m}{M} \tag{3.17}$$

Workstation Busy Rate The busy rate of a workstation is given by determining the arrival rate of jobs at the queue in front of the workstation and the raw process time of the workstation. Equation (3.16) serves to determine the effective process rate of the workstation, and if it is divided by the workstation availability (Equation 3.17), the workstation's raw process rate PR_{ws} may be found. Thus the equation for the busy rate of a workstation is

$$B_{ws} = \frac{AR_{ws}}{PR_{ws}} \tag{3.18}$$

Workstation Occupancy Rate The occupancy rate of a workstation is the percentage of time it is in the busy state per time period. Designated as $\rho_{ws,}$ the workstation occupancy rate is given by

$$\rho_{ws} = \frac{AR_{ws}}{EPR_{ws}} \tag{3.19}$$

or alternately (using Equation 3.18) as

$$\rho_{ws} = \frac{B_{ws}}{A_{ws}} \tag{3.20}$$

Workstation Production Control Channel The production control channel of a workstation is denoted as PCC_{ws}. Equations for the determination of PCC_{ws} include

$$PCC_{ws} = 1 - \rho_{ws} \tag{3.21}$$

and

$$PCC_{ws} = \frac{A_{ws} - B_{ws}}{A_{ws}} \tag{3.22}$$

Factory Performance

Metrics that have been used in an attempt to measure the performance of an overall factory include but are definitely not limited to

- Factory cycle time CT_f

- Factory cycle-time efficiency CTE_f
- Factory throughput rate TH_f
- Factory maximum sustainable capacity SC_f
- Factory maximum theoretical capacity EPR_f
- Product lead time
- Factory moves
- Factory inventory WIP_f

Factory Cycle Time If computed properly, factory cycle time is one of a handful of important performance metrics. Unfortunately, some firms fail to compute or interpret this measure correctly. Equation (3.1) is needed to compute raw factory cycle time and is repeated here:

$$CT_f = \sum_{ps=1}^{P} CT_{ps}$$

where CT_f = cycle time of the entire factory
CT_{ps} = cycle time of a given process step
P = total number of process steps in the factory

Note that the cycle time of all process steps, including those involving transit and inspection/test (if a predetermined operation in the process flow), must be summed to arrive at the value of raw factory cycle time. As you will discover, however, the cycle time of a factory will vacillate, often dramatically, with its loading. For example, a factory operating close to its maximal capacity may have a cycle time of, say, 100 days. However, simply by reducing the loading a small amount, say, 5 or 10 percent, the cycle time could—depending on the specific scenario—fall to just 50 days. Remember this the next time you attempt to compare the performance of two factories or evaluate the impact on cycle time of any changes within a particular factory!

Factory Cycle-Time Efficiency As with factory cycle time, factory cycle-time efficiency can be an extremely useful measure, but only if it is computed and interpreted correctly. A means to determine raw factory cycle-time efficiency is given by Equation (3.23):

$$CTE_f = \frac{Process\ Time_f}{CT_f} \tag{3.23}$$

Recall from Figure 3.5 that a factory's process time includes the time devoted to all value-added as well as non-value-added process steps. Alternative representations of factory cycle-time efficiency may omit any non-value-added process step time (e.g., time consumed by transit, inspection, or test). As long as you are consistent, however, either definition may suffice. (The inverse of cycle-time efficiency, by the way, is a metric that has been denoted as the *X-factor*.)

The problem with the factory cycle-time efficiency metric (and the X-factor) is precisely the same as pointed out for factory cycle time. Specifically, unless this metric is normalized for the loading imposed on the factory, it fails to provide valid information.

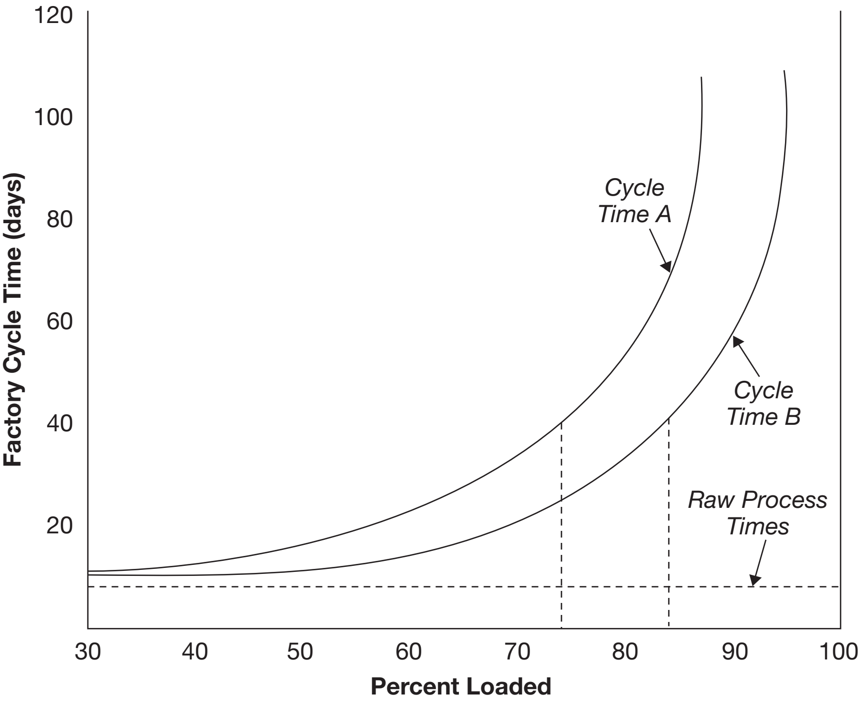
Factory Throughput Rate A factory's throughput rate is the average, over a specific time period, of the rate of flow of jobs through the entire factory. For example, if the number of jobs exiting the factory averages 900 units per week, the throughput rate is given as 900 units per week. It must be stressed, however, that the average number of jobs started into the factory each week over the period of interest might be considerably more than 900 units per week. This will happen if either there is a high scrap rate or—and more likely—if the factory capacity limits factory throughput to just 900 units per week.

Factory Maximum Sustainable Capacity Some firms assume that a factory's capacity is the *maximum* theoretical capacity (e.g., upper bound on throughput in terms of jobs per unit time) of the factory's bottleneck workstation (or workstations). If, however, the factory actually operated at the theoretical limit of its bottleneck (or even close to it), its cycle time would approach infinity. Consequently, a factory's maximum sustainable capacity is determined by the maximum factory cycle time that the firm can tolerate. Stated another way, *factory cycle time determines factory capacity.*

Note that this statement is the converse of conventional wisdom, which says that factory capacity determines factory cycle time. Figure 3.8 serves to confirm the fact that, in practice, cycle time determines capacity. Two factory operating curves (labeled "*Cycle Time A*" and "*Cycle Time B*") have been developed using a simulation model of a real-world factory. A factory operating curve, in turn, is simply a plot of factory loading (i.e., the ratio of starts to capacity) versus the associated factory cycle time (Aurand and Miller, 1997).

FIGURE 3.8

Factory operating curves.



The sum of all raw process times for all process steps in the factory (including such non-value-added steps as inspection and transit) has been determined and is indicated by the dashed horizontal line. This value is approximately eight days.[10]

The operating curve labeled "*Cycle Time A*" was developed for the factory when it operated under its original level of variability. The curve labeled "*Cycle Time B*" was developed for the same factory after some reduction in variability.

At a low factory loading (i.e., low factory throughput rate), the cycle time for the factory under condition A is close to its raw process time (only loadings from 30 to 100 percent of the maximum theoretical factory loading have been plotted). Once the loading

---

[10] As mentioned previously, some analysts define the sum of all raw process times to be the sum of only all value-added process times (i.e., transit and inspection times are not included). The choice is one of personal preference, and either may be used if employed in a consistent manner.

increases, however, the factory cycle time increases. At a loading of 74 percent, for example, factory cycle time is 40 days (about five times its raw process time). At a loading of 87 percent, the cycle time has *gone ballistic;* that is, it is increasing exponentially with loading.

With a reduction in factory variability, however, cycle-time performance is improved significantly. For example, while factory A, at a loading of 74 percent, had a 40-day cycle time, factory B had the same 40-day cycle time at 84 percent loading. Furthermore, at a loading of 87 percent (the same loading that "broke" factory A), the cycle time of factory B is just 43 days. Factory B's cycle time does not, in fact, go ballistic until its loading (i.e., throughput) reaches about 95 percent of its maximum theoretical capacity.

Returning to the notion of factory capacity and its relation to factory cycle time, it is hopefully obvious that the maximum permissible value of cycle time determines (or should determine) factory capacity. For example, and using factory A as a basis, if our firm (and our customers) cannot tolerate more than a 60-day cycle time, then the maximum sustainable factory loading must be 82 percent or less.

Factory Lead Time The *lead time* for a given product type is the time allotted for its production. For example, if we have promised a customer his or her delivery in 20 days, then 20 days is the lead time. Clearly, one should have a good estimate of factory cycle time (both the average cycle time and the variability about that time) before making a lead-time promise.

Factory Moves The *moves* within a factory are given by the sum of the number of jobs that have flowed through each factory workstation over a given time period. I've encountered some factory managers who rely on factory moves as their favorite measure of factory (or workstation or machine) performance. This attraction is based on the belief that the more moves within the factory, the better it must be performing. There is, however, no basis for this belief, and moves—as will be discussed in more detail in Chapter 8—are actually one of the worst ways to evaluate a factory.

Factory Inventory Factory inventory, known as *work in progress* (WIP), is determined by the factory throughput rate and its cycle time. Little's equation (a.k.a. *Little's law*) states that

$$WIP_f = TH_f \bullet CT_f \tag{3.24}$$

Little's equation is the first of the three fundamental equations necessary for determining a factory's performance. The equation also may be used to estimate the amount of inventory in a given workstation. This level of WIP may be found simply by multiplying the throughput of jobs through the workstation by the workstation's cycle time. Little's equation and the two other fundamental equations will be covered in detail in Chapter 5.

PUTTING IT ALL TOGETHER

I've listed and briefly discussed a fair number of terms and concepts in this chapter. The best way to both clarify and reinforce the material just covered is by means of a numerical example. Figure 3.9 depicts a factory with three workstations that will be employed to support the illustration. Jobs arrive at this factory at a constant rate of three jobs every two hours, or 1.5 jobs per hour. Table 3.1 serves to indicate most of the pertinent data associated with the factory.

It is obvious from the figure that the DoR value of the factory is 2 (i.e., six operations divided by three workstations). There is one nest, composed of all three workstations, with the same DoR. As noted previously, the throughput rate into the factory (i.e., jobs arriving at workstation A from outside the factory) is 1.5 jobs per hour. We shall assume that the factory operates 168 hours per week.

From Table 3.1, we may compute the effective process rate EPR_m of each machine in the example. To accomplish this, we must

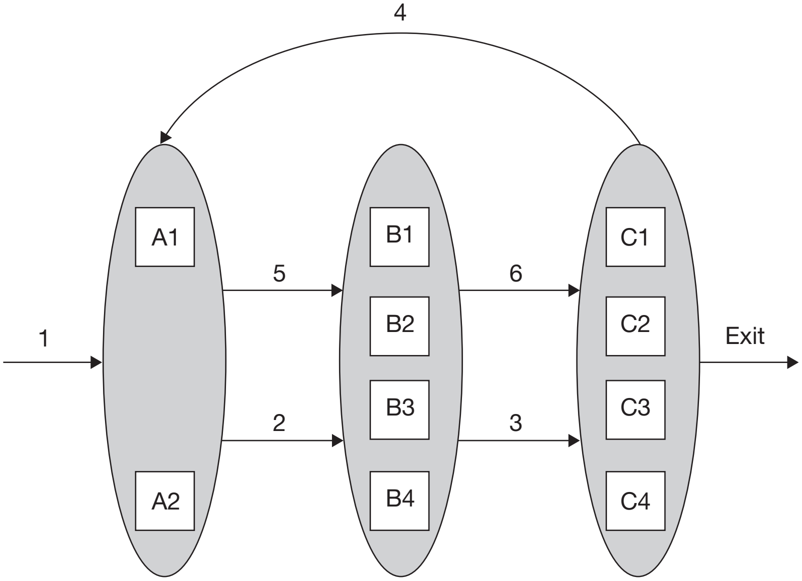
TABLE 3.1

Factory Data, Phase 1

Workstations	A		B				C			
Machines	A1	A2	B1	B2	B3	B4	C1	C2	C3	C4
Block time (hours/week)	6.8	6.8	5.2	5.2	5.2	5.2	2	2	2	2
Downtime (hours/week)	10	10	20	20	20	20	6.4	6.4	6.4	6.4
Downtime plus block time (hours/week)	16.8	16.8	25.2	25.2	25.2	25.2	8.4	8.4	8.4	8.4
Process rate (jobs/hour)	2	2	1	1	1	1	0.9	0.9	0.9	0.9

FIGURE 3.9

Reentrant factory illustration.



first determine the availability of each machine by means of Equation (3.2), that is,

$$A_m = \frac{T - (DT_m + BT_m)}{T}$$

The sum of the downtime and blocked time for each machine is provided in the row of Table 3.1 labeled "Downtime plus block time," and the total time T is simply 168 hours. To keep matters simple, it has been assumed that each machine in a workstation is identical and has identical performance.

The calculations for the availability of two of the machines, A1 [designated as A_m(A1)] and B1 [designated as A_m(B1)], are shown below and serve to illustrate the procedure employed to determine the availability of all the machines in the factory.

$$A_m(\text{A1}) = \frac{T - (DT_{\text{A1}} + BT_{\text{A1}})}{T} = \frac{168 - (16.8)}{168} = 0.90 = 90 \text{ percent}$$

$$A_m(\text{B1}) = \frac{T - (DT_{\text{B1}} + BT_{\text{B1}})}{T} = \frac{168 - (25.2)}{168} = 0.85 = 85 \text{ percent}$$

We repeat this process to develop the availabilities of all 10 machines. Then, using Equation (3.6), we may compute the effective process rates of the machines.

For example, the effective process rates (i.e., the maximum theoretical capacity) of machines A1 and B1 are given by

$$EPR_m(\text{A1}) = A_m(\text{A1}) \bullet PR_m(\text{A1}) = 0.90 \bullet 2 = 1.80 \text{ jobs/hour}$$

and

$$EPR_m(\text{B1}) = A_m(\text{B1}) \bullet PR_m(\text{B1}) = 0.85 \bullet 1 = 0.85 \text{ jobs/hour}$$

This is repeated for all 10 machines, and the results have been inserted into Table 3.2.

At this point we might wish to conduct a "sanity check." Specifically, is the factory configuration and capacity of Figure 3.9 sufficient to accommodate the throughput rates imposed on each workstation? To answer this, we must determine the total throughput imposed on each workstation and compare that with the workstation's maximum theoretical capacity.

Assuming that there are no losses (e.g., no scrap) in the network, the throughput rate imposed on each workstation is 1.5 + 1.5, or 3, jobs per hour. For this simple factory, the maximum theoretical capacity of each workstation may be computed by adding up the EPR_m values of the machines in the workstation. That is,

$$EPR_{ws}(\text{A}) = 1.8 + 1.8 = 3.6 \text{ jobs/hour}$$
$$EPR_{ws}(\text{B}) = 0.85 + 0.85 + 0.85 + 0.85 = 3.4 \text{ jobs/hour}$$
$$EPR_{ws}(\text{C}) = 0.855 + 0.855 + 0.855 + 0.855 = 3.42 \text{ jobs/hour}$$

TABLE 3.2

Factory Data, Phase 2

Workstation	**A**		**B**				**C**			
Machine	A1	A2	B1	B2	B3	B4	C1	C2	C3	C4
Downtime plus block time (hours/week)	16.8	16.8	25.2	25.2	25.2	25.2	8.4	8.4	8.4	8.4
Availability	0.9	0.9	0.85	0.85	0.85	0.85	0.95	0.95	0.95	0.95
Process rate (jobs/hour)	2	2	1	1	1	1	0.9	0.9	0.9	0.9
Effective process rate (jobs/hour)	1.8	1.8	0.85	0.85	0.85	0.85	0.855	0.855	0.855	0.855

Since the maximum theoretical capacities (i.e., upper bound on capacity) of each workstation exceeds the throughput rate of three jobs per hour, we may assume, at least for now, that each workstation is capable of supporting the job flow.

Next, let's consider a transformation of the workstation-centric model of Figure 3.9 into a process-step-centric model. To accomplish this, we must first determine the specific machine-to-process-step dedications in each workstation. We'll begin by assuming that every machine in a workstation is capable of supporting any process step that flows through that workstation. This leads to the process-step-centric flowchart in Figure 3.10. (I've assumed, for sake of simplicity, that every process step is a value-added operation, and thus the process-step numbers are enclosed by white circles.)

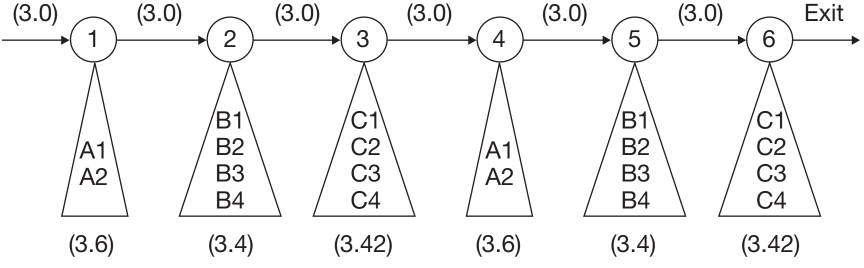
The throughput rate imposed on each process step is listed, in parentheses, above the arrows leading into the process step. The total capacity (i.e., maximum theoretical capacity) of the machines supporting each of the process steps flowing through each workstation (as shown in the triangles) is listed below the triangles.

Now examine what would happen if we were to reallocate machines to process steps in each workstation. Specifically, consider the following allocations:

- Process step 1→ machine A1
- Process step 2→ machines B1 and B2
- Process step 3→ machines C1 and C2
- Process step 4→ machine A2
- Process step 5→ machines B3 and B4
- Process step 6→ machines C3 and C4

FIGURE 3.10

Process-step-centric representation.



Employing these allocations, we may configure a new process-step-centric flow model for this factory. This model is depicted in Figure 3.11.

Notice that by simply changing machine to process-step assignments, a new factory configuration has been created. This new configuration supports precisely the same process-step flow but now reflects a complete decoupling of the factory involved. This is evident if we construct the workstation-centric flow model for the factory configured in Figure 3.11. This model is shown in Figure 3.12. The factory of Figure 3.12 has no reentrant loops (and thus a DoR value of 1) but is equivalent, in terms of the process-step flow, to the original reentrant factory of Figure 3.9.

The decoupling of the factory leads to new designations for the workstations. Now, rather than having three workstations (A, B, and C), we have six (virtual) workstations (A, B, C, A′, B′, and C′). Beneath each workstation is listed the upper bound on its capacity (i.e., the sum of the EPR_m values of the machines in the

FIGURE 3.11

Fully decoupled factory in process-step-centric form.

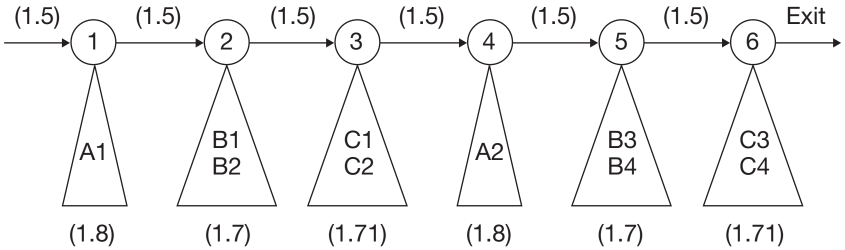
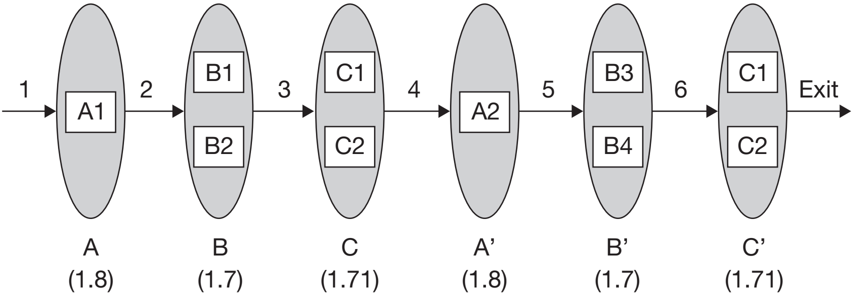


FIGURE 3.12

Fully decoupled factory in workstation-centric form.



workstations). Since the arrival rate is the same for every workstation, that is, 1.5 jobs per hour, we can determine their occupancy rate by means of Equation (3.19). These values are listed below.

$$\rho_{ws}(\mathrm{A}) = \frac{1.5}{1.8} = 0.8333 = 83.33 \text{ percent} = \rho_{\mathrm{ws}}(1)$$

$$\rho_{ws}(\mathrm{B}) = \frac{1.5}{1.7} = 0.8824 = 88.24 \text{ percent} = \rho_{ws}(2)$$

$$\rho_{ws}(\mathrm{C}) = \frac{1.5}{1.71} = 0.8772 = 87.72 \text{ percent} = \rho_{ws}(3)$$

$$\rho_{ws}(\mathrm{A'}) = \frac{1.5}{1.8} = 0.8333 = 83.33 \text{ percent} = \rho_{ws}(4)$$

$$\rho_{\mathrm{ws}}(\mathrm{B'}) = \frac{1.5}{1.7} = 0.8824 = 88.24 \text{ percent} = \rho_{ws}(5)$$

$$\rho_{ws}(\mathrm{C'}) = \frac{1.5}{1.71} = 0.8772 = 87.72 \text{ percent} = \rho_{ws}(6)$$

From these values we can identify (under some very restrictive assumptions that will be relaxed in Chapter 5) the bottleneck (i.e., choke point or constraint) process steps and workstations. Specifically:

- Process steps 2 and 5, having the highest occupancy rates, are the bottleneck operations.
- Workstations B and B′, because they are composed of the machines supporting the bottleneck process steps, are the bottleneck workstations.

In addition (and under the same restrictive assumptions), we may determine the capacity of the entire factory—the upper bound on the throughput supported by the bottleneck process steps. This upper bound on factory throughput is determined by finding the lowest upper bound of process-step effective process rates. This is 1.7 jobs per hour (for either process steps 2 or 5). Thus, given ideal conditions and the assumptions to be relaxed in Chapter 5, at this point we will assume the factory capacity to be its maximum theoretical capacity, that is, 1.7 jobs per hour.

Finally, let's determine the cycle time of the factory under the same restrictive assumptions. If we assume that there is absolutely no variability in the machines, process rates, and throughput rate, the cycle time of the factory may be determined by adding the cycle times of all the process steps—including those of transit times.

Assuming that the time required to move from one nontransit process step to another is five minutes (0.0833 hours) and that the transit process steps are $CT_1, CT_2, \ldots, CT_6$, then the factory cycle time is given by

$$CT_f = CT_1 + CT_{ps}(1) + CT_2 + CT_{ps}(2) + CT_3 + CT_{ps}(3) + CT_4 + CT_{ps}(4) + CT_5 + CT_{ps}(5) + CT_6 + CT_{ps}(6)$$

We know that CT_1, CT_2, CT_3, CT_4, CT_5, and CT_6 are each 0.0833 hour in duration, and thus the transit portion of the factory cycle time is 6 • 0.0833, or 0.5, hours. We next determine the nontransit process-step times, which are given by finding the inverse of their effective process times, that is,

$$CT_{ps}(1) = \frac{1}{EPR_{ps}(1)} = \frac{1}{1.8} = 0.5556$$

$$CT_{ps}(2) = \frac{1}{EPR_{ps}(2)} = \frac{1}{1.7} = 0.5882$$

$$CT_{ps}(3) = \frac{1}{EPR_{ps}(3)} = \frac{1}{1.71} = 0.5848$$

$$CT_{ps}(4) = \frac{1}{EPR_{ps}(4)} = \frac{1}{1.8} = 0.5556$$

$$CT_{ps}(5) = \frac{1}{EPR_{ps}(5)} = \frac{1}{1.7} = 0.5882$$

$$CT_{ps}(6) = \frac{1}{EPR_{ps}(6)} = \frac{1}{1.71} = 0.5848$$

Adding these process-step cycle times (which total 3.4572 hours) to the total transit time, we determine the cycle time of the factory to be 3.4572 + 0.5 = 3.9572 hours.

Employing Equation (3.24), we also could determine the total inventory in the factory, that is, the product of the factory throughput (1.5 jobs per hour) times the job cycle time (3.9572 hours). The total factory inventory at any given time thus is predicted to be 5.9358 jobs.

There are two matters in particular that should be clarified at this point. First, while under perfect conditions the cycle time of the factory might be 3.9572 hours (or something on the order of 4 hours), under more realistic circumstances, the actual factory cycle time could be several times this value. For example, in a less than ideal environment, this factory's cycle time easily could exceed 25 hours! The reason for this is variability, a factor ignored thus far.

Second, the transformation of the factory of Figure 3.9 (a fully coupled system with a DoR of 2) into that of Figure 3.12 (a completely decoupled system with a DoR of 1) is not nearly so easy to accomplish in a real factory—nor necessarily practical. However, for purpose of illustration, the factory, its throughput, and effective process rates were carefully selected so as to permit the development of a completely decoupled system without the need to add more machines.

This does not diminish, however, the importance of at least attempting to reduce the DoR of any real factory. In fact, as we shall see, it actually may be worthwhile to buy some additional machines simply for the sake of DoR reduction. The cost of those machines could well be more than made up for by improved factory performance.

CHAPTER SUMMARY

A number of important concepts—and terminology, definitions, and notation—have been covered in this chapter. But it must be recognized that the discussion has been restricted to metrics measured by their average values. Variability, one of the three enemies of factory performance, has been ignored. This omission will be rectified in Chapter 5.

One of the most important messages contained in this chapter is that there are two ways to measure the capacity of process steps, machines, workstations, or factories. Specifically, there is a significant practical difference between an entity's maximum *sustainable* capacity *SC* and its maximum *theoretical* capacity *EPR*.

Chapter 4 will allow you to combine what has been covered in this chapter with your experience, judgment, intuition, and insight so as to determine how to improve the performance of a simple factory. First, though, let's check into the happenings at Muddle, Inc. More specifically, just how do Dan and Brad feel about their one week of training in lean manufacturing?

CASE STUDY 3: DAN IS NOT AMUSED

In Case Study 2 we left Dan Ryan and Brad Simmons in the company cafeteria. Brad warned Dan not to mention that he had some (limited) previous schooling in factory performance improvement prior to attending Muddle's *LEAN* Forward training class. It's now Friday, and the week-long class (the two-week off-site class at the ritzy resort was restricted to management), as taught by Sally Swindel, is over. The purpose of this class allegedly was to "train the trainer"; that is, each person who has taken the class is assumed to know, at its conclusion, enough about lean manufacturing to teach it to other factory personnel. They, in turn, are then assumed to know enough to teach it to the personnel in their departments.

Once again we encounter Dan and Brad in the company cafeteria, now mulling over the lean manufacturing training course.

* * *

"Brad, I kept my mouth shut this entire week, just as you advised. But now that the course is over, I've got to say that it was a joke. A really bad joke. I've . . ." Dan pauses as a well-dressed woman (an oddity in the casual atmosphere of a Muddle factory site) takes a seat at their table. Brad introduces her.

"Dan," says Brad, "I'd like you to meet Julia Austen. You may recall that Julia also was in this week's course. She was sitting in the back of the room."

"How do you do," says Dan, warily.

"I'm doing quite well," replies Julia, "but do go on. You were saying that the course was a joke . . . a really bad joke."

"Dan, old boy," interjects Brad, "not to worry. Julia shared her thoughts on the course with me this morning. I'd say that the three of us are at least somewhat in agreement as to our impressions of the course. It was pretty much a pep talk coupled with lots of slogans and some rather obvious advice on how to do some rather elementary things, like clean up the factory floor and put tools where they belong. But, if I do say so, it really wouldn't hurt to follow that advice. We've got some real messy people out there." Julia nods in agreement.

"I agree that several of the ideas that were presented made sense," says Dan. "And I sure as heck agree that there is a lot of waste and sloppiness in the factory. But, for heaven's sake, how can we now be expected to 'go forth and teach the masses.' Good grief, we've only had a week of training—some rather dubious training I might add. Furthermore, based on the lessons my former colleagues learned at ToraXpress, there's a whole lot more to factory performance than what Sally Swindel covered. Frankly, we could clean up the clutter and polish every machine in this factory until we see our reflections, but I'm not convinced that's all this company needs to obtain real, significant, and sustainable performance improvement."

"I absolutely agree that a week is hardly enough to become an expert in lean, but the instructor did provide us with a book," replies Brad, pointing to a copy of *Lean Is the Answer.*

"ToraXpress, you say," Julia says, changing the subject. "That's the firm Muddle bought and had to shut down. How about sharing the lessons you say you learned from your time there?"

"Sure," says Dan. "But let me say that I was working as an intern in ToraXpress's finance department at the time and not directly involved in factory performance improvement. So a lot of what I'm going to tell you is second hand."

"That's alright," says Julia, "I'm just curious as to how ToraXpress managed to so quickly improve itself and why things went sour so soon afterward."

"Well," Dan replies, "here's what I believe happened. As you may know, ToraXpress was in a bad way for years. The owner of the company brought in consultant after consultant. They tried every management and manufacturing fad you could think of. In fact, they even implemented lean manufacturing based on the recommendation of Sally Swindel, the very same Sally Swindel who just spent this week telling us that lean would cure this company's ills."

"So," says Brad, "what happened? Did lean turn things around? Was it really the answer?"

"Actually," says Dan, "I'm told that things just went from bad to worse. Every once in a while, there would be a brief period of improvement—something Professor Leonidas calls the Hawthorne effect—but then things would return to the norm or worse. For example, the lean teams would conduct waste walks and *kaizen* events and what not. They'd clean up work areas and take lots of before-and-after photographs. By the way, I was told that management really liked those pictures; they gave them the feeling that all the firm's problems would go away. But, within a few weeks or months, the work areas would revert back to the same old mess, and you'd see the same old sloppy habits reappear. In the meantime, factory cycle time just got worse. As Professor Leonidas told us later, you've got to change the company's culture and get the involvement and engagement of everyone up to and including the CEO. And you've got to provide an explanation for doing things, and that requires some knowledge of the science of manufacturing."

"That fits in with my reaction to Sally's course," replies Julia. "I kept wondering how you maintain performance improvement, and most of all, I wondered how cleaning up a workplace, or reducing batch sizes, or whatever directly and indirectly affected such things as cycle time and capacity. But first, Dan, who is this Professor Leonidas you mentioned?"

"Yeah," Brad agrees, "who is this guy, and when can we meet him?"

"Professor Leonidas, Professor Aristotle Leonidas to be exact, has a ranch about 30 miles from here. He's a retired professor. The owner of ToraXpress happened to meet the professor on a fishing trip. He was so impressed that he asked Leonidas to present a one-week course on what the professor called the science of manufacturing to the top management at ToraXpress. Shortly after that, the professor was asked to present the same course to all our managers and engineers. He went on to teach several four-week courses to our factory engineers. Within a year, factory cycle time was reduced by 75 percent, we increased our capacity—without buying any new equipment—and we improved the accuracy of our lead-time forecasts. Of course, that's when Muddle bought out ToraXpress and put in its own methods for manufacturing. And that's when our performance went down the drain."

"Those were pretty impressive results," remarks Brad, "but our senior plant manager, Tommy Jenkins, is definitely adverse to science. He's said more than once that you can't replace experience and gut feelings with science."

"I imagine," says Dan, "that's why he didn't resist the introduction of the lean manufacturing courses in this factory. The way that Sally Swindel presented the material, you'd be hard pressed to find much in the way of science."

"So," remarks Brad, frowning, "I take it that your professor friend doesn't think much of lean manufacturing."

"No, you're absolutely wrong about that," replies Dan, "Professor Leonidas is a firm believer in most of the concepts and methods that are now included in what is called lean manufacturing. He simply told us that lean manufacturing is only part of the solution, not *the* solution."

"Interesting," says Julia. "When can we meet this gentleman? Do you think we could convince him to present his lectures on the science of manufacturing at this site? How about it, fellows?"

"Hold on," replies Brad. "I'd like to meet the professor myself, but before we bring this matter up to management—particularly

Tommy Jenkins—we need to get real. As I mentioned before, Tommy doesn't even want to hear the word *science.* We might all wind up 'redeployed' or—at the least—sent to Room 101[11] if we ask Tommy to invite some guy here to talk about the science of manufacturing."

"Agreed," says Julia. "But what's stopping the three of us from talking to the professor? If we do so on our own time and keep our mouths shut, we should be okay. How about it, Dan, would you be able to arrange a meeting with the professor?"

"I can try, but like I said, he's retired and only presented the courses to ToraXpress as a favor to the firm's owner. I'll give it a shot; I've got his e-mail address somewhere. I'll let the two of you know what he says once I contact him."

"Great," says Brad, "I sure hope we can meet with the gentlemen. In the meantime, I hope to learn a little more about Sally Swindel; she's quite attractive, don't you think?"

* * *

We can conclude from the preceding discussion that Brad, Julia, and—particularly—Dan haven't yet been convinced that lean manufacturing is the answer—at least in the format being presented by Sally Swindel. Neither are they convinced that they, after just a one-week slide show, are now experts on lean manufacturing and ready and able to teach their coworkers—and, in particular, to provide intelligent answers to any questions that might be raised. Perhaps they're just wrong. Perhaps lean manufacturing is so simple that you can learn everything you need to know in a week of training, followed by a reading of *Lean Is the Answer*.

Then again, perhaps you can become a world-class brain surgeon or fully qualified rocket scientist in a week. Sarcasm aside, perhaps it takes just a bit more. Perhaps Professor Aristotle Leonidas can fill in the blanks. Then again, what does an old, retired professor know about how to improve Muddle? After all, isn't every factory different? Doesn't it take years of actual experience in the factory even to begin to think about improving its performance?

---

[11] Many of Muddle's employees would rather be fired than be sent to the firm's infamous Room 101. As we'll discover later, Julia Austen has had the unfortunate experience of being sent to Room 101. As did Winston Smith, a man we'll meet later.

Tommy Jenkins, the senior plant manager, is convinced that all it takes to run a factory is about 10 years of experience coupled with a "gut feel." In fact, many of the firm's plant and department managers are convinced that all it takes to manage a factory is intuition. If this is true, then you, dear readers, just might be able to improve the performance of the simple factory discussed in Chapter 4.

By the way, just what did Brad Simmons imply by his mention of hoping to learn more about Sally Swindel? And just who is he meeting for dinner tonight?

CHAPTER 3 EXERCISES

1. Given the factory workstation-centric model shown in Figure 3.13, develop its process-step-centric representation under the following set of job/machine dedications:
    - Process step 1→ machines A1 and A2
    - Process step 2→ machines B1, B2, and B3
    - Process step 3→ machines C1 and C4
    - Process step 4→ machine A2

FIGURE 3.13

Exercise 1.

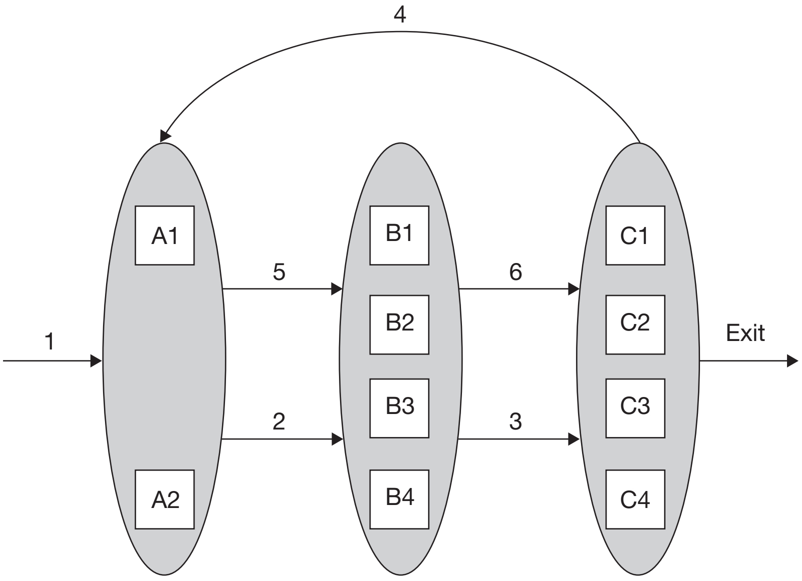


TABLE 3.3

Exercise 2 Data

State	Average Time (hours)	Percentage of Time
Waiting for a batch to form	1.3	13.68
Waiting in queue as part of a completed batch	2.2	23.16
Rework	0.5	5.26
Inspection	0.4	4.21
In processing (excluding rework)	3.9	41.05
In transit	1.2	12.63
Average cycle time	9.5	100

TABLE 3.4

Exercise 4 Data

State	Average Time in Hours per Week
Scheduled downtime	12
Up and running but being qualified	7
Processing (busy) time	96
Up and running but under inspection	6
Unscheduled downtime	25
Idle time	22

- Process step 5→ machines B2, B3, and B4
- Process step 6→ machines C2 and C3

2. A typical job flowing through a factory spends, on average, the amount of time in certain states as listed in Table 3.3. Construct the equivalent factory cycle-time components plot (in terms of percentages) for this factory.
3. What is the cycle-time efficiency of the factory described in Exercise 2?
4. A machine located in a factory with a 168-hour workweek spends the following amounts of average time in the states listed in Table 3.4. Given this information,
   - Plot the machine states.
   - Determine the availability of this machine.

CHAPTER 4

Running a Factory: In Two Dimensions

In this chapter you are provided with the opportunity to manage and run a simulated factory. More specifically, you are asked to improve the cycle time of the factory (i.e., reduce its cycle time subject to certain budget limitations). There are no tricks to this problem, nor is there any attempt to mislead you. Simply employ what you have learned from whatever source to date (e.g., your real-world experience, your education or training, or simply your intuition and "gut feel") to achieve the cycle-time reduction goal.

THE ATTRIBUTES OF THE FACTORY

The factory you will manage—and seek to improve its performance—is an exceptionally simple facility. Its attributes may be summarized as follows:

- Twelve workstations connected in series (see Figures 4.1 and 4.2).
- Each workstation consists of a number of identical machines running at identical effective process rates (e.g., with identical maximum theoretical capacities).
- Neither batching nor cascading is employed.
- A single product type flowing from the first workstation to the second and so on until it exits the final (twelfth) workstation is being processed.
- There is zero transit time between workstations.

FIGURE 4.1

Workstation-centric flowchart for a 12-workstation factory.

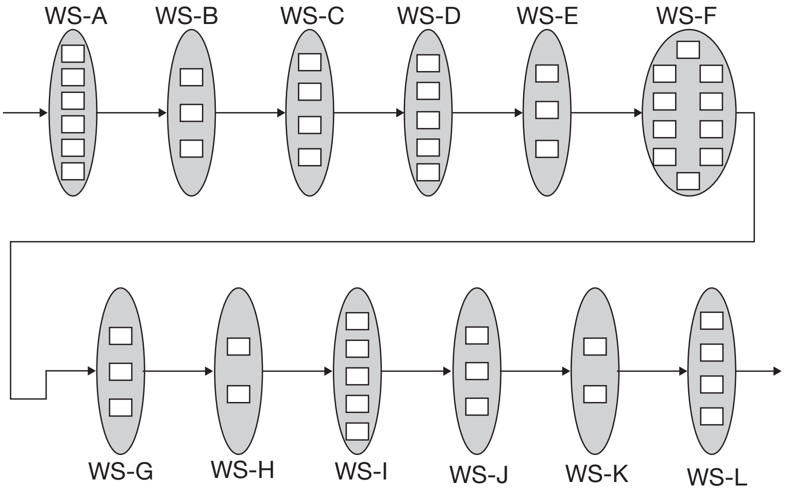
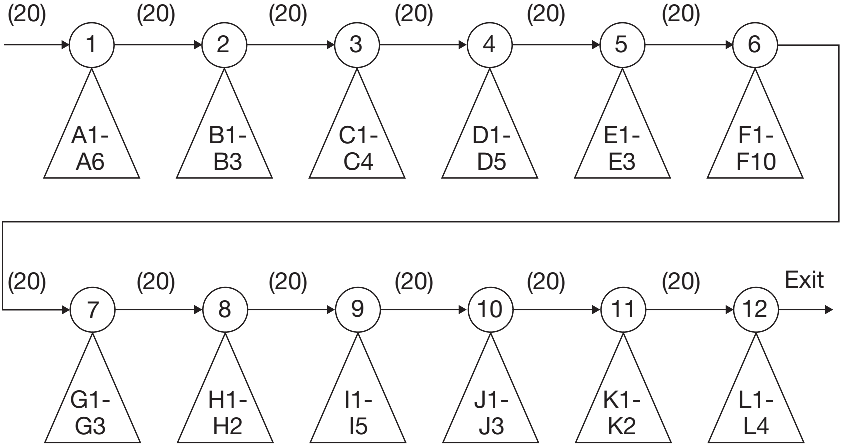


FIGURE 4.2

Process-step-centric flowchart for a 12-workstation factory.



- There is no inspection or monitoring (i.e., the product simply moves from one value-added workstation to the next via the zero-time-transit process).
- There is no reentrancy (i.e., each workstation and its machines support a single operation in the process-step flow).

- There is no rework or scrap (i.e., it is assumed that the product flows directly from one workstation to the next without the need for any rework and no loss in yield).

Figure 4.1 presents the workstation-centric flowchart of the 12 workstations. The blocks within each workstation indicate the number of machines that initially exist in the associated workstation. For example, workstation A (WS-A) presently has six machines, whereas workstation F (WS-F) has 10. The direction of job flow from workstation to workstation is depicted by the arrows.

Assuming that every machine in a given workstation is qualified to support the process step conducted by that workstation, an equivalent process-step-centric model may be constructed for the 12-workstation factory. This model is shown in Figure 4.2. In this figure, the machines supporting each process step are listed in the triangle under the associated process step. For example, process step 2 is supported by machines B1, B2, and B3 (i.e., B1 through B3, designated in the figure as B1–B3) of workstation B.

The numbers in parentheses above each transit-step arrow indicate that the throughput flow rate of jobs through the factory and through each workstation in the factory is, on average, 20 units per day. Additional details as to the attributes of the factory are presented in the next section.

PROBLEM STATEMENT

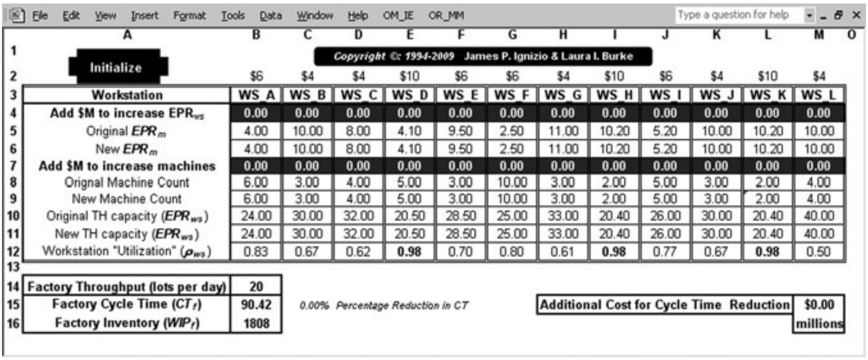
Presently, the cycle time of this factory is 90.42 days—which is much, much worse than your hypothetical competition. Your job is to reduce the cycle time by means of either

- Adding additional machines to one or more of the workstations, or
- Improving the effective process rate EPR_{ws} (see Chapter 3 for a review of this parameter) of the existing machines in one or more workstations, or
- Using some combination of the preceding

Since additional machines or the improvement of effective process rates (either by increasing availability or by increasing run rates) cost money, you must achieve your goal within a limited budget. Specifically, the total amount you are permitted to spend is limited to $13M. (These funds may be allocated, up to the total amount of $13M, to the darkened cells of the 12-workstation simulation

FIGURE 4.3

Twelve-workstation factory simulation model, initial scenario.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1					Copyright ©: 1994-2009 James P. Ignizio & Laura I. Burke								
2	Initialize	\$6	\$4	\$4	\$10	\$6	\$6	\$4	\$10	\$6	\$4	\$10	\$4
3	**Workstation**	**WS_A**	**WS_B**	**WS_C**	**WS_D**	**WS_E**	**WS_F**	**WS_G**	**WS_H**	**WS_I**	**WS_J**	**WS_K**	**WS_L**
4	**Add \$M to increase EPR_{ws}**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Original EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
6	New EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
7	**Add \$M to increase machines**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	Orignal Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
9	New Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
10	Original TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
11	New TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
12	Workstation "Utilization" (ρ_{ws})	0.83	0.67	0.62	**0.98**	0.70	0.80	0.61	**0.98**	0.77	0.67	**0.98**	0.50
13													
14	**Factory Throughput (lots per day)**	**20**											
15	**Factory Cycle Time (CT_f)**	**90.42**	*0.00% Percentage Reduction in CT*							**Additional Cost for Cycle Time Reduction**			**\$0.00**
16	**Factory Inventory (WIP_f)**	**1808**											**millions**

model.) Figure 4.3 summarizes in matrix form the existing condition of the factory.

Note in Figure 4.3 that such attributes as factory throughput (i.e., the rate of flow of jobs through the factory), factory cycle time, factory inventory, number of machines in each workstation, and the capacity (i.e., $EPR_{ws,}$ the maximum theoretical capacity) of each workstation are listed. The cells associated with these parameters are indicated in Table 4.1.

Next, we need to determine how much it will cost either to increase the maximum theoretical capacity (i.e., *EPR*) of each machine in a workstation or to add more machines to a workstation. The cost of an additional machine in each workstation is shown in Table 4.2. For example, if you wish to add one machine to those already existing in WS-A, it will cost \$6M. Adding a machine to workstation B (WS-B) will require the allocation of \$4M.

Next, consider what it will cost to improve the *EPR* of each and every machine in a given workstation. We know that the effective process rate of a machine is found by multiplying its availability by its raw process rate (i.e., ideal run rate in jobs per unit time). This means that to increase a machine's effective process rate, you can either (1) increase its availability, (2) increase its process speed, or (3) attempt to increase both the availability and process rate. To keep matters simple, we'll use Equation (4.1) to predict the impact of funds on increases in workstation *EPR* values by whatever means:

$$\$M = (\text{new } EPR_{ws} - \text{old } EPR_{ws})^5 \tag{4.1}$$

TABLE 4.1

Factory or Workstation Attributes

Attribute	Value	From Cell	Comments
Factory throughput	20 jobs/day	B14	Customer demand rate
Factory cycle time	90.42 days	B15	Average factory *CT*
Factory inventory	1808 jobs	B16	Average factory *WIP*
Effective process rate of each machine in WS-A	4 jobs/day	B5	This is the initial value of *EPR* per machine
EPR per machine in WS-A after improvement	4 jobs/day	B6	In initial matrix, no improvements have been made
Original machine count in WS-A	6 machines	B8	Initially, there are 6 machines in the workstation
Machine count in WS-A after improvement	6 machines	B9	In initial matrix, no additional machines have been added
Original workstation theoretical capacity for WS-A	24 jobs/day	B10	6 machines times 4 jobs/machine = 24 jobs/day
Theoretical capacity of WS-A after improvement	24 jobs/day	B11	No change from B10 because no improvement yet
WS-A workstation utilization (occupation rate)	0.83 (83 percent)	B12	Equals factory *TH*/ workstation capacity ρ_{ws}, or 20/24
Additional cost	\$0.00M	M15	Cost incurred by improvements
Funds allocated to *EPR* improvement	\$0.00M	B4:M4	No funds allocated
Funds allocated to adding machines	\$0.00M	B7:M7	No funds allocated

TABLE 4.2

Machine Cost

Workstation	Cost of Each Additional Machine, in \$M
A	6
B	4
C	4
D	10
E	6
F	6
G	4
H	10
I	6
J	4
K	10
L	4

This equation, for example, would predict that a change in the *EPR* of a workstation (a.k.a. *maximum theoretical capacity*) from a rate of 4 jobs per day to 4.5 jobs per day would require

$$\$M = (4.5 - 4)^5 = 0.5^5 = \$0.03125M, \text{ or } \$31{,}250$$

While this equation is merely a rough approximation used for purposes of illustration, it indicates the fact that an increase in the *EPR* of a workstation (i.e., by increasing the availability or run rates of the existing machines) requires funds that increase exponentially with the desired increase in the workstation's *EPR* value.

PROBLEM SOLUTION

Given the data and information in the preceding section, you now should be prepared to find a solution to the 12-workstation problem that will reduce factory cycle time subject to a budget limitation of $13M. You can try your skill, luck, gut feel, intuition, or prayers in solving this problem by using the simulation model provided at the following Web site:

www.mhprofessional.com/Ignizio/12WS_Ch4

Just one of the many approaches that have been employed is described below. It centers about the notion of *elevating the factory constraint.*

If you happen to be a fan of the theory of constraints (ToC), you might try to elevate the factory constraints one at a time. If, however, you examine the workstation utilization entries in cells B12 through M12, you will notice that there are *three* factory constraints, that is, workstation D, workstation H, and workstation K, each with utilization (i.e., occupation rate) of approximately 0.98. This raises some interesting questions—just some of which are listed below:

- Which factory constraint (i.e., workstation) should you begin with given a factory with multiple constraints?
- Should you add machines to the constraint?
- Or should you improve the *EPR* of the constraint (i.e., by using funds to increase the availability and/or run rate of the existing machines in the constraint workstation)?

- Or should you try some combination of adding machines and improving workstation *EPR*?

The decision you make with regard to each of these questions will make a difference—likely a big difference—in the solution you ultimately reach. This fact alone should be reason enough to give advocates of the theory of constraints some concern.

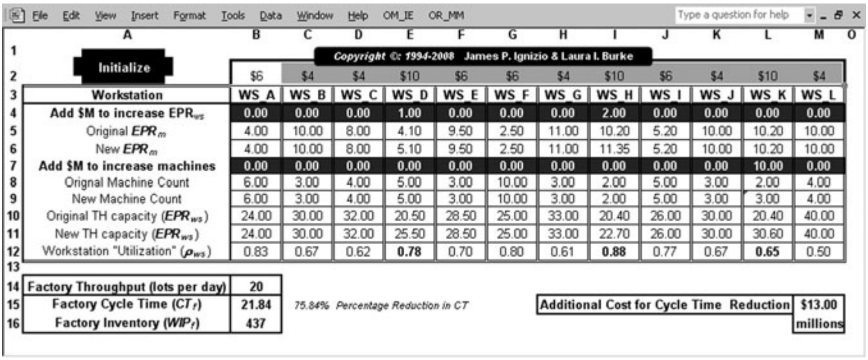
Once the theory of constraints advocate decides on which of the three factory constraints to begin with, the procedure employed is to add just enough resources (i.e., funds for either more machines or an increase in workstation *EPR*) so that the workstation selected for the allocation of funds is no longer a constraint. This is known as *elevation of the factory constraint.* The elevation procedure then is repeated for the new factory constraint. This process is continued until the budget limitation ($13M) is reached.

Any number of other approaches might be employed for the allocation of the $13M budget for factory performance improvement. Your task is to employ whatever method you prefer to accomplish a reduction in factory cycle time. So go ahead and see how you do. But don't look at the solution provided herein until after you've done your very best to reduce factory cycle time while staying within the $13M budget.

I've listed in Figure 4.4 one of the better solutions (i.e., most ToC-based solutions that have been generated by students and course attendees actually have been worse) arrived at by means of

FIGURE 4.4

Twelve-workstation factory simulation model with ToC-based solution.



	$6	$4	$4	$10	$6	$6	$4	$10	$6	$4	$10	$4
Workstation	**WS_A**	**WS_B**	**WS_C**	**WS_D**	**WS_E**	**WS_F**	**WS_G**	**WS_H**	**WS_I**	**WS_J**	**WS_K**	**WS_L**
Add $M to increase EPR_{ws}	0.00	0.00	0.00	1.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00
Original EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
New EPR_m	4.00	10.00	8.00	5.10	9.50	2.50	11.00	11.35	5.20	10.00	10.20	10.00
Add $M to increase machines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00
Orignal Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
New Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	3.00	4.00
Original TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
New TH capacity (EPR_{ws})	24.00	30.00	32.00	25.50	28.50	25.00	33.00	22.70	26.00	30.00	30.60	40.00
Workstation "Utilization" (ρ_{ws})	0.83	0.67	0.62	**0.78**	0.70	0.80	0.61	**0.88**	0.77	0.67	**0.65**	0.50

Factory Throughput (lots per day)	**20**
Factory Cycle Time (CT_f)	**21.84**
Factory Inventory (WIP_f)	**437**

75.84% Percentage Reduction in CT

Additional Cost for Cycle Time Reduction	**$13.00 millions**

the theory of constraints. First, a machine is added to workstation K (at a cost of $10M), then $2M is provided to improve the *EPR* of workstation H, and finally, $1M is allocated to workstation D for *EPR* improvement. The resulting cycle time is 21.84 days—a reduction of 75.84 percent over the initial value of 90.42 days. The degree of improvement is certainly impressive.

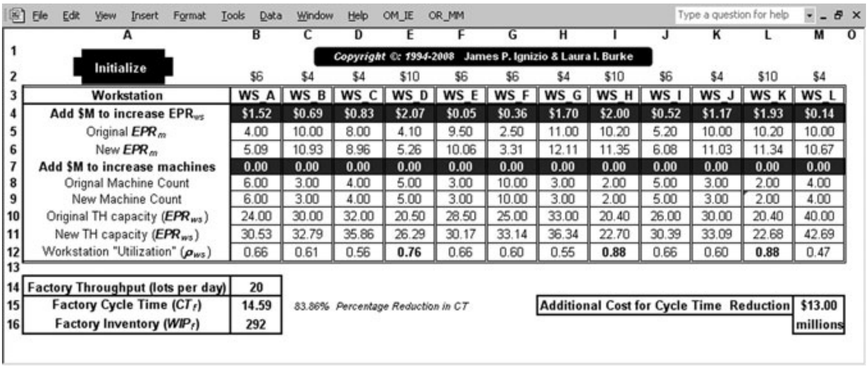
While the solution shown in Figure 4.4 achieved a 75.84 percent cycle-time reduction via the expenditure of $13M, consider the solution shown in Figure 4.5. Here, by means of optimization [i.e., genetic algorithms (Goldberg, 1989)], the factory cycle time has been reduced by an even more impressive 83.86 percent to 14.59 days!

Note that the optimal solution[1] in Figure 4.5 allocates funds across all 12 workstations.[2] These funds happen to be restricted solely to the improvement of workstation effective process rates rather than to the purchase of any machines.

The message one may take away from the ToC-based approach of Figure 4.4 and the optimization results [achieved via genetic algorithms (Goldberg, 1989)] of Figure 4.5 is that the theory of constraints is a strictly heuristic approach and as such cannot be

FIGURE 4.5

Twelve-workstation factory simulation model, optimized.



Copyright ©: 1994-2008 James P. Ignizio & Laura I. Burke

	$6	$4	$4	$10	$6	$6	$4	$10	$6	$4	$10	$4
Workstation	**WS_A**	**WS_B**	**WS_C**	**WS_D**	**WS_E**	**WS_F**	**WS_G**	**WS_H**	**WS_I**	**WS_J**	**WS_K**	**WS_L**
Add $M to increase EPR_{ws}	**$1.52**	**$0.69**	**$0.83**	**$2.07**	**$0.05**	**$0.36**	**$1.70**	**$2.00**	**$0.52**	**$1.17**	**$1.93**	**$0.14**
Original EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
New EPR_m	5.09	10.93	8.96	5.26	10.06	3.31	12.11	11.35	6.08	11.03	11.34	10.67
Add $M to increase machines	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Orignal Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
New Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
Original TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
New TH capacity (EPR_{ws})	30.53	32.79	35.86	26.29	30.17	33.14	36.34	22.70	30.39	33.09	22.68	42.69
Workstation "Utilization" (ρ_{ws})	0.66	0.61	0.56	**0.76**	0.66	0.60	0.55	**0.88**	0.66	0.60	**0.88**	0.47

Factory Throughput (lots per day)	**20**
Factory Cycle Time (CT_f)	**14.59**
Factory Inventory (WIP_f)	**292**

83.86% Percentage Reduction in CT

Additional Cost for Cycle Time Reduction **$13.00 millions**

---

[1] Actually, this is the solution reached during just the first phase of an optimization procedure.

[2] Obtaining accurate estimates of *EPR* improvement per dollar allocated and attempting to distribute these funds in the manner shown likely would be impractical in a real-world situation with imprecise real-world data.

guaranteed to reach an optimal solution or even a close to optimal solution. In fact, in any real-world factory, one can virtually guarantee that the theory of constraints will not achieve the best possible solution. Some of the reasons for the limitations of the theory of constraints include that

- Almost any real-world factory has multiple constraints.
- Factory constraints migrate (i.e., they change as a consequence of even slight changes in such things as product mix, starts policy, maintenance policies, etc.).
- The crucial impact of variability on factory—and bottleneck—performance is completely ignored.

This doesn't mean that the theory of constraints is "bad," only that there are usually more effective and less costly ways to improve factory performance. (More about this will be said in Chapter 6.)

Before proceeding to the next section, allow me to pose a question: Do you believe that it is possible to reduce the cycle time of a single workstation (while keeping all other factors in the factory constant) and actually wind up increasing *overall* factory cycle time? In other words, if you are an advocate of, say, lean manufacturing, would you believe that you actually could overdo the improvement of a single workstation at the expense of the factory? I will employ the 12-workstation model to investigate these matters.

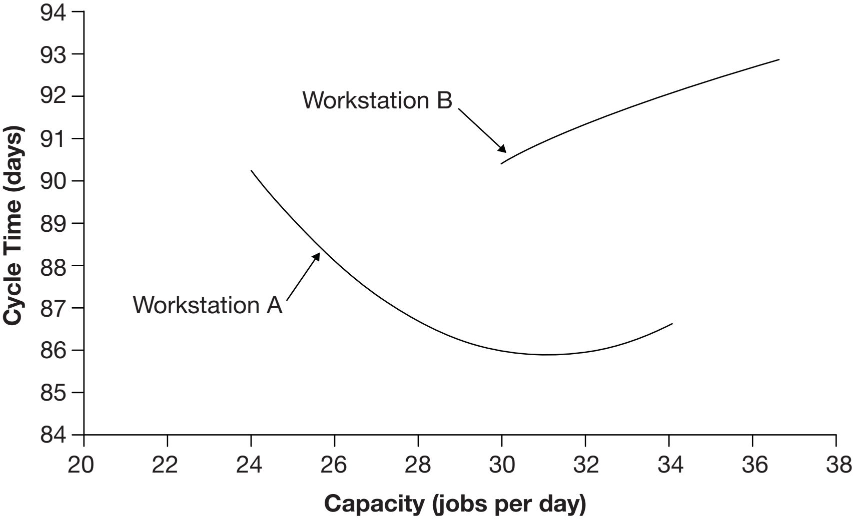
YOUR INTUITION IS LIKELY TO BE WRONG

Return to the original 12-workstation factory scenario (accomplished by clicking on the icon labeled "Initialize" in the upper left-hand corner of the 12-workstation spreadsheet found on the Web site provided earlier). After initialization, the factory cycle time should revert to its original value of 90.42 days.

Now gradually increase the funds devoted to an increase in the effective process rate *EPR* of workstation A or, alternately, simply continue to add funding to increase the total number of machines in the workstation. (Feel free to ignore the $13M budget limit.) Either way, you are increasing the maximum theoretical capacity (i.e., EPR_{ws}) of the workstation. Figure 4.6 presents a graph that serves to indicate how factory cycle time changes with each increase in capacity (in terms of jobs per day) of either workstation A or workstation B.

FIGURE 4.6

Cycle times of workstations A and B as capacity is increased.



Notice in Figure 4.6 that as you increase the capacity of workstation A (while leaving all other workstations alone), the factory cycle time gradually drops to about 86 days. After that, however, any increase in the capacity of workstation A actually begins to increase factory cycle time. Increasing the capacity of workstation B (again, while leaving all other workstations alone), on the other hand, always results in an increase of factory cycle time over the range under consideration.

These results are counterintuitive to some people. I have, in fact, encountered individuals who refused to believe that the improvement of a single workstation (i.e., increasing its capacity) could possibly degrade a factory's overall performance. Once the three fundamental equations are covered in Chapter 5, it should become clearer, however, as to just when and how such results may happen. In the meantime, be wary of any methodology that fails to take a holistic view of the entire factory.

More specifically, recall that a real-world factory is a nonlinear, stochastic, dynamic system with feedback. When faced with such a system, you can rest assured that your intuition is almost always wrong. In short, factories are complex systems, and no matter how intelligent and experienced you might be, it is vital to avoid jumping to conclusions. Thankfully, there is a science that allows an objective analysis of such systems.

WHAT ABOUT LEAN MANUFACTURING?

The methods discussed thus far for the reduction of cycle time in a 12-workstation factory were based on guessing, intuition, the theory of constraints, and optimization. A lean manufacturing advocate may want to consider yet another approach. Specifically, a number of prominent lean manufacturing advocates have asserted that the workload in a factory should be *balanced.* More specifically, they state that the cycle time of each workstation ideally should be identical and that the factory must run at the customer demand rate (designated as the *takt rate*).[3]

Just a few of many statements of this belief are quoted below:

> A core principle of JIT [These authors state that just-in-time is synonymous with lean manufacturing] is that every operation within a production process should produce at the takt rate, regardless of the fact that most operations are capable of producing much faster [Hiroyuki Hirano and Makoto Furuya, *JIT Is Flow,* Vancouver, WA, PCS Press, 2006, p. 35].
>
> But what many companies fail to do is the more difficult process of stabilizing the system and creating "evenness"—a true balance lean flow of work. This is the Toyota concept of *heijunka.* . . . achieving *heijunka* is fundamental to eliminating *mura,* which is fundamental to eliminating *muri* and *muda* [Jeffery K. Liker, *The Toyota Way*, New York, McGraw-Hill, 2004, p 115].
>
> . . . work progresses from each station to the next in accordance with takt time and at the same rate as final assembly.

---

[3] Examining Figure 4.5, wherein factory cycle time was minimized via optimization, note that the *EPR* values (and utilization) of the workstations differ considerably—indicating a production line that is most definitely *not* balanced. Yet we minimized factory cycle time via this procedure. Furthermore, factory inventory was minimized. This result, in itself, should give pause to a belief in balanced production lines.

> . . . the work in each step has been carefully balanced with the work in every other step so that everyone is working to a cycle time equal to takt time [J. P. Womack and D. T. Jones, *Lean Thinking*, New York, The Free Press, 2003, p. 63].
>
> Level out the workload (*heijunka*) to the rate of customer demand or pull [Jay Arthur, "Core Ideas of Lean," in *Lean Six Sigma Demystified*, New York, McGraw-Hill, 2007, p. 31].

As mentioned, a *balanced line* is achieved by having all workstations process jobs at the same rate as that of customer demand (i.e., takt time). An alternate and equivalent definition of a balanced line is one in which the cycle times of each workstation are identical. There are, in fact, numerous references in the lean manufacturing literature asserting that a balanced line will minimize factory inventory. This assertion, if true, also would result in minimization of factory cycle time. So, once again, what about using lean manufacturing to solve the 12-workstation problem?

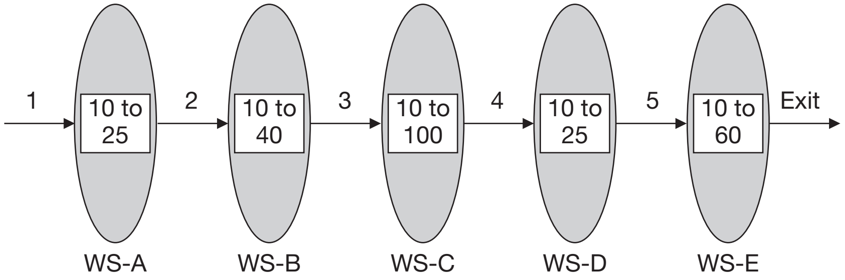
Unfortunately, the simulation spreadsheet for the 12-workstation problem was not designed to accommodate attempts to balance the line. Specifically, it was developed so that one may only increase the maximum theoretical capacity of the workstations. I have, however, developed an even simpler factory model (one consisting of just five workstations) that does permit line balancing (Ignizio, 2008b, 2008c). And if a balanced line achieves the desired cycle-time minimization on the 5-workstation model, it certainly would achieve similar results for the 12-workstation model.

The five-workstation model is shown in workstation-centric form in Figure 4.7. To keep things simple, as well as to permit the development of a perfectly balanced production line, each workstation's effective process rate is assumed to be continuously variable over specific ranges.

In the five-workstation model, we shall assume that customer demand rate is 20 jobs per hour. This is the rate (i.e., the takt rate) at which the factory throughput shall be set. For simplicity, we assume that all transit times are zero. The process rate of each of the five workstations is continuously adjustable from a minimum to a maximum speed (e.g., workstation A can be adjusted to a process rate of from 10 to 25 jobs per hour, whereas workstation B can be adjusted over the range of 10 to 40 jobs per hour). It would not be wise, however, to set the workstation effective process rates below

FIGURE 4.7

The five-workstation model.



roughly 20.1 jobs per hour because, as a consequence of inherent factory variability, this would not allow for a sufficient gap between capacity and utilization. The factory simulation spreadsheet for this model may be found at

www.mhprofessional.com/Ignizio/5WS_Ch4

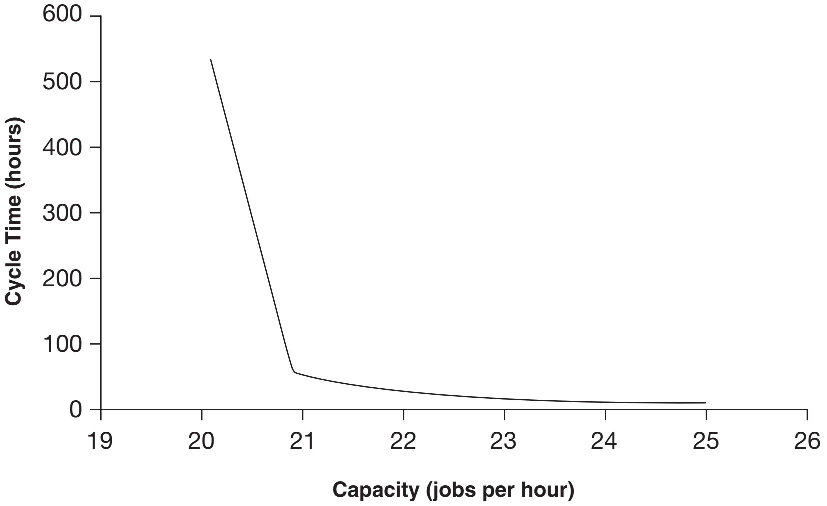
Readers are invited to observe what happens if the line is balanced according to the fundamental premise of lean manufacturing. The initial simulation scenario provided at the Web site for the factory is, in fact, a balanced line wherein every workstation has an effective process rate of 20.5 jobs per hour. The average cycle time and average inventory under this balanced scenario is 104.45 hours and 2088.98 units, respectively.

You are invited to try whatever scheme you believe might be superior, including running all workstations at their maximum effective process rate or balancing the line at effective process rates ranging from 20 to 25 jobs per hour (balancing at any higher rate than 25 jobs per hour is impossible owing to the limitations of workstations A and D).

The results of balancing the line using effective process rates from 20.1 (much lower and the factory will experience a near-infinite cycle time) to 25 units per hour (workstations A and D serve to determine this upper limit) are shown in Figure 4.8 (i.e., while the factory throughput is maintained at 20 units per hour.) One might assume from these results and from the statements in the lean manufacturing literature that cycle time and inventory are minimized via a balanced line in which all five workstations run at

FIGURE 4.8

Cycle times for balanced lines.



a rate of 25 jobs per hour. At this process rate, the balanced-line cycle time is 9.39 hours, and factory inventory is 187.76 units.

There is, however, a much better solution. Simply set the effective process rates of each workstation to their upper limit (e.g., 25, 40, 100, 25, and 60 jobs per hour, respectively) and note the results. In this (very) unbalanced line, both factory cycle time and factory inventory level are reduced over that of any balanced line. Cycle time is 5.03 hours, whereas factory inventory is 100.59 units. This is a reduction of more than 46 percent over the best balanced line.

In short, the factory performance of a balanced line, in terms of cycle time and inventory, is inferior to the performance of the five-workstation factory in which every workstation is set at its maximum speed. This should give pause to those who have accepted on face value assertions in the lean manufacturing literature that a balanced line running at the rate of customer demand is optimal (i.e., in terms of minimizing factory inventory and cycle time). Does this mean that what some denote as the fundamental basis of lean manufacturing is invalid? The answer is, "Not exactly."

The basis for the belief that a factory should employ a balanced line running at takt speed is a consequence of a narrow focus on *synchronous* factories. An ultimate example of a synchronous factory might be that of a soft-drink bottling plant. In such a plant, the flow of each job (i.e., each bottle) is synchronized with every other job. There is no extra room on the conveyor belt connecting one workstation to another, so balance and synchronization are essential.

Automobile assembly lines, while not necessarily strictly synchronous, are very close to being synchronized. In a moving automobile assembly line or a perfectly synchronized line, a balanced line makes sense. But this does not hold for *asynchronous* factories such as semiconductor wafer fabrication facilities.

The belief that balanced lines optimize factory performance originated in the study of traditional factories, specifically those with little or no automation. In such factories, it appeared to make sense to balance the workload. It simply did not seem fair to have the workers in one workstation almost always busy while the workers in another station were idle most of the time. In such a situation, a typical recommendation would be to move some of the workers from the mostly idle workstation to the much busier one, that is, balance the production line.

However, when one is dealing with factories that are highly automated, as in the case of the five-workstation factory demonstration, and particularly when the primary focus is on fast cycle time, it is almost always better to have every machine running at its maximum process rate—while factory throughput is maintained at the rate of customer demand. The caveat of "almost always" is employed because there are instances in which the cost (e.g., in terms of maintenance events or the provision for dealing with queues in front of slower workstations) may outweigh the advantage of faster cycle time.

The point is, however, that balanced lines may not be the best way (and quite often are most definitely *not* the best way) to configure and run a modern-day factory. Despite this, it has proven extremely difficult to convince some in the lean manufacturing community that there are situations in which science trumps lean. This simply does not fit the accepted narrative.

Before we leave this topic, it should be noted that while an unbalanced production line—with each workstation running at its maximum process rate—is almost always superior to a balanced line, it is not necessarily the case that such a line is optimal in terms of performance (i.e., in terms of minimal factory cycle time and inventory). This will be clarified and illustrated in Chapter 6.

CHAPTER SUMMARY

When I developed the 12-workstation model, more than 25 years ago, it was used to demonstrate methods for performance improvement in supply chains and business processes. With but minor changes in terminology, the model was changed to encompass performance improvement in factories. Whether the situation involves a factory, a supply chain, or a business process, the 12-workstation model illustrates the complexity inherent in even the most simple process flow. Moreover, the model has proven to be an extremely effective teaching tool.

In this chapter, our solutions to the 12-workstation model have been restricted, for the most part, to the first two dimensions of manufacturing, that is, to physical changes to workstations. That is, we were constrained to adding machines or increasing effective process rates.

The first alternative, adding machines, is definitely physical (and undeniably costly). The second, increasing machine *EPR* rates (i.e., increasing their maximum theoretical capacity—which also may be quite costly), may be achieved either by physical means or by dealing with complexity.

For example, we could change the physical nature of the machines in the workstation to increase their process rates. Or we could change the physical nature of the machines so as to increase their average availability (e.g., incorporate parts that are less likely to fail or require less frequent and less involved maintenance procedures). But we also could increase the *EPR* of the machines by other than physical means. That is, we could employ the approaches available in the third dimension of manufacturing to increase availability. This might be achieved by reducing the number of steps required to conduct a maintenance event, by reducing clutter in the workstation, by improving the training of the workstation operators and maintenance crew, or by improving the content and clarity of the maintenance specifications.

Alternately, we might employ a balanced line, a concept asserted to be the fundamental premise of lean manufacturing and to lead to minimized factory cycle time and inventory. As demonstrated by the five-workstation model, however, an unbalanced line may—and generally does for asynchronous factories—achieve superior performance.

The avenue thus far not open to us, however, was that of reducing the *variability* of the factory. In fact, thus far we have completely ignored variability—one of the three enemies of factory performance. Referring back to Figures 4.3 through 4.5, you may notice there were no data provided with regard to variability. The limited amount of data presented in those matrices served implicitly to restrict choices. Many firms, in fact, do not record data necessary to determine the variability existing in the factory.

Reduction of variability, however, is almost always easier and less costly to achieve—and has greater impact on factory performance—than any other approach. Before we proceed to exploitation of variability reduction, it is first necessary to introduce the concept of variability and then discuss and illustrate the three fundamental equations of manufacturing, the topics of Chapter 5.

CASE STUDY 4: PROFESSOR ARISTOTLE LEONIDAS

Dan Ryan contacted Professor Aristotle Leonidas via e-mail, just as he had promised. A meeting this weekend, at the professor's ranch, was agreed on. Dan, Brad, and Julia have arrived at the ranch and are presently engaged in a discussion with the professor.

"So let me get this straight," says the professor, "you'd like for me to present my course on the science of manufacturing to the members of Muddle's *LEAN* Forward team. More specifically, to those members of the team resident at your factory site. Is that correct?"

Julia, as the senior member of the visiting group, has been taking the lead in answering the professor's questions. "What we'd first like to have done," replies Julia, "is to have you present just a brief overview of the topic, say, at a brown-bag lunch meeting. That way the team, and our management, can get an idea of how we might include more science in our lean efforts."

"Ah," says the professor, "what you want is for me to convince your folks of the need for the science of manufacturing . . . over lunch. In other words, you'd like for me to put it all in a nutshell. Is that it?"

"That's right," says Julia. "Our management has a short attention span, and our senior plant manager isn't at all keen on science. Frankly, while he's a nice guy, he thinks all professors—or anyone with a Ph.D.—are 'eggheads.' It may be difficult to convince him, particularly if you use the word *science.* I'd suggest that you just call your work something like factory performance improvement."

Brad nods in agreement while Dan's eyes roll in disbelief.

"Children," replies the professor, "it sounds as if you have a bigger problem than the lack of science in your factory. Frankly, I'd be more concerned about your firm's managers, culture, and values. If what you say is any indication of your management's vision, my guess is that they want a quick and dirty solution—one that's void of anything as troublesome as needing to have an appreciation of science. So let me just say that I'm really not interested in being your managers' and the *LEAN* Forward team's lunchtime entertainment. If they're not willing to give me their full, undivided attention for at least eight hours, there's no point in wasting their time or mine."

* * *

At first, no one said a word on the drive back to the factory. After a few minutes, however, Dan breaks the silence.

"My recommendation is that we try to convince the *LEAN* Forward team and our management to attend an eight-hour presentation on the science of manufacturing. Good grief, our managers recently spent two whole weeks in training classes on lean manufacturing. So what's the big deal about rounding out their education with an eight-hour meeting? Why don't we . . ."

"Did you hear that old man?" Julia interrupts, ignoring Dan's question. "Your professor friend called us children!"

"Is that what's been bothering you?" asks Dan. "Julia, Professor Leonidas is 88 years old, for heaven's sake! He fought in World War II. The man worked with people like W. Edwards Deming and Joseph Juran after the war. He was involved with the training programs presented to the Japanese in the 1950s, the very same training programs that companies like Toyota admit to having had a major influence on their production systems. Besides, I don't think he meant anything by it, and if the professor wants to call us children, I've got no complaints. He's an educator, for heaven's sake, not a diplomat."

In response, Brad simply nods in agreement. Julia, for her part, stares straight ahead.

"Okay," says Dan, "what about my question? Why don't we at least try to convince the *LEAN* Forward team and our management to attend the professor's eight-hour talk? The worst that can happen is that they say no."

"Alright," replies Julia, "I'll do what I can to convince them. I've known and worked with Tommy Jenkins, our senior plant manager, for more than 10 years. We may not see eye to eye all the time, but he seems to respect my work. If I can get him to agree, the rest of the herd will follow, that I promise you."

"Besides," adds Brad, "if we can't get the three plant managers to attend, no one else will. That's standard operating procedure in this company. Unless management shows interest in this, no one else will—no matter how great the concept. So go ahead, Julia; give it your best shot."

"Agreed," Julia replies. "By the way, fellows, I just heard something very interesting last night. There's evidently a huge fight brewing between the *LEAN* Forward team leaders and the factory's quality control team."

"Really," says Brad, "tell us more."

"It seems," Julia continues, "that the quality control team intends to put up posters all over the factory and office areas next week. The posters have a slogan on the top and a warning on the bottom. The slogan states, 'Quality Is Priority One.' The wording beneath the slogan says, 'No matter how long it takes, you absolutely must achieve or exceed your quality goals,' and then they cite the maximum rate of defects they intend to impose as the goal."

"I'm not sure why that's a problem," says Brad, puzzled. "After all, it is important to reduce defects."

"It's a problem, *children*," says Julia, "because the *LEAN* Forward team leaders have prepared posters that state, 'Cycle Time Reduction Is Priority One.' Evidently the *LEAN* Forward team leaders are following Sally Swindel's advice to reduce the number of inspections. The quality control team, naturally, thinks that this will increase defects. The whole mess has been escalated to Tommy Jenkins. It should be interesting to see how he resolves it."

* * *

It would seem that Professor Aristotle Leonidas is abrasive as well as idealistic. He appears to believe that the members of the *LEAN* Forward team and, in particular, factory management are going to take eight hours out of their busy schedule to listen to an old man rave on about the need for science in factory performance-improvement efforts.

The fact that management was able to find two whole weeks to attend the lean manufacturing training was due, for the most part, to the dictate by Muddle's CEO. No such dictate has been issued—at least at this point—in regard to any training in the science of manufacturing.

It is also interesting to note that the *LEAN* Forward team and the quality control team are at loggerheads. The lean team wants to reduce non-value-added activities in the factory and believes that certain inspection steps do not add value. The quality control team wants to reduce defects and believes that the more inspections the better. Each team sees the other's goal as a threat to its effort.

Actually, several other shoes are about to fall. Tommy Jenkins has recently established a cost reduction team. He's also put in place a capacity improvement team. This means that at this point in time the following "factory performance" teams exist within Tommy's factory:

- *LEAN* Forward team (with an emphasis on the reduction of waste—or, as Sally Swindel insists on calling it, *muda*)
- CANDO team (responsible for cleaning up workplaces and reducing clutter)
- Quality control team (with an emphasis on the reduction of defects)
- Cycle-time reduction team (with an emphasis on the reduction of factory cycle time)
- Cost reduction team (with an emphasis on reducing funds expended)
- Capacity improvement team (with an emphasis on increasing factory capacity/maximum sustainable throughput)
- Equipment maintenance team (with an emphasis on increasing the availability of the factory's workstations)
- Factory utilization team (this team has been ordered to make sure that the utilization of every machine and every factory floor worker is 90 percent or more; that is, they cannot be idle any more than 10 percent of the time)
- Spare parts team (with an emphasis on determining the number of spare parts to keep in inventory subject to budget and space restrictions)
- Metrics team (with the responsibility of collecting data in support of the numerous factory performance metrics)

Tommy, like many other plant or factory managers, has failed to notice that the mission statements (and goals) of each and every one of these teams are in conflict. As mentioned, the *LEAN* Forward team wants to reduce inspection steps—to reduce what they consider waste—whereas the quality control team actually wants to add such steps—in the belief this will reduce defects.

Besides being in conflict, every one of the metrics by which the performance of these teams is being measured can be easily "gamed." For example, factory floor personnel have discovered that they can increase the utilization of their workstations simply by conducting unnecessary rework efforts. In turn, they can make themselves appear busier than they actually are by scheduling more meetings. Since meetings count toward personnel utilization at Muddle, this has been a particularly attractive means to "improve" their performance—and simultaneously have the firm provide them with lots of free pizza and soft drinks.

To worsen matters, there is no single point of oversight with regard to the activities of each of the teams. Each one remains focused on the metric by which it is measured, and each of these metrics is in conflict with what should be the goal of simply improving overall factory performance.

By the way, we've just learned that Tommy Jenkins has agreed (as a result of Julia's persuasion) to allow Professor Leonidas to give an eight-hour presentation to the plant managers, department managers, Muddle Fellows, and members of the *LEAN* Forward team. Tommy also has finalized the composition of the team. He's going to be the team's coach, and Donna Garcia (Dan and Brad's former boss) and Roger Durbin (a long-time Muddle employee and close friend of Tommy Jenkins) will serve as the two-in-a-box team leaders. Furthermore, even though he has not received an invitation to (and was intentionally omitted from the list of attendees invited to) Professor Leonidas' presentation, it's rumored that the mysterious Winston Smith might attend.

CHAPTER 4 EXERCISES

1. Using the 12-workstation factory simulation model of this chapter, perform the following exercises:
   - Initialize the simulation model and then change the factory throughput rate (cell B14) from 2 lots per day up to 20 lots per day (in 1 lot per day increments)

  and develop a plot of factory cycle time versus throughput rate.
- Initialize the simulation model and then employ the theory of constraints to decrease factory cycle time. Do not, however, allocate any funds for the purchase of additional machines (i.e., allocate funds only to the increase in workstation effective process rates). Compare your results with those found in the chapter.

2. Explain why the 12-workstation model limits your decisions to (mainly) the first two dimensions of manufacturing.
3. Explain why the cost of increasing a machine's *EPR* rises exponentially.

CHAPTER 5

Variability

It was possible to improve the performance of the 12-workstation factory significantly in Chapter 4 “simply” by adding machines or by increasing the availability and/or process rate of workstations. By means of a theory of constraints (ToC)–influenced approach, cycle time was reduced by 75.84 percent. Using optimization (i.e., genetic algorithms), the reduction was an even better 83.86 percent.

Of course, those degrees of improvement were achieved only by consuming the entire $13M budget. In Chapter 6 you’ll be asked to deal with this same factory once again. There will be two very significant differences, however. First, rather than being provided with $13M, you’ll be permitted to expend only $500,000 (i.e., $0.5M). Second, a new avenue for improvement will be open to you—the reduction of variability. With the introduction of variability into the decision-making process, you will have at your disposal all three dimensions of manufacturing.

If you are to exploit variability reduction most effectively, however, you must first be able to

- Appreciate the role that variability plays in factory performance
- Locate the sources of variability
- Collect the data required to measure variability
- Properly interpret the data used to measure variability
- Compare the variability inherent in two or more machines, workstations, or factories
- Comprehend the three fundamental equations of manufacturing

We begin our discussion with a brief overview of variability and several variability metrics. Following that, the three fundamental equations of manufacturing will be presented and illustrated. Once this material has been covered (and understood), you will be armed with insight into the most powerful and cost-effective tools available for factory performance improvement.

MEASURING VARIABILITY

Thus far our attention has been focused on attributes and metrics based on averages, that is, average cycle time, average throughput rate, average process rate, average occupancy rate, etc. If, however, you wish to appreciate the scope and limitations of a factory (i.e., a nonlinear, dynamic, stochastic system with feedback), you absolutely must address variability.

We begin our discussion by first defining and illustrating the notion of the coefficient of variability (a.k.a. *coefficient of variation*). While certainly not perfect, the coefficient of variability *CoV* provides us with a practical and—for our purposes—reasonably effective means to compare the variability of two different populations (e.g., two different factories or the before and after performance of a given factory).

CoV = Coefficient of Variability

The equation for *CoV* is

$$CoV = \frac{\sigma}{\mu} = \frac{\text{standard deviation}}{\text{mean}} \tag{5.1}$$

For the sake of illustration, assume that we wish to compare the variability of the process rates of two different machines. Machine X has a mean process rate of 100 units per day and a standard deviation of 50, whereas machine Y has a mean process rate of 20 units per day and a standard deviation of 30.

The coefficients of variability of the process rates of each machine thus are

$$CoV[PR(\text{X})] = \frac{50}{100} = 0.50$$

$$CoV[PR(\text{Y})] = \frac{30}{20} = 1.50$$

Despite the fact that the value of the standard deviation of the process time of machine X is much larger in absolute terms than that of machine Y, the coefficient of variability of the process time of machine Y is greater (i.e., three times greater). The greater the variability (i.e., *CoV*) of a machine or factory, the worse will be its performance.

C_{AR} = Coefficient of Variability of Arrivals

I will use C_{AR} to represent the variability about the arrival rate of jobs *at a given process step*. More precisely, C_{AR} is the coefficient of variability about the interarrival times of those jobs entering the associated process step.

Since our focus is at the process-step level, it will be assumed that all variability metrics, including $C_{AR,}$ represent variability with respect to a given process step. When we need to discriminate between different process steps, the notation employed will be C_{AR}(*ps*,) where *ps* will indicate the specific process step of interest.

Assume, for example, that we record the times at which individual jobs arrive at a particular process step, say, process step 7. Given these data, we may compute the interarrival times of the jobs by subtracting the time of arrival of one job from the time the preceding job arrived. To illustrate, the derivation of the coefficient of variability for a small sample of job arrival times is developed for the data shown in Table 5.1.

TABLE 5.1

Process Step 7 Job Arrivals (Assuming One Job per Batch)

Job	Arrival Time	Interarrival Time (in Minutes)
1	8:00 a.m.	—
2	8:15 a.m.	15
3	8:50 a.m.	35
4	8:56 a.m.	6
5	9:40 a.m.	44
6	9:48 a.m.	8
7	10:02 a.m.	14
8	10:50 a.m.	48
9	10:58 a.m.	8
10	11:33 a.m.	35
11	11:40 a.m.	7

Our interest lies in the third column, the times between arrivals of jobs (i.e., the interarrival rate) at the process step. We simply find the mean and standard deviation of the 10 values in that column (this is accomplished easily by means of entering the preceding data into a MicroSoft Excel spreadsheet and using a data analysis tool to determine the associated statistics), where

μ = 22 minutes (the mean of the interarrival times)
σ = 16.613 minutes (the standard deviation of the interarrival times)

The value of C_{AR} for this process step (recall that we have assumed that this is for process step 7) thus is

$$C_{AR}(7) = \frac{\sigma}{\mu} = \frac{16.613}{22} = 0.755$$

It must be emphasized that just 10 samples of interarrival times is highly unlikely to provide a sufficient sample size. This small number of samples has been used, however, simply to illustrate the mechanics of the process. Details on the determination of proper sample sizes may be found in the references (Ignizio and Gupta, 1975; Kennedy and Neville, 1964).

Before we leave this example, consider an extremely important matter—the employment of batches in place of individual jobs. In the example, it was assumed that the arrival times listed were for individual jobs (i.e., one job per batch). Now consider what happens if instead of individual jobs, the jobs arrive—simultaneously—in batches of four (i.e., of four jobs per batch). Employing the arrival-time data used previously, we note that at 8:00 a.m., the first batch arrives. At 8:15 a.m., the next batch arrives. At 8:50 a.m., the third batch arrives. The change from individual jobs to batches of jobs has a significant impact on the value of C_{AR}.

Table 5.2 lists the batch arrivals along with the interarrival rates of each individual job within the batch. Notice carefully that for the second batch (jobs 5, 6, 7, and 8), the first job in that batch arrives 15 minutes after the last job in batch 1 (jobs 1, 2, 3, and 4). The second job in batch 2 also arrives 15 minutes after the last job in batch 1, and the same is true for the third and fourth jobs of batch 2.

When the arrival of jobs is in batches, the coefficient of variability of arrivals increases. In this case, C_{AR} for the original

TABLE 5.2

Arrivals in Batches (of Four Jobs per Batch)

Job	Batch Arrival Time	Individual Job Interarrival Time (Minutes)	Job	Batch Arrival Time	Individual Job Interarrival Time (Minutes)
1	8:00 a.m.	0	25	10:02 a.m.	14
2		0	26		0
3		0	27		0
4		0	28		0
5	8:15 a.m.	15	29	10:50 a.m.	48
6		0	30		0
7		0	31		0
8		0	32		0
9	8:50 a.m.	35	33	10:58 a.m.	8
10		0	34		0
11		0	35		0
12		0	36		0
13	8:56 a.m.	6	37	11:33 a.m.	35
14		0	38		0
15		0	39		0
16		0	40		0
17	9:40 a.m.	44	41	11:40 a.m.	7
18		0	42		0
19		0	43		0
20		0	44		0
21	9:48 a.m.	8			
22		0			
23		0			
24		0			

data—where the batch size was one (i.e., one job per batch)—was 0.755. This is a relatively modest degree of variability. However, when the jobs arrive in batches of four, C_{AR} becomes 2.41—a very significant degree of variability. As we shall soon discover, the coefficient of variability of job interarrivals plays a significant role in processing entity performance.

We may conclude that as the batch size of the preceding workstation is increased, the coefficient of variability seen by the machines supporting the next process step increases. It should be noted that there are equations that allow computation of the optimal batch size for a given workstation. These serve to minimize the cycle time of the batching workstation. On the surface, this might seem to be a good thing.

Unfortunately, the optimal batch size of a workstation actually may impose significant arrival-rate variability on one or more downstream workstations. As a consequence, while the cycle time of the batching workstation might be reduced, the cycle time of the overall factory actually could increase. This is an illustration of *sub-optimization,* that is, the danger of focusing on the improvement of just one element of a system rather than the system as a whole.

C_{PT} = Coefficient of Variability of Raw Process Times

I will use $C_{PT}(ps)$ to represent the coefficient of variability of the raw process times *of a given process step* (i.e., actually, that of each of the machines supporting that process step). To determine $C_{PT,}$ we should record (or at least estimate) the raw process times of a given process step. Since these are the *raw* process times, we only measure the time that the entity supporting the step is actually processing a job (i.e., we ignore any blocked time or downtime occurring after the job is started or before it is finished).

The data for an example illustrating the derivation of C_{PT} is provided in Table 5.3. Assume, for sake of discussion, that the process step of interest is again step 7, and thus we seek the value of $C_{PT}(7)$. Specifically, for a sample of 10 jobs, the raw process times (of the machines supporting the given process step) have been listed.

TABLE 5.3

Derivation of the Coefficient of Variability of Raw Process Times

Job	Raw Process Time (in Minutes)
1	31
2	32
3	29
4	30
5	32
6	28
7	30
8	31
9	30
10	31

Given these data, the coefficient of variability of raw process times is

$$C_{PT}(7)=\frac{\sigma}{\mu}=\frac{1.265}{30.4}=0.042$$

A *CoV* of 0.042 is extremely small but might be possible for the raw process times of some high-precision machines. What is far more important, however, is determination of the coefficient of variability of the *effective* process times, or C_{EPT}.

C_{EPT} = Coefficient of Variability of Effective Process Times

$C_{EPT}(ps)$ is used to represent the variability of the effective process times of a process step designated as *ps*. This particular *CoV* is a function of such factors as the coefficient of variability of both blocked and down events (either scheduled or unscheduled), designated here as $C_{DE,}$ as well as such parameters as availability of the entity, its raw process time, and the mean time required to recover *MTTR* from either a blocked or down event.

Equation (5.2) provides a means to approximate the square of the coefficient of variability of the effective process time (i.e., C^2_{EPT}) for a nonreentrant ($DoR = 1$), single machine ($M = 1$) workstation. It also may be employed to provide an even rougher (but, for our purposes, adequate) approximation of C^2_{EPT} for a nonreentrant, multiple-machine workstation.

$$C^2_{EPT}(ps)=C^2_0+A\bullet(1-A)\bullet\frac{MTTR}{PT}+C^2_{DE}\bullet A\bullet(1-A)\bullet\frac{MTTR}{PT} \tag{5.2}$$

where C_0 = inherent variability of the process times of the machines supporting the process step of interest

C_{DE} = variability of the recovery times (from both blocked and down events) of the machines supporting the process step of interest

A = average availability of the machines supporting the process step of interest

$MTTR$ = mean time to recover from both blocked and down events of the machines supporting the process step of interest

PT = average raw process time of the machines supporting the process step of interest

For example, assume that a workstation in which all machines support a single process step (say, process step 7) has the following characteristics:

$$\text{Mean time between events } MTBE = 90 \text{ hours}$$
$$MTTR = 10 \text{ hours}$$

Thus the availability of those machines is given by Equation (3.3) as

$$A = \frac{MTBE}{MTBE + MTTR} = \frac{90}{90+10} = 0.90$$

In addition, assume for sake of discussion that we know that

- $C_{PT}(7) = 0.042$ (which typically is close to the value of C_0).
- $C_{DE}(7) = 1.5$ (i.e., the average *CoV* of the down event recovery times).
- $PT(7) = 1$ hour (i.e., the average process time of each of the machines).

These values may be substituted into Equation (5.2) to approximate C_{EPT}^2 of the process step under consideration:

$$C_{EPT}^2(7) = 0.042^2 + 0.9 \bullet (1-0.9) \bullet \frac{10}{1} + 1.5^2 \bullet 0.9 \bullet (1-0.9) \bullet \frac{10}{1} = 2.93$$

Notice that even though the inherent (i.e., raw) variability of the process step (i.e., roughly that of the *CoV* of its raw process time) may have been small, because of blocked and down events, the *CoV* of the effective process time is rather large (i.e., the square root of 2.93, or 1.71). This is just one reason why you must consider the impact of blocked events, maintenance, and repairs if factory improvement is to be achieved.

There is yet another message to be gleaned from Equation (5.2). Specifically, given all other factors equal, the coefficient of variability of the effective process time may be reduced by dividing scheduled down events [preventive maintenance (PM)] into more frequent, smaller segments. To illustrate, assume that there are no blocked events and that the only down events are regularly scheduled PM events (i.e., events over which we have some control).

In the preceding illustration, the mean time to recover from a blocked or down event was 10 hours. Assume that these down events are solely PM events and may be divided into segmented PM events of 5 hours each and conducted every 45 hours. Thus

$$MTBE = 50 \text{ hours}$$
$$MTTR = 5 \text{ hours}$$

and

$$A = \frac{MTBE}{MTBE + MTTR} = \frac{45}{45+5} = 0.90$$

Even though we have segmented the PM events and halved the time between PM events, the availability of the workstation remains 90 percent. We assume that all other parameters (i.e., C_0, PT, and C_{DE} for the process step) have the same values as before.

Notice what happens to $C_{EPT}(ps)$ when we substitute the new value of $MTTR$ into Equation (5.2):

$$C^2_{EPT}(7) = 0.042^2 + 0.9 \bullet (1-0.9) \bullet \left(\frac{5}{1}\right) + 1.5^2 \bullet 0.9 \bullet (1-0.9) \bullet \left(\frac{5}{1}\right) = 1.464$$

In other words, simply by conducting shorter and more frequent PM events, we have reduced the squared *CoV* of effective processing time from 2.93 to 1.464. This degree of reduction may have, as we shall see, a significant positive impact on factory performance.

I now proceed to a presentation of the three fundamental equations of manufacturing. I begin with Little's equation (a.k.a. *Little's law*). It should be noted that it is the only one of the three equations that relies solely on averages. But first a warning:

> The forms of the fundamental equations that follow are based on the assumption of a factory in which every workstation supports just one process step and every machine in the workstation supports only that process step. Furthermore, it is assumed that the machines within each workstation are identical, with identical raw and effective process rates. While these equations may be extended to encompass more complex factory configurations, we will still be able to identify the general characteristics of the factory phenomena of interest, if not their precise values, from the simplified models.

FUNDAMENTAL EQUATION ONE

Intuitively (although, as mentioned, you really need to be careful about relying on intuition), it would seem that factory inventory should increase as factory starts (i.e., factory throughput or loading) increase. This is, in fact, true. In 1961, John Little developed an equation—known as *Little's equation* or *law*—relating factory inventory, designated as work in progress *WIP* to factory cycle time *CT* and factory throughput *TH* (Little, 1961). The same equation may be used to relate workstation inventory to workstation cycle time and throughput. Little's equation is

$$WIP = CT \bullet TH \tag{5.3}$$

To demonstrate, consider a factory whose average cycle time is 50 days and whose average throughput (i.e., flow of jobs through the factory) is 700 units per week. Changing all units to days (and making sure that all parameters are indeed in the same units), the expected inventory of the factory at any given time will be

$$WIP = 50 \text{ days} \bullet 100 \text{ units/day} = 5{,}000 \text{ units}$$

Little's equation should provide a reasonably good approximation for either total factory inventory or the inventory existing at any given workstation or at an individual process step—under the assumptions stated previously. More important, however, is the fact that the equation serves to clearly relate cycle time and throughput to inventory. The equation is in some respects the factory equivalent of Newton's most famous law—force equals mass times acceleration.

FUNDAMENTAL EQUATION TWO

The second fundamental equation is more commonly known as the *P-K equation* (an abbreviation, for obvious reasons, of the *Pollaczek-Khintchine equation*). This equation typically is used to predict the cycle time of either a factory, a portion of a factory, or some individual workstation. However, here, we will focus on the cycle time at the process-step level. To determine total factory cycle time, we find the sum of all cycle times across all process steps.

The form of the second fundamental equation requires the determination of a number of the factors covered in Chapter 3 plus those just introduced in this chapter. These are

- $CT_{ps,}$ the cycle time of the process step. It is once again emphasized that in this text our interest extends to the process-step level rather than stopping with the workstation or machine.
- $C_{AR,}$ the coefficient of variability of arrivals at the process step.
- $C_{EPT,}$ the coefficient of variability of effective process times of the machines that support the process step.
- $EPR_{ps,}$ the effective process rate (maximum theoretical capacity) of each of the identical machines that support the given process step.
- A, the average availability of the machines that support the process step.
- ρ, the average occupation rate (a.k.a. *utilization*) of the machines supporting the process step.
- BS, the batch size—if any—of the machines supporting the process step.
- AR, the arrival rate of the jobs arriving at the process step.
- m, the number of (identical) machines supporting the process step.

The specific form of the P-K equation depends on the situation addressed (e.g., number of machines and existence or nonexistence of batching, cascading, or reentrancy). For the purpose of this discussion, we will restrict our interest, for the moment, to determination of the cycle time of a process step supported by m nonreentrant and nonbatching machines. Thus the equation for cycle time of a given process step, that is, the second fundamental equation of manufacturing, is

$$CT_{ps} = \underbrace{\left(\frac{C_{AR}^2 + C_{EPT}^2}{2}\right) \bullet \left[\frac{\rho^{\sqrt{2(m+1)}-1}}{m \bullet (1-\rho)}\right] \bullet \left(\frac{1}{EPR_{ps}}\right)}_{\text{wait in queue time}} + \underbrace{\left(\frac{1}{EPR_{ps}}\right)}_{\text{effective process time}} \tag{5.4}$$

If the process step is supported by only a single machine (i.e., $m = 1$), the form of the second fundamental equation of manufacturing is

$$CT_{ps} = \underbrace{\left(\frac{C_{AR}^2 + C_{EPT}^2}{2}\right) \bullet \left[\frac{\rho}{(1-\rho)}\right] \bullet \left(\frac{1}{EPR_{ps}}\right)}_{\text{wait in queue time}} + \underbrace{\left(\frac{1}{EPR_{ps}}\right)}_{\text{effective process time}} \tag{5.5}$$

Alternately, if the process step is supported by m machines and these machines employ batching, the form of the second fundamental equation becomes

$$CT_{ps} = \underbrace{\frac{BS-1}{2 \bullet AR}}_{\text{batch forming time}} + \underbrace{\left(\frac{\frac{C_{AR}^2}{BS} + C_{EPT}^2}{2}\right) \bullet \left[\frac{\rho^{\sqrt{2(m+1)}-1}}{m \bullet (1-\rho)}\right] \bullet \left(\frac{1}{EPR_{ps}}\right)}_{\text{wait in queue time}} + \underbrace{\left(\frac{1}{EPR_{ps}}\right)}_{\text{effective process time}} \quad (5.6)$$

If the process step is supported by nonreentrant, cascading machines, the form of the second fundamental equation must be revised accordingly [i.e., see Hopp and Spearman (2001) or Buzacott and Shanthikumar (1993) for these forms of the P-K equation]. For our purposes, however, it is not vital that the form for nonreentrant, cascading machines be discussed. In fact, we shall restrict our attention to just Equation (5.4), that is, m machines and no batching.

To illustrate, assume that we wish to determine the cycle time of process step 2 given the data provided in Table 5.4.

Substituting the values in Table 5.4 into Equation (5.4), we may find the cycle time of process step 2 as follows:

$$CT_{ps} = \underbrace{\left(\frac{C_{AR}^2 + C_{EPT}^2}{2}\right) \bullet \left[\frac{\rho^{\sqrt{2(m+1)}-1}}{m \bullet (1-\rho)}\right] \bullet \left(\frac{1}{EPR_{ps}}\right)}_{\text{wait in queue time}} + \underbrace{\left(\frac{1}{EPR_{ps}}\right)}_{\text{effective process time}}$$

$$CT_{ps}(2) = \underbrace{\left(\frac{6.17^2 + 2^2}{2}\right) \bullet \left[\frac{0.67^{\sqrt{2(3+1)}-1}}{3 \bullet (1-0.67)}\right] \bullet \left(\frac{1}{10}\right)}_{\text{wait in queue time}} + \underbrace{\left(\frac{1}{10}\right)}_{\text{effective process time}} = 1.10 \text{ days}$$

TABLE 5.4

Data for Application of Second Fundamental Equation

Parameter	Parameter Description	Value
M	Number of machines supporting the process step	3
C_{AR}	*CoV* of interarrivals	6.17
C_{EPT}	*CoV* of effective process times	2.00
ρ	Occupancy rate of the *m* machines supporting process step 2	0.67
EPR	Effective process rate of each of the machines supporting process step 2 (jobs per day)	10

Since the 12-workstation model of Chapter 4 dealt with a series of nonreentrant workstations and batching was not employed, the cycle time of each of the workstations (each of which supports a single process step) may be (and was) determined by means of Equation (5.4) in conjunction, as we shall see, with the first and third fundamental equations of manufacturing.

FUNDAMENTAL EQUATION THREE

The third fundamental equation is known more commonly as either the *linking equation* or the *propagation of variability equation.* This approximating equation is employed to estimate the coefficient of variability of the jobs departing a given process step. Given m machines and no reentrancy, the form of the third equation of manufacturing is

$$C_{DR}^2 = 1 + \left(1 - \rho^2\right) \bullet \left(C_{AR}^2 - 1\right) + \left(\frac{\rho^2}{\sqrt{m}}\right) \bullet \left(C_{EPT}^2 - 1\right) \tag{5.7}$$

If only a single machine ($m = 1$) supports the process step, the equation reduces to

$$C_{DR}^2 = \rho^2 \bullet C_{EPT}^2 + (1 - \rho^2) \bullet C_{AR}^2 \tag{5.8}$$

To illustrate, consider a process step supported by three machines ($m = 3$) with an occupancy rate of 0.67 ($\rho = 0.67$), a coefficient of variability of interarrivals of 6.17 ($C_{AR} = 6.17$), and a coefficient of variability of effective process times of 2.0 ($C_{EPT} = 2.0$). Using Equation (5.7), we may determine the coefficient of variability of the jobs departing this process step:

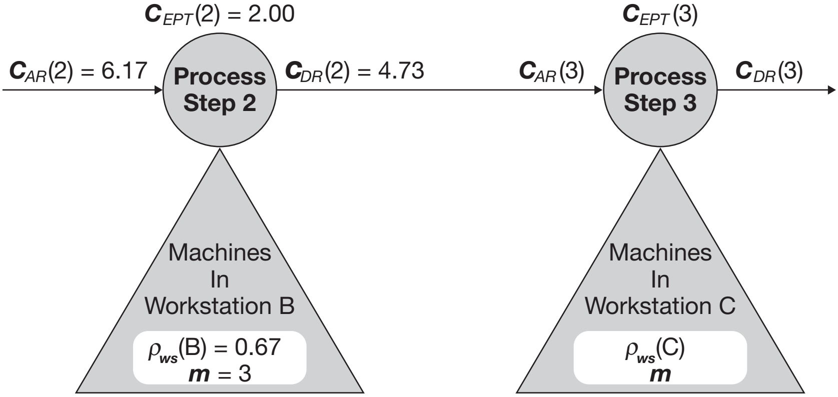
$$C_{DR}^2 = 1 + \left(1 - 0.67^2\right) \bullet \left(6.17^2 - 1\right) + \left(\frac{0.67^2}{\sqrt{3}}\right) \bullet (2^2 - 1) = 22.21 \text{ and thus}$$

$$C_{DR} = \sqrt{2.221} = 4.7315$$

Given that process step 2 is supported by the machines in workstation B and that the next process step (i.e., process step 3) is supported by the machines in workstation C, Figure 5.1 may be employed to represent the situation.

FIGURE 5.1

Propagation of variability illustration.



The values of the interarrival rate coefficient of variability and effective process time coefficient of variability are listed next to the circle representing process step 2. Under the assumptions cited earlier, all machines in this workstation (workstation B) support process step 2 and only that process step. In the triangle under process step 2, the occupancy rate of those machines ($\rho = 0.67$) and their number ($m = 3$) are specified. Using Equation (5.7), the coefficient of variability of the jobs leaving process step 2 is 4.7315.

This is shown above the arrow leading from process step 2 to process step 3. If the transit step between process step 2 and process step 3 has negligible variability and high capacity, the value of the coefficient of variability of interarrivals at process step 3 will be essentially equal to that of $C_{DR}(2)$.

By means of the three fundamental equations, we may approximate (where the key word is *approximate*) the cycle times of each process step, the variability propagated from one process step to another, and the average inventory at each process step. This, in fact, is precisely what was used to develop the 12- and 5-workstation models of Chapter 4, as well as the 12-workstation model to be employed in Chapter 6.

CAPACITY AND VARIABILITY

In Chapter 4 we saw that any increase in the throughput capacity of workstation B (recall Figure 4.6) resulted in an unexpected increase in overall factory cycle time. This happens to also be the case for any increase in the throughput capacity of workstation C. Given the three fundamental equations, particularly the third (the propagation of variability equation), this phenomenon may be explained.

In the 12-workstation factory, under its initial conditions, the values for the parameters of workstation C (which supports process step 3) are listed in Table 5.5.

Substituting the values in Table 5.5 into Equation (5.7), we obtain the following value for the squared coefficient of variability of the departures C_{DR} from workstation C (i.e., process step 3):

$$C_{DR}^2 = 1 + \left(1-\rho^2\right) \bullet \left(C_{AR}^2 - 1\right) + \left(\frac{\rho^2}{\sqrt{m}}\right) \bullet \ (C_{EPT}^2 - 1)$$

$$C_{DR}^2 = 1 + \left(1-0.625^2\right) \bullet \left(4.7315^2 - 1\right) + \left(\frac{0.625^2}{\sqrt{3}}\right) \bullet \ (3^2 - 1)$$

$$= 15.5954 \text{ and thus } C_{DR}(3) = 3.9491$$

Now assume that we increase the maximum theoretical capacity *EPR* of each of the four machines of workstation C from their initial values of 8 jobs per day to, say, 18 jobs per day—a substantial increase in the capacity of the workstation. This would seem to be a good thing. The new data for workstation C are listed in Table 5.6.

TABLE 5.5

Workstation C Parameters

Parameter	Value	Comments
Process step supported by workstation C	3	—
Number of machines *m*	4	—
EPR per machine	8 jobs/day per machine	—
Throughput capacity (*EPR* per workstation)	32 jobs/day	4 machines times 8 jobs/day
Occupancy rate ρ (utilization) of workstation	0.6250	20 jobs/day factory throughput (takt rate) divided by 32 jobs/day capacity
C_{AR}	4.7315	—
C_{EPT}	3.0000	—

TABLE 5.6

Workstation C after Capacity Increase

Parameter	Value	Comments
Process step supported by workstation C	3	—
Number of machines *m*	4	—
EPR per machine	18 jobs/day per machine	Increase in *EPR*
Throughput capacity (*EPR* per workstation)	72 jobs/day	4 machines times 18 jobs/day
Occupancy rate ρ (utilization) of workstation	0.2778	20 jobs/day factory throughput (takt rate) divided by 72 jobs/day capacity
C_{AR}	4.7315	—
C_{EPT}	3.0000	—

Substituting the values in Table 5.6 into Equation (5.7), we obtain the following value for the new squared coefficient of variability of the departures C_{DR} from workstation C (i.e., process step 3):

$$C_{DR}^2 = 1 + \left(1 - 0.2779^2\right) \bullet \left(4.7315^2 - 1\right) + \left(\frac{0.2779^2}{\sqrt{3}}\right) \bullet (3^2 - 1)$$
$$= 20.9425 \text{ and thus } C_{DR}(3) = 4.5763$$

Note that by increasing the maximum theoretical capacity of workstation C (from 32 to 72 jobs per day), the coefficient of variability of the jobs departing workstation C (i.e., process step 3) has increased from 3.9491 to 4.5763. Consequently, via the second fundamental equation of manufacturing (Equation 5.4), the cycle time of the next process step (process step 4, supported by the machines in workstation D) must increase.

The data being employed for this illustration actually come from that used in the 12-workstation factory. As a consequence, it may be shown that the increase in $C_{DR}(3)$ of workstation C (i.e., supporting process step 3) from 3.9491 to 4.5763 will increase the cycle time of workstation D from 23.39 to 28.42 days; i.e., an increase of more than five days. It so happens that as a consequence, the cycle time of the entire factory will increase by somewhat less than five days (i.e., there is a decrease in workstation C's cycle time). Once again it is demonstrated that improving the performance of a single workstation may indeed degrade overall factory performance.

By means of the fundamental equations, we may determine when an increase in the throughput capacity of one workstation will either help or hurt overall factory cycle time. To accomplish this feat, though, we must have the data required to determine the coefficient of variability of both arrivals and departures. In Chapter 6 these essential data will be provided—allowing us to employ a more intelligent (and cost-effective) approach to factory cycle-time reduction for the 12-workstation factory.

CHAPTER SUMMARY

The impact of variability on process-step cycle time (and subsequently on factory cycle time) is evident from the second and third fundamental equations of manufacturing. With these equations, plus Little's equation (the first fundamental equation of manufacturing), one may investigate the impact of variability and throughput capacity (as well as occupancy rate) on factory performance.

Via extensions to the second and third fundamental equations, more complex factories may be modeled. These extended equations, however, are mostly of academic interest (a polite way of implying that they have limited practical value). Predictions of the performance of more complex factories are, at present, best achieved via discrete event simulation models or those employing fluid networks (Billings and Hasenbein, 2002) or electromagnetic networks (Ignizio, 2000). Even the most carefully crafted and detailed of these, however, still only provides rough estimates of the performance of large, complex factories (e.g., semiconductor fabricators).

The real importance of the fundamental equations lies in their ability to illustrate the impact of variability and complexity. Too much time, in fact, is wasted on attempts to derive precise values of factory cycle time, factory capacity, and the uncertainty about delivery times via the fundamental equations and their countless extensions when it can and should be more productively allocated to simply reducing factory variability and complexity. However, we shall continue our investigation of the simple 12-workstation factory in Chapter 6, where yet more insight into factory performance may be gained.

CASE STUDY 5: JUST WHO IS WINSTON SMITH?

Julia, Dan, and Brad are in Factory 7's largest meeting room, trying to make sure that everything is ready for Professor Leonidas's eight-hour presentation. At about ten to eight, the professor arrives.

"Here's the memory stick with my presentation," says Professor Leonidas. "But where's the audience?" he adds, staring at a nearly empty room.

"Don't worry, Professor," replies a very worried Julia Austen, "no meeting at Muddle ever starts on time. We'll have a full house, I assure you. All three plant managers promised me they'd be here, and if they come, the rest of the herd will follow."

At about ten past eight, a gaggle of department managers, Muddle Fellows, *LEAN* Forward team members, and senior factory engineers begin to arrive. Julia advises Dan to delay the introduction of Professor Leonidas until the three plant managers arrive. Some 15 minutes later, it is obvious to everyone that Tommy Jenkins and his fellow plant managers are not going to attend this meeting. When this realization sets in, all the factory department managers (with the lone and curious exception of Donna Garcia) make a hasty exit, followed by at least half the other members of the audience.

As those individuals leave the meeting room, one person does enter. He's a distinguished looking middle-aged gentleman with salt-and-pepper hair. When Julia sees him, she emits an audible gasp. Professor Leonidas has an entirely different reaction.

"Winston, my boy, what on earth are you doing here?" says Professor Leonidas as he extends his hand. "My goodness, the last I heard, you had decided to abandon academia and move to New Zealand and raise sheep."

"Hello, Professor," Winston replies. "I did indeed leave the Ivory Tower, but now I work for Muddle. It's a rather long story."

"Well, my boy, let's chat over lunch. Right now, if I correctly read the hand-waving of Miss Julia, it's time to start the presentation."

Following the introduction, Professor Leonidas walks to the podium and places his hand on the conference room laptop, ready to start the first slide of the presentation. At the same time, a frantic looking fellow with lots and lots of facial hair and a T-shirt reading, "Safety Rules," races to the podium and inserts himself between the professor and the laptop.

“Oh my gosh,” whispers Brad, “that’s Ed, the safety and ergonomics Nazi.”

Ed insists that before the presentation is permitted to begin, the laptop must be raised (about half an inch) and that the mouse being used is replaced by one that satisfies the very latest, official Muddle ergonomic specifications. In the meantime, the professor stands aside, a bewildered look on his face.

* * *

Julia, Dan, and Brad are meeting in the company cafeteria. The professor’s presentation was completed about an hour ago. Conversation among the threesome has been minimal to nonexistent since they bade their good-byes to the professor. Based on the pained expressions of their faces, things did not go well.

Dan breaks the silence. “Damn, what a disaster. Damn, damn, damn. Where were Tommy Jenkins and his pals? Damn it, he gave his word.”

“I called Tommy’s administrative assistant during the first coffee break,” Julia replies, “It seems they ‘just forgot’ the meeting. Instead, they were doing a factory walk-through. That, by the way, is the code their administrative assistants use when the three of them are golfing. Based on the professor’s performance today, however, I’ve got to say that I’m glad they passed on his presentation.”

“Why’s that?” asks Dan. “I thought that the professor made some very good points. He certainly seems up to speed on Muddle factories. His remarks about the impact of poorly written PM specifications sure hit home with me.”

“You must have not been attending the same presentation as me,” Julia replies, shaking her head. “The good professor was critical of just about everything we do. Weren’t you listening when he asked Donna Garcia if she knew what the three fundamental equations of manufacturing are? Or when he asked if we used moves as a measure of factory performance and said that was quite possibly one of the worst metrics around? Good grief, he implied in no uncertain terms that we’re doing just about everything wrong.”

“So what?” says Dan. “He’s spot on with his criticism. Julia, if we were doing things right, we wouldn’t have such ridiculously long factory cycle times or so many unscheduled machine downs—or such a low stock price. Unless this company admits it has problems, how are we going to solve them?”

"Dan," Brad replies, "I love your enthusiasm. But Julia's right, the professor ticked off pretty much everybody but you. He may be spot on, but he's put everyone on the defensive. The people in this firm aren't used to that. When outsiders present here, they always tell us that we're doing great. Didn't you hear what Sally Swindel told us in the *LEAN* Forward course? She said that we were on the verge of greatness. All we needed to do was implement a few lean manufacturing concepts. And you know darn well she didn't mean it."

"Okay," says Dan, "so he wasn't very tactful. But do we want to have people tell us that things are fine when we know that our performance is terrible? I'd rather have an honest appraisal than have someone try to flatter me."

"That may be so," says Julia, "but he could have been a little more diplomatic. I'm betting that Donna Garcia is going to give Tommy Jenkins a blow-by-blow description of today's presentation. And her version, I promise you, will be even more critical than ours. Just wait and see."

"Oh my," says Dan. "Maybe we did make a mistake in inviting the professor. Although at least one fellow, that Winston Smith guy, sure seemed pleased to see him."

Dan's comment is met with frowns on the part of both Julia and Brad.

CHAPTER 5 EXERCISES

1. If the data in Table 5.1 were for batches (i.e., replace "Job" with "Batch" as the heading of the first column) consisting of *three* jobs per batch, what is the coefficient of variability of interarrival times?
2. A nonreentrant workstation supporting a single process step has the following performance characteristics. Determine its coefficient of effective process times.

$$MTBE = 50 \text{ hours}$$
$$MTTR = 10 \text{ hours}$$
$$C_{PT} = 0.1$$
$$C_{DE} = 2.0$$
$$PT = 2 \text{ hours}$$

3. A factory's average level of inventory at any given time is 50,000 units. Units flow through the factory at an average rate of 5,000 units per week. What is the factory's average cycle time in days?

TABLE 5.7

Data for Exercise 4

Parameter	Value
C_{AR}	4.0
C_{EPT}	3.0
Availability	90 percent
Arrival rate	7 jobs/hour
EPR	10 jobs/hour

4. Process step 19 of a process flow is supported by a single, nonreentrant machine. The performance parameters of that machine are provided in Table 5.7. Determine, using the second fundamental equation of manufacturing, the expected cycle time for process step 19.

5. If, in Exercise 4, it were possible to reduce the value of the coefficient of variability of interarrivals by half, what would be the expected cycle time?

6. Provide your personal assessment of the behavior of Professor Aristotle Leonidas in his presentation at Muddle. What might he have done, without compromising his integrity, to have softened the effect of his opinions?

This page intentionally left blank

CHAPTER 6

Running a Factory: In Three Dimensions

In Chapter 4 you were asked to reduce the cycle time of the 12-workstation factory, subject to a budget limitation of $13M. But the only data provided (e.g., in Figure 4.3) pertained solely to quantities (e.g., number of machines in the workstations) and averages (e.g., average *EPR* per machine and average occupancy rate per workstation). The data appearing in Figure 4.3 limited your options to either increasing the effective process rate of the existing machines in the workstation (via improvements in availability and/or process rates) or adding new machines. Still, by means of optimization, we were able to reduce the factory cycle time from 90.42 to 14.59 days after expending the entire $13M budget on increasing the effective process rates of the machines in each workstation.

In this chapter you have the same mission: Reduce factory cycle time. But now your budget is limited to just $0.50M (i.e., $500,000—which represents more than a 96 percent reduction in funding). You will, however, have one significant advantage. Rather than being limited to the first two dimensions of manufacturing (i.e., changing the physical features of the factory or its components), you now may extend your options into manufacturing's third dimension—changing factory protocols to reduce variability.

More specifically, you are now provided with data pertaining to variability and, by means of the three fundamental equations of manufacturing, permitted to allocate your funds to variability reduction. This reduction of variability, in turn, may be achieved by changes in the practices, policies, and procedures employed in the facility. For the time being, we shall simply assume that we may allocate funds to efforts that will identify and mitigate sources of variability in the factory. Specific recommendations on how to achieve these changes effectively in actual practice will be provided and illustrated in Chapters 10 and 11.

Figure 6.1 presents the particulars of the same 12-workstation factory as encountered in Chapter 4. This time, however, additional rows have been included.

FACTORY ATTRIBUTES

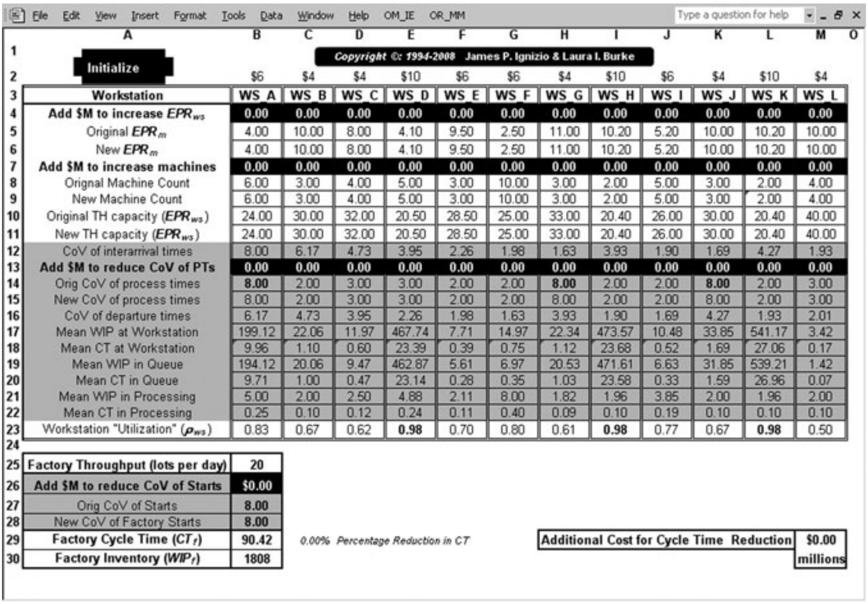
In Figure 6.1, (crucial) shaded rows 12 through 22 and 26 through 28 have been added. The contents of these new rows are defined in Table 6.1. The simulation model for employment may be found at

www.mhprofessional/Ignizio/12WS_Ch6

As before, you are to allocate funds either to increase the effective process rates of the machines in a workstation or to add machines to a workstation. In addition, however, you now also may allocate funds to reduce the coefficient of variability *CoV* of factory

FIGURE 6.1

Twelve-workstation factory simulation model, initial scenario.



	A	B	C	D	E	F	G	H	I	J	K	L	M	O
1	Initialize		Copyright ©: 1994-2008 James P. Ignizio & Laura I. Burke											
2		$6	$4	$4	$10	$6	$6	$4	$10	$6	$4	$10	$4	
3	**Workstation**	**WS_A**	**WS_B**	**WS_C**	**WS_D**	**WS_E**	**WS_F**	**WS_G**	**WS_H**	**WS_I**	**WS_J**	**WS_K**	**WS_L**	
4	**Add $M to increase EPR_{ws}**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	
5	Original EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00	
6	New EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00	
7	**Add $M to increase machines**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	
8	Orignal Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00	
9	New Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00	
10	Original TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00	
11	New TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00	
12	CoV of interarrival times	8.00	6.17	4.73	3.95	2.26	1.98	1.63	3.93	1.90	1.69	4.27	1.93	
13	**Add $M to reduce CoV of PTs**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	
14	Orig CoV of process times	**8.00**	2.00	3.00	3.00	2.00	2.00	**8.00**	2.00	2.00	**8.00**	2.00	3.00	
15	New CoV of process times	8.00	2.00	3.00	3.00	2.00	2.00	8.00	2.00	2.00	8.00	2.00	3.00	
16	CoV of departure times	6.17	4.73	3.95	2.26	1.98	1.63	3.93	1.90	1.69	4.27	1.93	2.01	
17	Mean WIP at Workstation	199.12	22.06	11.97	467.74	7.71	14.97	22.34	473.57	10.48	33.85	541.17	3.42	
18	Mean CT at Workstation	9.96	1.10	0.60	23.39	0.39	0.75	1.12	23.68	0.52	1.69	27.06	0.17	
19	Mean WIP in Queue	194.12	20.06	9.47	462.87	5.61	6.97	20.53	471.61	6.63	31.85	539.21	1.42	
20	Mean CT in Queue	9.71	1.00	0.47	23.14	0.28	0.35	1.03	23.58	0.33	1.59	26.96	0.07	
21	Mean WIP in Processing	5.00	2.00	2.50	4.88	2.11	8.00	1.82	1.96	3.85	2.00	1.96	2.00	
22	Mean CT in Processing	0.25	0.10	0.12	0.24	0.11	0.40	0.09	0.10	0.19	0.10	0.10	0.10	
23	Workstation "Utilization" (ρ_{ws})	0.83	0.67	0.62	**0.98**	0.70	0.80	0.61	**0.98**	0.77	0.67	**0.98**	0.50	
24														
25	**Factory Throughput (lots per day)**	**20**												
26	**Add $M to reduce CoV of Starts**	**$0.00**												
27	Orig CoV of Starts	**8.00**												
28	New CoV of Factory Starts	**8.00**												
29	**Factory Cycle Time (CT_f)**	**90.42**		*0.00% Percentage Reduction in CT*					**Additional Cost for Cycle Time Reduction**				**$0.00 millions**	
30	**Factory Inventory (WIP_f)**	**1808**												

TABLE 6.1

Factory or Workstation Attributes

Attribute	Value	From Cell	Comments
CoV of interarrival times C_{AR}	8.00	B12	Variability of arrivals at WS-A
Add $M to reduce C_{EPT}	0.00	B13:M13	Funds allocated thus far to reduce C_{EPT}
Original *CoV* of process times	8.00	B14	Initial C_{EPT} of each machine in WS-A
New *CoV* of process times	8.00	B15	New C_{EPT} of each machine in WS-A
CoV of departure times	6.17	B16	C_{DR} from WS-A
Mean work in process *WIP* at workstation	199.12	B17	Mean number of jobs at WS-A
Mean cycle time *CT* at workstation	9.96	B18	Initial *CT* at WS-A
Mean *WIP* in queue	194.12	B19	Mean number of jobs in WS-A queue
Mean *CT* in queue	9.71	B20	Initial mean *CT* in queue at WS-A
Mean *WIP* in processing	5.00	B21	Mean *WIP* processed in WS-A
Mean *CT* in processing	0.25	B22	Mean *CT* of processing in WS-A
Add $M to reduce *CoV* of starts	$0.00M	B26	Funds allocated thus far to reduce variability of factory starts
Original *CoV* of starts	8.00	B27	Initial variability of starts into factory
New *CoV* of factory starts	8.00	B28	New variability of factory starts

starts or to reduce the *CoV* values of the effective process times of the machines in each workstation. To reduce the variability of factory starts, you must assign funds to cell B26. To reduce the variability of effective process times, allocations of funds must be made to cells B13 through M13.

It is obvious that with a budget of just $500,000, there is no possibility of adding new machines to any workstation. Thus your only rational options are to (1) increase the effective process rates of the existing machines in one or more workstations, (2) reduce the variability of factory starts, or (3) reduce the variability of the effective process times of one or more workstations. We've previously discussed the way in which funds allocated to effective process rates (recall Equation 4.1) affect factory throughput capacity. We now need to appreciate how to allocate funds to the reduction of either the variability of factory starts or the variability of effective process times.

The new assumption to be employed in the 12-workstation model is that for every \$10,000 (\$0.01M) allocated, the coefficient of variability of either factory starts or effective process times is reduced by one unit. This is stated in Equation (6.1):

$$\text{New } CoV = \text{old } CoV - \$\text{M}/0.01 \tag{6.1}$$

For example, if the existing *CoV* is, say, 5.00 and we allocate \$40,000 (\$0.04M) to reduce its value, the new *CoV* value is given as

$$\text{New } CoV = 5.00 - \$0.04/0.01 = 5.00 - 4.00 = 1.00$$

In allocating funds to the reduction of *CoV* values, we also must follow certain rules. First of all, *CoV* values cannot be negative (e.g., in the preceding example, an allocation of \$60,000 would indicate that the new *CoV* value is −1.00). Second, the cost of reducing variability becomes increasingly difficult if the desired *CoV* value is less than 1.0. Consequently, and for sake of discussion, we shall assume that *CoV* values will not be reduced to less than 1.0 (which is considered a moderate level of variability). Thus Equation (6.1) should be replaced with Equation (6.2):

$$\begin{aligned} &\text{New } CoV = \text{old } CoV - \$\text{M}/0.01 \\ &\text{where } \$\text{M}/0.01 \leq \text{old } CoV - 1 \end{aligned} \tag{6.2}$$

The factory simulation spreadsheet has in fact been set up to limit funding for variability reduction so that coefficient of variability values will never be less than 1.0. Again, the simulation model may be found at

www.mhprofessional/Ignizio/12WS_Ch6

GREEDY HEURISTIC SOLUTION

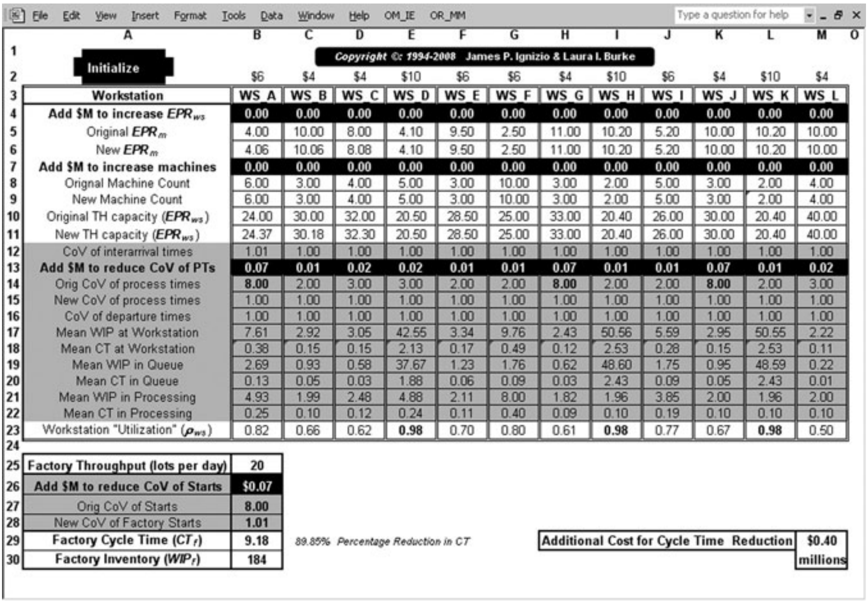
Figure 6.2 shows the resulting cycle time (of 9.18 days) after employing the first phase of a "greedy heuristic" (Ignizio and Cavalier, 1994). This phase of the heuristic simply allocates funds to reduction of the highest *CoV* values, where priority is given to the highest *CoV* values and those closest to the input of the factory. This is continued until all *CoV* values are 1.0 or funds run out.

Since the solution obtained in Figure 6.2 consumed only $400,000, we might improve on it by allocating the remaining funds ($100,000) to increasing effective process rates. One way to accomplish this is by allocating funds for *EPR* increases to the factory constraint workstations. The output of the second phase of the greedy heuristic, resulting in a cycle-time value of 3.94 days, is shown in Figure 6.3.

The solution obtained in Figure 6.3 is actually very close to that which would be obtained via optimization for this problem (i.e., 3.94 days for the heuristic versus 3.84 days for optimization). While the results obtained by the greedy heuristic are unlikely to always be this close, they are usually quite good. Considering the fact that the fundamental equations of manufacturing are approximations and that factory data are hardly perfect, the greedy heuristic provides an effective and practical means to improve factory performance. The two phases of the greedy heuristic for factory performance improvement are summarized below.

FIGURE 6.2

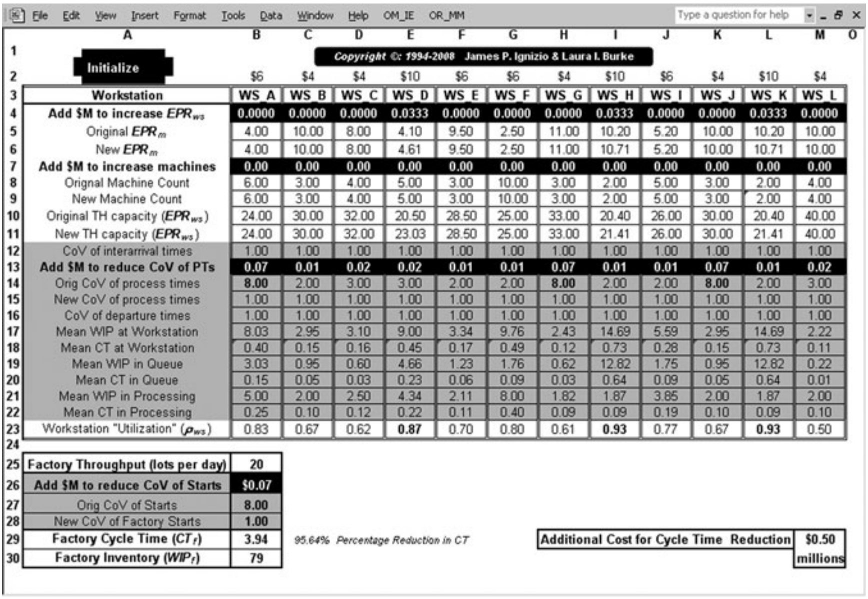
Twelve-workstation factory simulation model, reduced variability.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1				**Copyright ©: 1994-2008 James P. Ignizio & Laura I. Burke**									
2		$6	$4	$4	$10	$6	$6	$4	$10	$6	$4	$10	$4
3	**Workstation**	**WS_A**	**WS_B**	**WS_C**	**WS_D**	**WS_E**	**WS_F**	**WS_G**	**WS_H**	**WS_I**	**WS_J**	**WS_K**	**WS_L**
4	**Add $M to increase EPR_{ws}**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
5	Original EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
6	New EPR_m	4.06	10.06	8.08	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
7	**Add $M to increase machines**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
8	Orignal Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
9	New Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
10	Original TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
11	New TH capacity (EPR_{ws})	24.37	30.18	32.30	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
12	CoV of interarrival times	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
13	**Add $M to reduce CoV of PTs**	**0.07**	**0.01**	**0.02**	**0.02**	**0.01**	**0.01**	**0.07**	**0.01**	**0.01**	**0.07**	**0.01**	**0.02**
14	Orig CoV of process times	**8.00**	2.00	3.00	3.00	2.00	2.00	**8.00**	2.00	2.00	**8.00**	2.00	3.00
15	New CoV of process times	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
16	CoV of departure times	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
17	Mean WIP at Workstation	7.61	2.92	3.05	42.55	3.34	9.76	2.43	50.56	5.59	2.95	50.55	2.22
18	Mean CT at Workstation	0.38	0.15	0.15	2.13	0.17	0.49	0.12	2.53	0.28	0.15	2.53	0.11
19	Mean WIP in Queue	2.69	0.93	0.58	37.67	1.23	1.76	0.62	48.60	1.75	0.95	48.59	0.22
20	Mean CT in Queue	0.13	0.05	0.03	1.88	0.06	0.09	0.03	2.43	0.09	0.05	2.43	0.01
21	Mean WIP in Processing	4.93	1.99	2.48	4.88	2.11	8.00	1.82	1.96	3.85	2.00	1.96	2.00
22	Mean CT in Processing	0.25	0.10	0.12	0.24	0.11	0.40	0.09	0.10	0.19	0.10	0.10	0.10
23	Workstation "Utilization" (ρ_{ws})	0.82	0.66	0.62	**0.98**	0.70	0.80	0.61	**0.98**	0.77	0.67	**0.98**	0.50
24													
25	**Factory Throughput (lots per day)**	20											
26	**Add $M to reduce CoV of Starts**	**$0.07**											
27	Orig CoV of Starts	**8.00**											
28	New CoV of Factory Starts	**1.01**											
29	**Factory Cycle Time (CT_f)**	**9.18**	*89.85% Percentage Reduction in CT*							**Additional Cost for Cycle Time Reduction**			**$0.40**
30	**Factory Inventory (WIP_f)**	**184**											**millions**

FIGURE 6.3

Twelve-workstation model, second phase of greedy heuristic.



Copyright ©: 1994-2008 James P. Ignizio & Laura I. Burke

	A	B	C	D	E	F	G	H	I	J	K	L	M
2		\$6	\$4	\$4	\$10	\$6	\$6	\$4	\$10	\$6	\$4	\$10	\$4
3	**Workstation**	**WS_A**	**WS_B**	**WS_C**	**WS_D**	**WS_E**	**WS_F**	**WS_G**	**WS_H**	**WS_I**	**WS_J**	**WS_K**	**WS_L**
4	**Add \$M to increase EPR_{ws}**	**0.0000**	**0.0000**	**0.0000**	**0.0333**	**0.0000**	**0.0000**	**0.0000**	**0.0333**	**0.0000**	**0.0000**	**0.0333**	**0.0000**
5	Original EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
6	New EPR_m	4.00	10.00	8.00	4.61	9.50	2.50	11.00	10.71	5.20	10.00	10.71	10.00
7	**Add \$M to increase machines**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
8	Orignal Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
9	New Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
10	Original TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
11	New TH capacity (EPR_{ws})	24.00	30.00	32.00	23.03	28.50	25.00	33.00	21.41	26.00	30.00	21.41	40.00
12	CoV of interarrival times	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
13	**Add \$M to reduce CoV of PTs**	**0.07**	**0.01**	**0.02**	**0.02**	**0.01**	**0.01**	**0.07**	**0.01**	**0.01**	**0.07**	**0.01**	**0.02**
14	Orig CoV of process times	**8.00**	2.00	3.00	3.00	2.00	2.00	**8.00**	2.00	2.00	**8.00**	2.00	3.00
15	New CoV of process times	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
16	CoV of departure times	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
17	Mean WIP at Workstation	8.03	2.95	3.10	9.00	3.34	9.76	2.43	14.69	5.59	2.95	14.69	2.22
18	Mean CT at Workstation	0.40	0.15	0.16	0.45	0.17	0.49	0.12	0.73	0.28	0.15	0.73	0.11
19	Mean WIP in Queue	3.03	0.95	0.60	4.66	1.23	1.76	0.62	12.82	1.75	0.95	12.82	0.22
20	Mean CT in Queue	0.15	0.05	0.03	0.23	0.06	0.09	0.03	0.64	0.09	0.05	0.64	0.01
21	Mean WIP in Processing	5.00	2.00	2.50	4.34	2.11	8.00	1.82	1.87	3.85	2.00	1.87	2.00
22	Mean CT in Processing	0.25	0.10	0.12	0.22	0.11	0.40	0.09	0.09	0.19	0.10	0.09	0.10
23	Workstation "Utilization" (ρ_{ws})	0.83	0.67	0.62	**0.87**	0.70	0.80	0.61	**0.93**	0.77	0.67	**0.93**	0.50

25	**Factory Throughput (lots per day)**	20
26	**Add \$M to reduce CoV of Starts**	**\$0.07**
27	Orig CoV of Starts	**8.00**
28	New CoV of Factory Starts	**1.00**
29	**Factory Cycle Time (CT_f)**	**3.94**
30	**Factory Inventory (WIP_f)**	**79**

95.64% Percentage Reduction in CT

Additional Cost for Cycle Time Reduction **\$0.50 millions**

- *Phase 1.* Allocate funds first to the reduction of variability (with priority given to the largest variability values) until all variability values have been reduced, where possible, to an *a priori* specified value (e.g., the value was 1.0 for the preceding example) or all funds have been expended. If there is a tie for the largest variability values, break it in favor of the process step farthest upstream (i.e., the one closest to the factory input).
- *Phase 2.* If any funds are left over, allocate them to increasing the effective process times (i.e., increase the availability and/or process rates of the machines) of the factory constraint workstations. If there is a tie for factory constraints, break it in favor of the factory constraint farthest upstream (i.e., the one closest to the factory input).

The real message of this exercise, however, is that the reduction of variability (wherever it exists and particularly in factory starts and effective process rates) is a cheap and effective way to improve factory performance. In Chapter 4, even with a budget of \$13M, the best cycle time achieved was 14.59 days. Here, by allowing a focus on variability reduction, we achieved 3.94 days of cycle time (or less, had optimization been employed) while spending only $0.5M.

REDUCING VARIABILITY TRUMPS INCREASING CAPACITY

Examination of the second and third fundamental equations of manufacturing, coupled with observations from Chapters 4, 5, and 6, provides an important message: *Reducing variability anywhere in the production line always improves overall factory performance—particularly cycle time—whereas an increase in a single workstation's capacity may or may not provide an overall benefit to the factory.* Furthermore, in almost any real-world factory, it is almost always faster and less expensive to reduce variability than to increase capacity.

RETURNING TO THE FIVE-WORKSTATION PROBLEM

In Chapter 4, an investigation of the so-called fundamental premise of lean manufacturing was conducted by means of introducing a factory (the five-workstation model) that provided a counterexample. Recall that the fundamental premise of lean manufacturing is that a balanced production line with each workstation running at the takt rate minimizes factory inventory (and thus minimizes factory cycle time).

The five-workstation model of Chapter 4 demonstrated that a factory in which each workstation ran at its highest possible process rate produced inventory and cycle-time results that were superior to those attained by any balanced line. In this section, the comparison of balanced versus unbalanced lines—and the fundamental premise of lean manufacturing—is extended.

I will use the same five-workstation factory as in Chapter 4 to demonstrate some additional points. More accurately, the five-workstation factory to be employed here is *physically* identical to that of Chapter 4. That is, once again, the customer demand is 20 units per hour, and the ranges of process rates for the workstations are as before:

- Workstation A process-rate range: 10 to 25 jobs per hour
- Workstation B process-rate range: 10 to 40 jobs per hour
- Workstation C process-rate range: 10 to 100 jobs per hour

- Workstation D process-rate range: 10 to 25 jobs per hour
- Workstation E process-rate range: 10 to 60 jobs per hour

The simulation model in support of this version of the five-workstation model is provided at

www.mhprofessional.com/Ignizio/5WS_Ch6

Again, this factory is *physically* identical to that in Chapter 4. There is, however, a difference in terms of the protocols being employed to run the two factories (which, in turn, change the variability values within the factory). This difference will become evident if you attempt to compare the balanced-line versus unbalanced-line versions of the factory.

The best balanced line for the five-workstation factory of this chapter is, once again, a facility in which the process rate of each workstation is set to the maximum speed dictated by the factory constraint; that is, each workstation's process rate is set to 25 jobs per hour. The cycle time and inventory produced by the best balanced line are 65.78 hours and 1315.59 units, respectively. This is a very different result, however, from that produced by the five-workstation model in Chapter 4, where the cycle time and inventory were 9.39 hours and 187.76 units, respectively.

Why the quite large difference? The answer lies solely in the difference in factory starts and process time variability of the two versions of the five-workstation model.

Next, set the process rates of this version of the five-workstation model to their maximum values (i.e., 25, 40, 100, 25, and 60 units per hour, respectively) while maintaining a factory starts rate of 20 jobs per hour. If this is done, the resulting cycle time is 51.04 hours, and the corresponding inventory level is 1020.72 units. Once again, it has been demonstrated that an unbalanced production line, contrary to the fundamental premise of lean manufacturing, provides superior results to that of the best balanced line.

But, you should ask, is this the optimal setting for the process rates for the workstations for this version of the five-workstation factory? The answer is, in a word, "No." To demonstrate, try setting the process rates as follows:

- Workstation A process rate: 25 jobs per hour
- Workstation B process rate: 40 jobs per hour

- Workstation C process rate: **38.276 jobs per hour**
- Workstation D process rate: 25 jobs per hour
- Workstation E process rate: 60 jobs per hour

The sole difference between the process-rate settings in the optimal solution just cited and those used with the maximum-run-rate settings happens to be the setting for workstation C (i.e., 38.276 jobs per hour rather than its maximum process rate of 100 jobs per hour). With these latest settings, the cycle time and inventory levels are 50 hours and 1,000 units, respectively. While this represents just a 2 percent reduction over the maximum-run-rate settings for this version of the five-workstation factory, the message delivered is that the optimal production line for this factory is still unbalanced.

CHAPTER SUMMARY

At this point we may summarize the most important concepts of Chapters 4, 5, and 6. These are

- Reducing variability within a factory provides factory performance-improvement results that are most usually faster and cheaper to achieve than those obtained by increasing workstation throughput capacity.
- The theory of constraints has certain potentially serious limitations. Specifically, its fundamental assumption is that of a production line in which variability is essentially ignored and but a single, fixed factory constraint exists. Real-world factories, on the other hand, invariably have multiple migrating constraints and are affected by numerous sources of variability.
- Lean manufacturing, while representing a generally positive force, is not a panacea. Its fundamental premise—that a balanced production line operating at takt speed minimizes factory inventory and cycle time—is based on the implicit assumptions of synchronous systems in which variability may be ignored.
- For significant and sustainable factory performance improvement, the art of manufacturing (e.g., the theory of constraints, lean manufacturing, etc.) must be coupled with the science of manufacturing.

CASE STUDY 6: ROOM 101

It's Saturday, and Julia, Dan, and Brad are meeting once again with Professor Leonidas. The trio had agreed previously that no matter what opinion their colleagues may hold of him, it still would be wise to seek the professor's counsel with regard to their concerns about factory performance. It would seem, however, that the professor has some questions for them.

"What precisely is the situation with Winston Smith? He was awfully evasive about his appointment at Muddle."

Brad notices that Julia's eyes are downcast and decides that he should reply. "Professor, Winston Smith's position at Muddle is a bit of a mystery." Glancing again at Julia, he continues, "It seems that something he did a few years ago displeased management. Frankly, most of us thought he would be fired. Instead, they sent him to Room 101. After that, he's been pretty much invisible in the company, although he continues to show up for work."

"What a waste!" says Leonidas. "Winston Smith is not only a true genius, but he's one of the finest men I've ever known. From the little he said to me during my visit, my impression is that he's terribly unhappy. Why he stays with your company is beyond me."

"I think I can explain," Julia replies, sighing. "There are lots of rumors about Winston and me, and I might as well set the matter straight."

"Julia," Brad interjects, "there's really no reason for that."

"Thanks, Brad," says Julia, "but I want to. First of all, as Brad and some others know, Winston and I were engaged to be married at one time. Winston had tired of academia and moved to the United States to accept a position with Muddle. He had been assured that he would be a valuable source of advice in the running of our factories. And he was." Julia takes at deep breath and continues.

"Unfortunately, Winston reported to Ben Arnold, and Ben took credit for each and every recommendation made by Winston. Winston voiced his displeasure with senior management, and they made it clear that if he was to be a team player, he should be proud to make his immediate superior look good. I should add that Winston also made me look good. Thanks to his advice and guidance, I managed to get several major programs implemented. Winston allowed me to take credit for the results, even though they would never have happened without him. I felt a bit guilty about it, but I rationalized things. After all, this type of behavior was and is rampant in Muddle."

"You are sure right about that," says Brad. "But go on. Sorry for interrupting."

"You all need to understand that my dream, ever since I joined Muddle out of college, was to be appointed a Muddle Fellow. It may seem silly, but that was my goal, and unfortunately, I didn't let anything stand in my way, including my feelings for Winston. Each year they appoint a few people to Fellows … "

"And promote about a hundred to vice presidents," Brad interjects.

Julia nods in the affirmative and continues, "I was one of the people nominated for a Fellow position. Winston wasn't. When he found out, he walked into Tommy Jenkins' office and demanded to know why he wasn't being considered for promotion to Muddle Fellow. Tommy flat out told him that he hadn't made any significant contributions, even though he must have known that wasn't true. Winston responded with a list of at least a dozen major contributions. Frankly, any one of them should have merited an appointment. Tommy's response was that he'd check into things and let Winston know his decision by the end of the week."

Julia's head sinks lower, and tears begin to appear. "I'm ashamed to say this, but when Tommy asked me about Winston's role in my projects, I inferred that he had been of some help but that I had come up with and implemented the ideas. Evidently, Ben Arnold was an even bigger liar. He told Tommy that Winston had played no role whatsoever in the projects that got Ben promoted. I'm quite sure that Tommy knew that wasn't true, but he sent Winston an e-mail telling him that he did not merit a nomination for Muddle Fellow. When I heard about that, I went straight to Tommy's office and told him that I hadn't given Winston the credit he deserved, and I was fully aware that Ben Arnold had taken advantage of Winston and used him as a means to get promoted to his present position."

"What was his response?" asks Dan. "Of course, based on the situation as it now exists, I can only guess that Tommy ignored your remarks."

"Not only did he ignore what I told him, but he had the audacity to send both Winston and me to Room 101. It was horrible."

"Okay," Dan replies, "I've heard rumors about this Room 101, but just what is it? What happened to the two of you there?"

"Room 101," Julia replies, "is where you are sent for what Muddle calls 'reeducation.' I was told that if I wanted to stay with

Muddle, I should keep my mouth shut and accept the nomination. Winston was warned that his actions could be interpreted as being sexist, that he was attempting to damage the career of a female employee. I agreed to keep quiet and spent the next six weekends in the Muddle reeducation program. It was dreadful, but what happened to Winston was worse."

Professor Leonidas shakes his head in disbelief. "I suspected that the corporate culture in your firm was dysfunctional, but this is just incredible. But you said that what happened to my friend Winston was worse. Would you elaborate?"

"Winston," says Julia, "was moved to a tiny cubicle in one of the parts and supplies buildings. He was threatened. The poor man was told that if he raised any further objections, Muddle would blackball him! He was told that he would never get another job anywhere if he persisted with his claims. He and I haven't spoken since then."

"But why," asks Dan, "didn't they just fire Winston?"

"Tommy, as well as other people in the executive offices, knows how brilliant Winston is and what he could do if he were hired by a competitor. They keep him here because they don't want any other firm to exploit his expertise. So he just sits in his little cube, except for one week a month. Then he's required to take a course on interpersonal relationships and business ethics. What a farce! I can never make it up to him."

"Perhaps," replies Leonidas, stroking his chin, "you can. I have an idea. Why don't the three of you team up with Winston? I'll continue to advise you on the science of manufacturing, and Winston can show you his special talents."

"I don't think that Winston would want to work with me," says Julia, "and I don't blame him."

"Nonsense," replies Leonidas, "this rift in your relationship has gone on long enough. It's time it was healed, and working together on one mission—the improvement of factory performance—could be the catalyst. Please, Julia, do consider it. I saw the way that Winston looked at you during my presentation. He stole glances at you whenever you weren't looking. It's quite obvious, even to an old man like me, that he still cares for you."

* * *

Brad schedules a meeting with Winston Smith. On Monday afternoon, he, Dan, and a very hesitant Julia approach Winston's diminutive cubicle in a remote and poorly lit corner of the parts and supply warehouse. After being assured that they will not reveal anything discussed in the encounter, Winston suggests they move the meeting to a small, windowless room in the rear of the building. A crudely fashioned plaque on its weathered door reads, "Authorized Personnel Only." Its interior is nothing like what Julia, Dan, or Brad expects.

Inside the room are a few chairs, several tables, and six computers—equipment Winston had rescued from the trash heap. The walls of the room are covered with graphs and plots. This, according to Winston, is his "war room."

"What, may I ask, do you do in here? Why so many computers?" asks Dan.

"I use this equipment to support my factory simulation efforts," replies Winston. "No one else ever comes here. In fact, no one in this company cares about what I do here—or its potential to help them."

"Are you running the firm's simulation package on those computers?" asks Brad. "I thought that software required the very latest, fastest computers. Those things I see appear to be at least 10 years old."

"Yes, they are old," Winston replies, "but I've rebuilt them, and no, I don't use Muddle's simulation software. First of all, I could never get approval to run that package. Second, I'm using a simulation approach based on fluid network modeling, a type of continuous simulation. It's enormously faster than Muddle's discrete event–based simulation, and it's better suited to my work."

"What exactly is your work?" asks Dan.

"I've built fluid network simulation models of all of Muddle's factories. I use these to experiment on. For example, what might happen if I increase the process rate of a workstation? Or what would factory performance be if I reduced the arrival-rate variability at a workstation? I can run a year's worth of simulations on an entire factory in a few minutes. If I used the Muddle simulation software, it would take hours or even days just to run a single replication. And, of course, for statistical significance, dozens of replications would be required. I don't have the level of detail in my models that Muddle's simulation group does, but I can get what I want in a fraction of the time—and cost."

"Impressive," says Brad, "could you give us an example of your findings?"

Pointing to a graph on the wall, Winston replies, "This plot contrasts the cycle time this factory now achieves versus what it could realize by nothing more than a declustering of factory starts. The time for an average product to pass through the factory could be reduced by anywhere between 2 and 30 percent just by means of smoothing out factory starts."

"Between 2 and 30 percent, you say," says Dan. "That's an awfully big range. Can't the model produce results that are more precise?"

"They could be a lot more precise," Winston replies, "if I just had certain data—like the coefficient of variability of job arrivals at our workstations or the variability of equipment downtimes. Unfortunately, I don't have access to the data I need to populate my models, and there's no way this company is ever going to allow me to gather those data. So, right now, I'm forced to just use a range of guesses."

"I think I can solve that problem," says Julia, avoiding eye contact. "I have access to all our factories' production-line data. I can provide you with those facts and figures, and with all of us working together; we could populate your simulation models with the data you need to get a better estimate of factory performance."

"That would be wonderful," Winston replies, "but it could get the three of you in a lot of trouble. I'm not someone you want to be seen with in this company."

"We'll just have to be careful," says Dan. "I'm game to spend some evenings and at least part of my weekend on this project."

"Me too," says Julia. "What about you, Brad?"

"I suppose I could spend some of my free time here," Brad answers without enthusiasm. "I'd definitely like to use Winston's models to test out the techniques that Professor Leonidas has been discussing, but I don't see much else in the way of a return on our investment."

"What do you mean by that?" asks Julia.

"Suppose that we try out the professor's concepts to improve the performance of Muddle's factories. Suppose that Winston's models validate those approaches. How is that going to help our careers? Someone else will take credit for all our hard work. This is, after all, the Muddle Corporation we're dealing with."

"Let's cross that bridge when we come to it," answers Julia. Dan nods in the affirmative. Brad shrugs his shoulders.

"Then I assume we're all in agreement," says Winston. "With Julia's assistance in obtaining the data, and with all of us working off-hours on this effort, we should be able to prove to Muddle's top brass that the science of manufacturing will solve this company's factory performance problems. In the meantime, we must be very discreet about this. No one outside the four of us in this room and Aristotle must know what we are doing."

* * *

Ben Arnold is working late. Putting the final touches on an e-mail, he presses SEND, and that interesting piece of correspondence is on its way to Jack Gibson, the junior member of the three plant managers at Factory 2. This, Ben thinks, could be the final nail in the coffin.

CHAPTER 6 EXERCISES

1. Employ, using your own tie-breaking rules, the greedy heuristic (phases 1 and 2) to reduce the cycle time of the 12-workstation simulation model (of Figure 6.1).
2. Employ, using your own tie-breaking rules, the greedy heuristic to reduce the cycle time of the 12-workstation simulation model (of Figure 6.1). This time, however, employ the second phase (e.g., allocate funds to increase workstation *EPR* values) first. Allocate no more than $250,000 to *EPR* increases, and then proceed to the allocation of funds to reduce variability.
3. Discuss the results obtained in Exercises 1 and 2. To what do you attribute the differences, if any?
4. What was the name of the main character in the classic novel, *Nineteen Eighty-Four,* by George Orwell? What fate did that character and his female friend suffer? What similarities are there between the world described in Orwell's book and the environment faced by employees of the Muddle Corporation?

This page intentionally left blank

CHAPTER 7

Three Holistic Performance Curves

In Chapters 4 and 6 we explored the 12-workstation factory. In this chapter we use that same model to illustrate three factory performance curves by means of which we may fairly and objectively evaluate and compare factory performance (Ignizio, 1997).

The first curve presented is the factory *operating curve* (OC). The second is the factory *load-adjusted cycle-time efficiency* (LACTE) *plot.* The final curve is the factory *profit curve* (PC). Each of these curves reveals useful information with regard to the overall performance of a factory.

FACTORY OPERATING CURVE

A factory operating curve (a.k.a. *factory performance curve*) is a plot of factory cycle time versus factory loading, where loading is given by either (1) the factory throughput rate (e.g., flow rate of jobs introduced into the factory) or (2) the ratio of factory throughput rate to the upper bound of factory capacity (i.e., maximum theoretical capacity of the factory constraint). In Chapter 13, a means for computing the upper bound on factory capacity for the general case will be presented. However, since we are dealing with the simple, nonreentrant 12-workstation factory (e.g., the machines in each workstation are identical in terms of effective process rates, and each is capable of supporting the single process step), the upper bound of the capacity of each workstation may be found—*for this special case*—simply by adding the effective process rates of its machines.

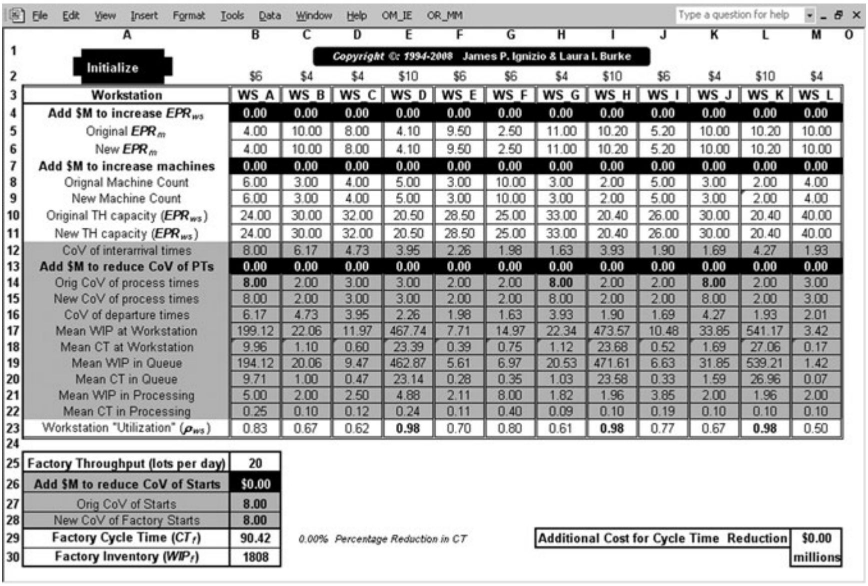
To clarify, we return to the 12-workstation factory of Chapters 4 and 6. The initial factory conditions were shown in Figure 6.1 and are repeated here as Figure 7.1. Note that the upper bounds on the capacities of each workstation are listed in cells B11 through O11. For example, the upper bound (maximum theoretical capacity) of the capacity (i.e., EPR_{ws}) of workstation H is 20.40 jobs per day. Since workstation H is one of the factory constraints, 20.40 jobs per day also must be the upper bound on the capacity of the 12-workstation factory—at least under its initial configuration.

To derive the data required to plot the factory operating curve, we record the cycle times for various values of factory throughput (i.e., where those values are entered into cell B25). The resulting plot for the 12-workstation factory (for the initial scenario) is provided in Figure 7.2. Figure 7.3 is the same plot but employs, for easier reading, a truncated cycle-time scale.

It is clear from either Figure 7.2 or Figure 7.3 that as factory loading increases, cycle time increases (i.e., precisely as predicted by the Pollaczek-Khintchine equation). Further, as factory loading approaches the upper bound of factory capacity (i.e., 20.40 jobs per day in this case), cycle time turns exponential. In fact, just from

FIGURE 7.1

Twelve-workstation factory simulation model, initial scenario.



Copyright ©: 1994-2008 James P. Ignizio & Laura I. Burke

	A	B	C	D	E	F	G	H	I	J	K	L	M
2		$6	$4	$4	$10	$6	$6	$4	$10	$6	$4	$10	$4
3	**Workstation**	**WS_A**	**WS_B**	**WS_C**	**WS_D**	**WS_E**	**WS_F**	**WS_G**	**WS_H**	**WS_I**	**WS_J**	**WS_K**	**WS_L**
4	**Add $M to increase EPR_{ws}**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Original EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
6	New EPR_m	4.00	10.00	8.00	4.10	9.50	2.50	11.00	10.20	5.20	10.00	10.20	10.00
7	**Add $M to increase machines**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	Orignal Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
9	New Machine Count	6.00	3.00	4.00	5.00	3.00	10.00	3.00	2.00	5.00	3.00	2.00	4.00
10	Original TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
11	New TH capacity (EPR_{ws})	24.00	30.00	32.00	20.50	28.50	25.00	33.00	20.40	26.00	30.00	20.40	40.00
12	CoV of interarrival times	8.00	6.17	4.73	3.95	2.26	1.98	1.63	3.93	1.90	1.69	4.27	1.93
13	**Add $M to reduce CoV of PTs**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	Orig CoV of process times	**8.00**	2.00	3.00	3.00	2.00	2.00	**8.00**	2.00	2.00	**8.00**	2.00	3.00
15	New CoV of process times	8.00	2.00	3.00	3.00	2.00	2.00	8.00	2.00	2.00	8.00	2.00	3.00
16	CoV of departure times	6.17	4.73	3.95	2.26	1.98	1.63	3.93	1.90	1.69	4.27	1.93	2.01
17	Mean WIP at Workstation	199.12	22.06	11.97	467.74	7.71	14.97	22.34	473.57	10.48	33.85	541.17	3.42
18	Mean CT at Workstation	9.96	1.10	0.60	23.39	0.39	0.75	1.12	23.68	0.52	1.69	27.06	0.17
19	Mean WIP in Queue	194.12	20.06	9.47	462.87	5.61	6.97	20.53	471.61	6.63	31.85	539.21	1.42
20	Mean CT in Queue	9.71	1.00	0.47	23.14	0.28	0.35	1.03	23.58	0.33	1.59	26.96	0.07
21	Mean WIP in Processing	5.00	2.00	2.50	4.88	2.11	8.00	1.82	1.96	3.85	2.00	1.96	2.00
22	Mean CT in Processing	0.25	0.10	0.12	0.24	0.11	0.40	0.09	0.10	0.19	0.10	0.10	0.10
23	Workstation "Utilization" (ρ_{ws})	0.83	0.67	0.62	**0.98**	0.70	0.80	0.61	**0.98**	0.77	0.67	**0.98**	0.50

	A	B
25	**Factory Throughput (lots per day)**	20
26	**Add $M to reduce CoV of Starts**	$0.00
27	Orig CoV of Starts	**8.00**
28	New CoV of Factory Starts	**8.00**
29	**Factory Cycle Time (CT_f)**	90.42
30	**Factory Inventory (WIP_f)**	1808

0.00% Percentage Reduction in CT

Additional Cost for Cycle Time Reduction **$0.00 millions**

FIGURE 7.2

Factory operating curve for 12-workstation factory (initial).

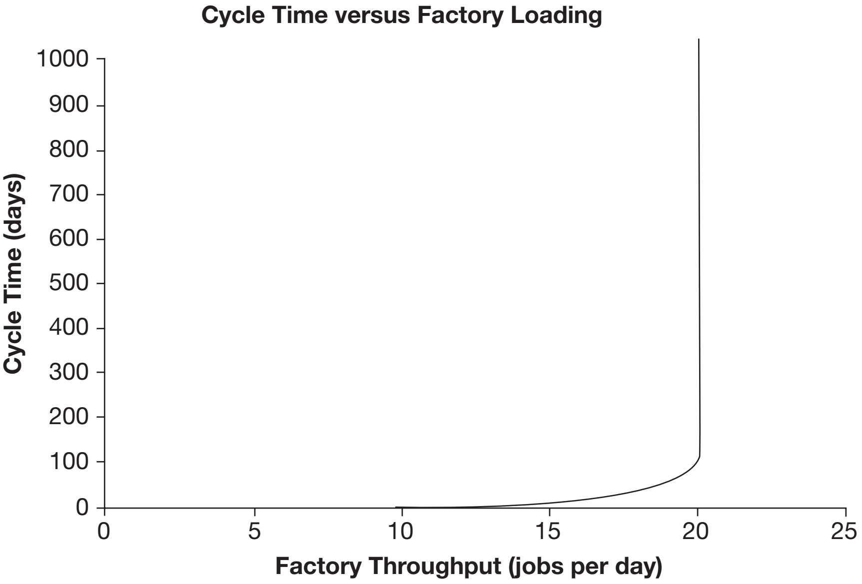
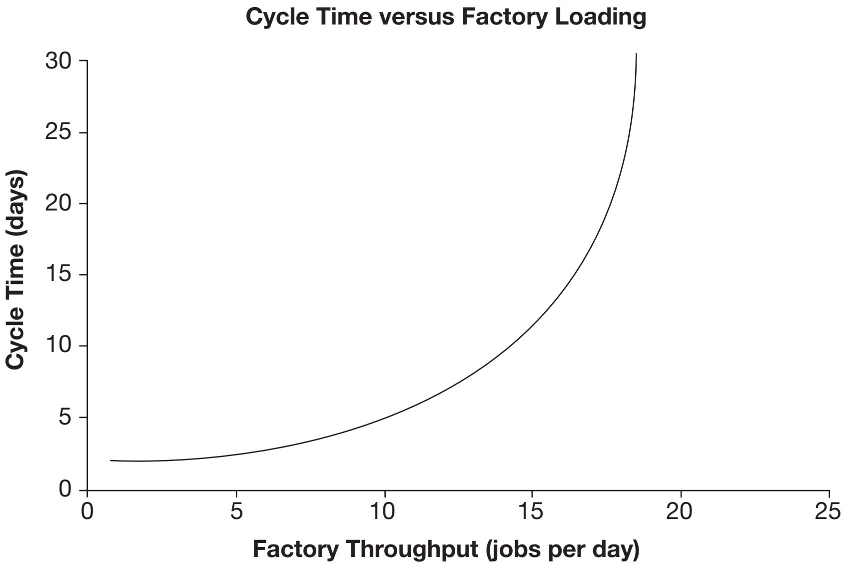


FIGURE 7.3

Factory operating curve for 12-workstation factory (truncated vertical axis).



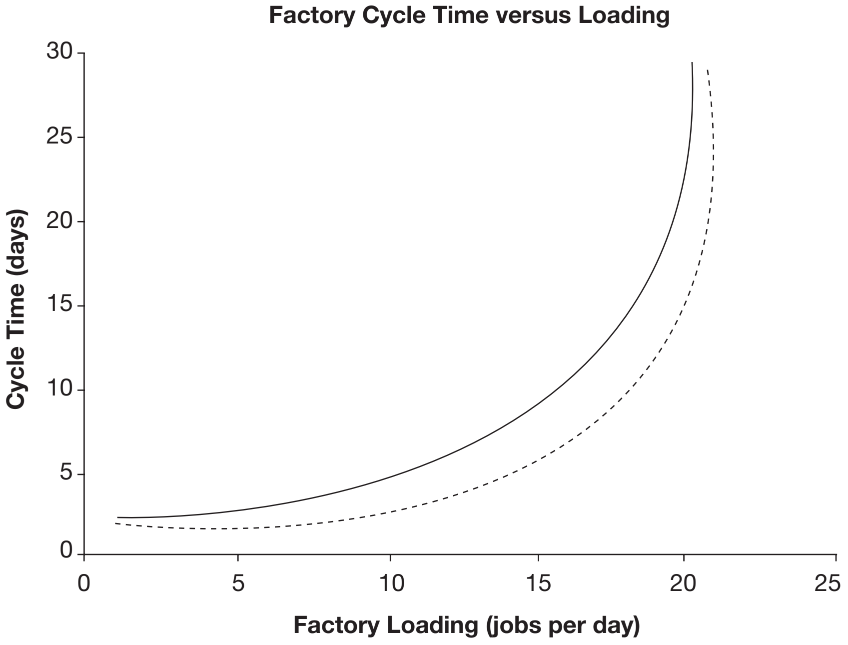
looking at Figure 7.3, I personally would be concerned about loading this factory at a rate of more than about 15 or so jobs per day.

The factory operating curve also provides a means to evaluate the impact of either reducing or increasing factory variability. Consider, for example, a reduction in the coefficient of variability *CoV* of factory starts from 8 to 1 per day coupled with a reduction in the *CoV* of the effective process times of all workstations (A through L) to values of 1 (i.e., the same results that were obtained by the first phase of the greedy heuristic and previously illustrated in Figure 6.2). The resulting factory operating curve may be compared with the original factory operating curve (i.e., of Figure 7.2 or Figure 7.3). This is shown in Figure 7.4, where the solid line is the factory operating curve for the initial scenario, whereas the dashed line is the operating curve after reductions in the variability of starts and effective process times for workstation A (i.e., after phase 1 of the greedy heuristic).

It is clear, or should be, from Figure 7.4 that simply by reducing factory variability (in this case the variability of both factory starts and effective process times) we have improved factory

FIGURE 7.4

Before and after operating curves for the 12-workstation factory.



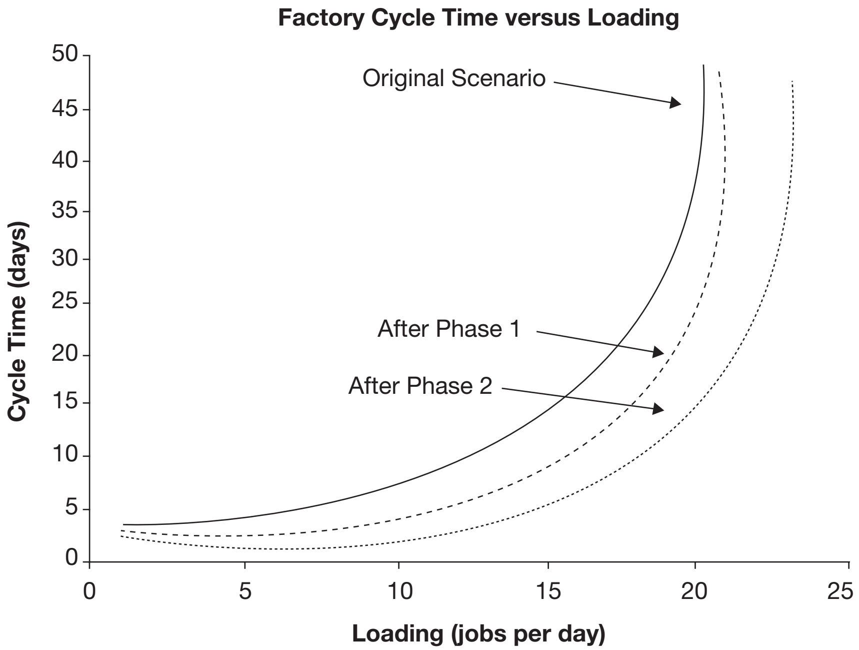
performance significantly. Prior to variability reduction, the cycle time for a factory loading of 20 jobs per day was 90.42 days. After reducing the sources of variability, the cycle time for the same loading is but 9.18 days (i.e., a reduction of about 90 percent).

It also should be noted that while the reductions in variability improved cycle times across all levels of factory loading, they did not change the upper bound on factory capacity (i.e., the *EPR* of the factory constraint workstation or workstations). Specifically, the upper bound on factory capacity (i.e., the maximum theoretical capacity) remains at 20.40 jobs per day.

What has been accomplished thus far is simply the conduct of the first phase of the greedy heuristic described in Chapter 6. If we employ the second phase (i.e., use any remaining funds, up to the $500,000 limit, to increase the *EPR* values of the factory constraints), the result is the factory depicted in Figure 6.3. The factory operating curve that may be developed after the second phase of the greedy heuristic is shown in Figure 7.5. In this figure, all three factory operating curves are shown, that is, that for the original scenario, for the reduction in variability (phase 1 of the greedy heuristic), and after both phases of the greedy heuristic.

FIGURE 7.5

Factory operating curves for the 12-workstation model.



For both the initial 12-workstation factory scenario and the facility after phase 1 of the greedy heuristic, the upper bound on factory capacity is 20.40 jobs per day. Note, though, that after the second phase of the greedy heuristic, the upper bound on factory capacity increased to 21.41 jobs per day (see Figures 6.3 and 7.5). This is so because the second phase is focused on increasing factory capacity—while ignoring variability. Readers are invited to derive these results using the 12-workstation factory simulation model.

The factory operating curve is also useful for a rough estimation of the practical capacity of a factory (i.e., the maximum sustainable factory throughput rate beyond which cycle time would be unacceptably high). The maximum sustainable factory capacity may be estimated by visually examining the factory operating curve. More specifically, it is the maximum capacity exhibited on the operating curve occurring "somewhat prior" to the cycle time going exponential.

For example, in Figure 7.5, I would assert that the maximum sustainable factory capacities for the various scenarios are

- Initial scenario sustainable factory capacity: ~15 to 17 jobs per day
- Scenario after phase 1 of greedy heuristic: ~17 to 18 jobs per day
- Scenario after both phases of heuristic: ~20 jobs per day

The most important message presented by the factory operating curve is that the maximum sustainable capacity of a factory is determined in large part by the variability inherent in its production line. Simply by reducing that variability, the maximum sustainable capacity may be increased, sometimes substantially.

The derivation of the data required to plot the factory operating curve may be obtained by

- Running the actual factory at various loadings and recording cycle times or
- Running a simulation of the factory at various loadings and recording cycle times where the types of simulations that might be employed include
  - Discrete event simulation models (Taha, 2006)
  - Simulation models employing fluid nets (Billings and Hasenbein, 2002)
  - Simulation models employing electromagnetic nets (Ignizio, 2000)

- ○ Simulations employing queuing models (Ignizio and Gupta, 1975)

Clearly, attempting to derive factory operating curve data from experimentation on an actual factory may be impractical (and most likely will be). Consequently, the most typical approach to the development of the required data is by means of simulation.

LOAD-ADJUSTED CYCLE-TIME EFFICIENCY

Recall from Equation (3.23) that the cycle-time efficiency *CTE* of a factory is the ratio of its process time to its cycle time. The equation for the *CTE* of a factory is repeated below:

$$CTE_f = \frac{Process\ Time_f}{CT_f} \tag{7.1}$$

For our purposes, we shall define a factory's *process time* as that which includes the time devoted to all value-added as well as non-value-added process steps. Alternative representations of factory cycle-time efficiency omit any non-value-added process step time (e.g., time consumed by transit, inspection, or test).

The problem—a particularly crucial one—with the *CTE* metric is the fact that it is not adjusted for factory loading. To illustrate, consider the 12-workstation factory operating curve in Figure 7.6. Assuming that the total process time required for the manufacture of the average product is 1.9035 days (which, indeed, is the case for the 12-workstation problem in its initial configuration), the cycle-time efficiencies for various values of factory loading are provided in Table 7.1.

It should be obvious that it would be patently unfair to compare the cycle-time efficiencies of two otherwise identical 12-workstation factories that are operating at different loadings. For example, the CTE_f of the factory at 73.53 percent loading (15 jobs per day) is 18.7 percent, whereas that of its twin, running at 98.04 percent loading (20 jobs per day), is just 2.11 percent. Despite this, I have seen, repeatedly, firms employ non-load-adjusted cycle-time efficiency (or, and even more often, non-load-adjusted cycle times) allegedly to compare the performance of several factories or allegedly to evaluate the results of the introduction of some new scheme for factory performance improvement.

If one is to employ cycle-time efficiency as a credible measure of factory performance, it *must* be adjusted for load. Furthermore,

FIGURE 7.6

Factory operating curve for 12-workstation factory (initial scenario).

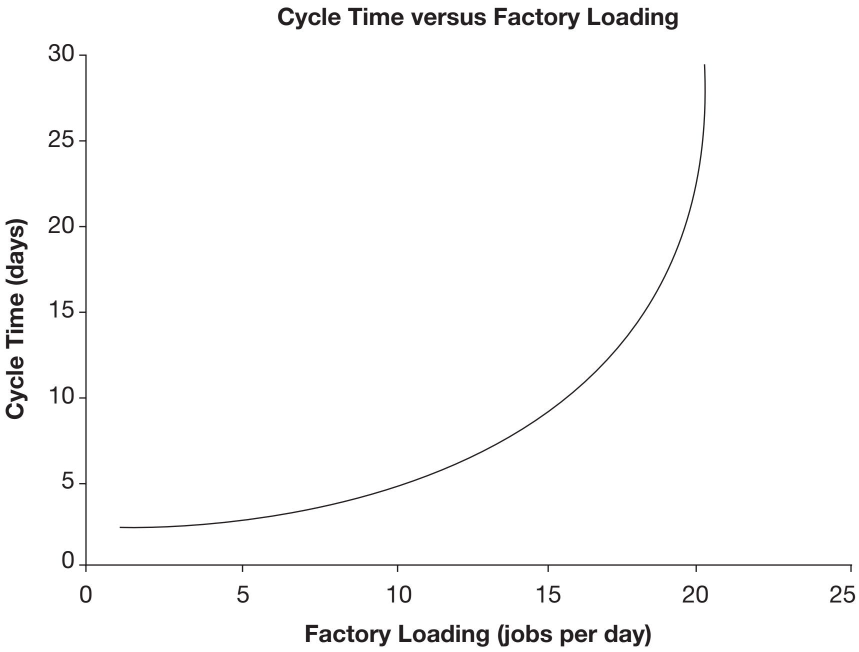


TABLE 7.1

Factory Loadings versus Cycle-Time Efficiencies

Scenario	Loading (Jobs/Day)	Loading (Percent of Maximum Theoretical Capacity)	Factory Cycle Time (Days)	Sum of Process Times (Days)	CTE_f
1	0	0.0000	1.9035	1.9035	1.0000
2	1	0.0490	1.96	1.9035	0.9712
3	5	0.2451	2.78	1.9035	0.6847
4	10	0.4902	4.89	1.9035	0.3893
5	15	0.7353	10.18	1.9035	0.1870
6	19	0.9314	33.31	1.9035	0.0571
7	20	0.9804	90.42	1.9035	0.0211
8	20.39	0.9995	2249.23	1.9035	0.0008

the entire load-adjusted cycle-time efficiency (LACTE) *curve*—rather than just a point—must be employed.

Equation (7.2) is used to develop each point on the LACTE curve. More specifically, it may be used to compute LACTE values for various factory loadings.

$$LACTE_{\text{loading}} = \left(\frac{\text{factory process time}}{\text{factory cycle time}}\right) \bullet \left(\frac{\text{factory throughput}}{\text{maximum theoretical factory capacity}}\right) \tag{7.2}$$

We may employ Equation (7.2) to compute the LACTE curve for the 12-workstation factory. To accomplish this, the initial factory scenario (e.g., Figure 7.1) will be employed. The computations required for development of this curve are summarized in Table 7.2.

Table 7.1 may be extended to include the factory loading percentage and, subsequently, to develop a number of *LACTE* point estimates. This is shown in Table 7.2. Note that a given *LACTE* value is found by multiplying the associated entry in column F by that in column C.

TABLE 7.2

Load-Adjusted Cycle-Time Efficiencies

A	B	C	D	E	F	G
Scenario	Loading (Jobs/Day)	Loading (Percent of Upper Bound of Capacity) = *B*/20.4	Factory Cycle Time (Days)	Sum of Process Times (Days)	CTE_f = D/E	*LACTE* = F • C
1	0	0.0000	1.9035	1.9035	1.0000	0.0000
2	1	0.0490	1.96	1.9035	0.9712	0.0476
3	5	0.2451	2.78	1.9035	0.6847	0.1678
4	10	0.4902	4.89	1.9035	0.3893	0.1908
5	15	0.7353	10.18	1.9035	0.1870	0.1375
6	19	0.9314	33.31	1.9035	0.0571	0.0532
7	20	0.9804	90.42	1.9035	0.0211	0.0206
8	20.39	0.9995	2249.23	1.9035	0.0008	0.0008

The resulting LACTE curve is plotted in Figure 7.7. Note that the peak *LACTE* value of 19.08 percent is at a loading of 10 jobs per day (49.02 percent loading) and that this peak is at a point slightly skewed to the left on the LACTE curve.

To compare factory performance (i.e., of several factories or of a factory before and after changes), it is necessary to compare the LACTE *curves* for each factory. To illustrate, we return to the 12-workstation problem. This time, however, we plot the LACTE curve after phase 1 of the greedy heuristic (i.e., for the factory configuration presented in Figure 6.2). The LACTE curve for this instance is shown in Figure 7.8. Notice that the peak *LACTE* value of 59 percent occurs at a factory loading of about 74 percent (i.e., of the upper bound on capacity of 20.40 jobs per day). In this instance, the peak is at a point on the curve that is skewed to the right.

The LACTE curves for both the initial scenario and that developed after phase 1 of the greedy heuristic are plotted in Figure 7.9. The reduction in variability (phase 1) in the 12-workstation factory produces a LACTE curve that dominates, for any value of factory loading, the curve developed for the initial scenario.

FIGURE 7.7

LACTE curve for 12-workstation factory (initial scenario).

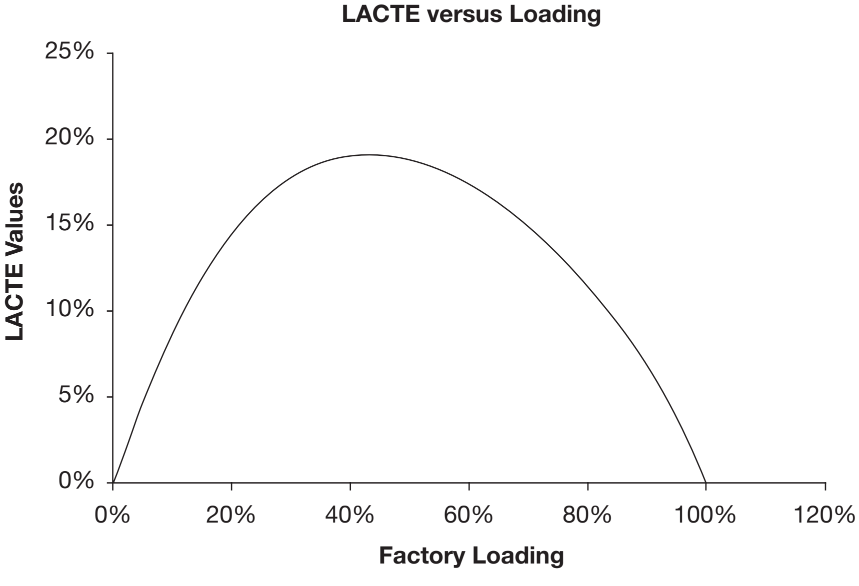


FIGURE 7.8

LACTE curve (after phase 1 of greedy heuristic).

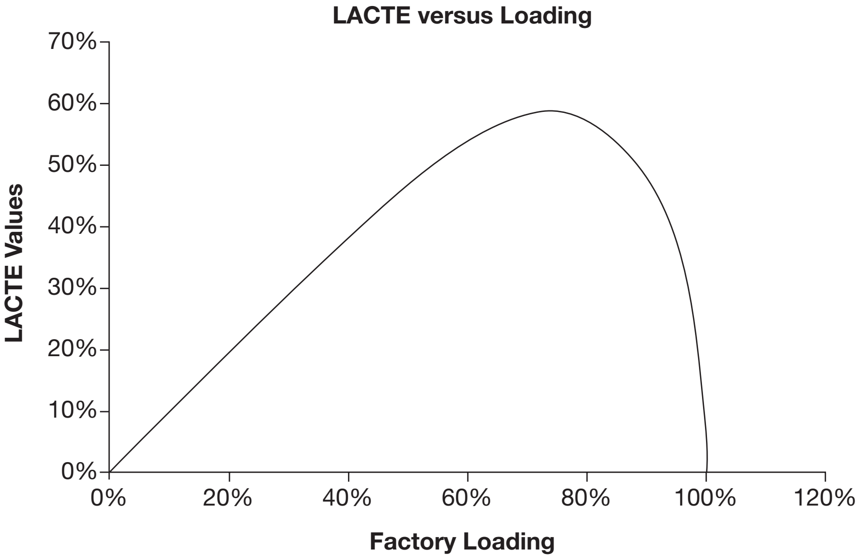
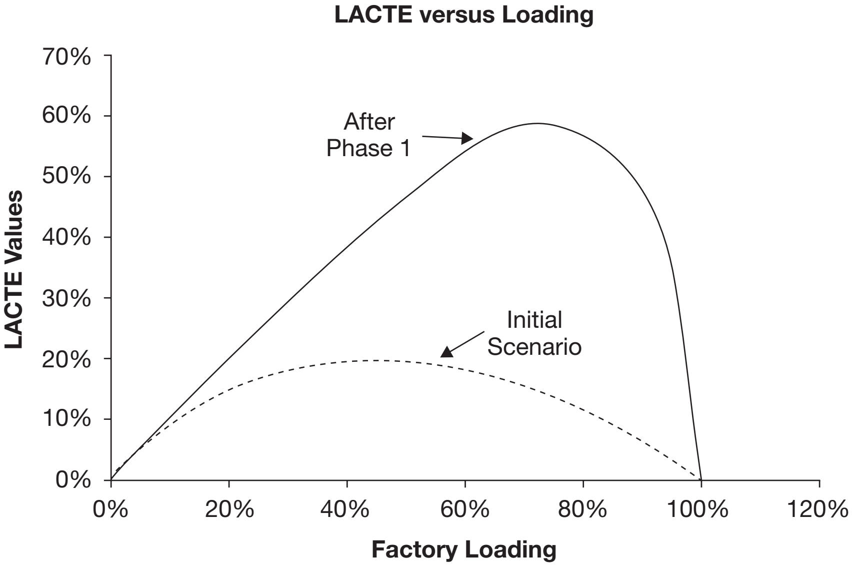


FIGURE 7.9

LACTE curves (before and after phase 1 of the greedy heuristic).



It is emphasized again that factory performance must be evaluated by a comparison of the LACTE *curves* rather than of point values. To illustrate, at a factory loading of 49 percent, the *LACTE* value associated with the initial scenario for the 12-workstation factory is approximately 19 percent. At a factory loading of 98 percent, the *LACTE* value associated with the factory after phase 1 of the greedy heuristic is about 15 percent. Clearly, it would be foolish to compare the before and after factory configurations using just these two *LACTE* point values because one would conclude erroneously that the initial configuration of the 12-workstation factory is the better performer.

Any LACTE curve for a factory in which the only changes are those owing to either reduction or variability increase must lie within the *LACTE envelope.* This is illustrated in Figure 7.10. The right triangle formed by the horizontal axis and the two straight lines form the LACTE envelope. Moreover, the LACTE envelope represents the utopian LACTE curve, that is, the curve that would be developed for a factory in which there is no variability whatsoever.

As a final illustration of the development and comparison of LACTE curves, consider Figure 7.11. In this figure, the LACTE

FIGURE 7.10

LACTE curves and the LACTE envelope.

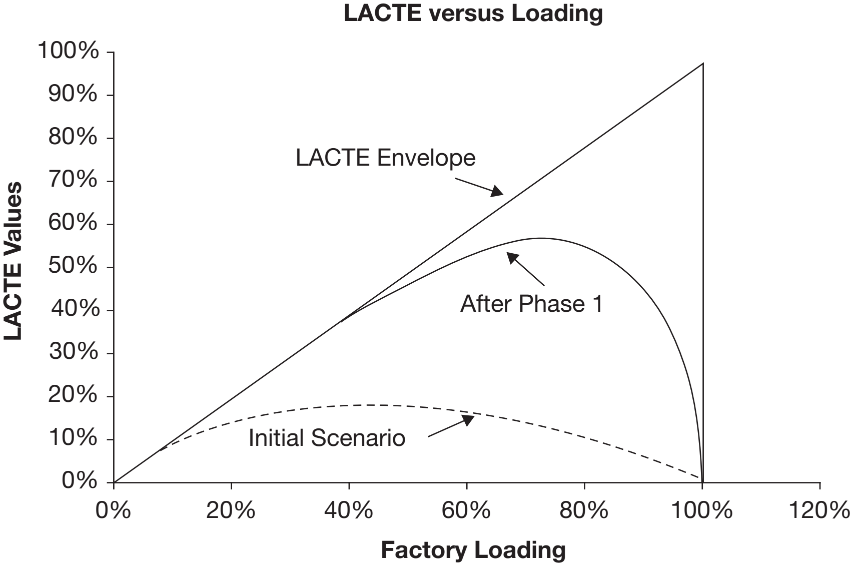
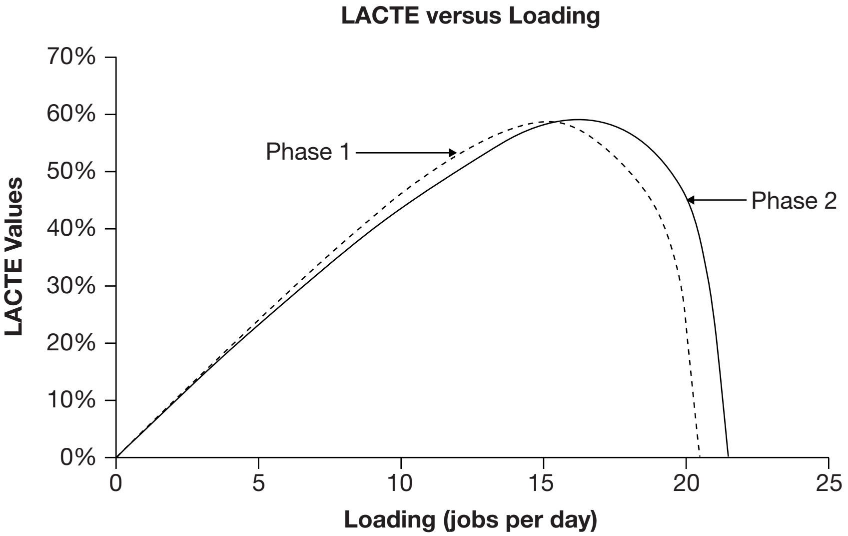


FIGURE 7.11

LACTE curves (after phases 1 and 2).



curve for the factory after phase 1 of the greedy heuristic (i.e., after reduction of variability) is compared with the LACTE curve after phase 2 (i.e., after an increase in the capacity of factory constraints).

It may be seen in Figure 7.11 that the upper bound on factory throughput capacity has increased (from 20.40 jobs per day to 21.41 jobs per day) as a result of the conduct of phase 2 of the greedy heuristic. Typically, phase 2 (i.e., increasing factory capacity) will not increase the peak value on the LACTE curve significantly but will move the LACTE envelope to the right (i.e., increase the upper bound on factory capacity).

FACTORY PROFIT CURVE

Some factory managers claim to want to minimize the cost of production. In fact, corporate-level management even may (and often do) provide their factory managers with a cost-reduction goal. If, however, cost reduction is truly the foremost factory goal, all one has to do to minimize cost is to stop production, lay off all personnel, and sell all assets charged to the factory.

Despite the obsession of some MBA programs, many companies, and almost all Wall Street analysts with cost reduction, any firm hoping to survive and prosper over the long run (e.g., such as

Toyota) must focus on increasing profit and market share. (This may require *increased* factory expenditures rather than reductions in cost.) To keep matters simple, I will focus herein solely on the goal of increased profit.

There is an unfortunate impression that profit is given by the following formula, wherein selling price and production costs are assumed to be constant:

$$\text{Profit} = \text{units sold} \bullet \text{selling price} - \text{units produced} \bullet \text{unit cost}$$

The fact is, however, that the selling price of a given product is seldom, if ever, constant. Instead, the price for which it may be sold typically decreases with time. (Consider, as just one example, the cost of large flat-screen television sets, DVD players, cell phones, and computer monitors.) Furthermore, the cost of manufacturing a product similarly is seldom, if ever, constant. Production cost typically decreases with time (e.g., as the bugs in the production line are worked out and as experience is gained by the workforce).

If the goal of a firm is, as it generally should be, to increase profit, then the factory loading for which profit is maximized should be computed. The factory profit curve serves to estimate that optimal level of loading. Derivation of the profit curve requires, as a first step, the development of estimates of profit over a given planning horizon.

Figure 7.12 presents the profit as a function of time curves for two different products, A and B. For sake of discussion, we will assume that product A is produced in a 12-workstation factory (designated as factory A) employing the configuration indicated in Figure 7.1 (i.e., the initial scenario of the 12-workstation factory). We further assume that product B is produced in a 12-workstation factory (designated as factory B) employing precisely the same configuration. It is clear from Figure 7.12 that the profit for product B decreases over time, at least initially, faster than that for product A. Our goal, then, is to determine the optimal level, in terms of profit, of factory loading for the two factories.

Simply by computing factory outs (i.e., the number of completed jobs leaving the factory) for each time period (or using a simulation model) and multiplying by the profit associated with that time period (i.e., from Figure 7.12), a graph of profit per factory loading may be easily derived. For the two factories and their two products, that graph is shown in Figure 7.13.

FIGURE 7.12

Profit versus time plots, products A and B.

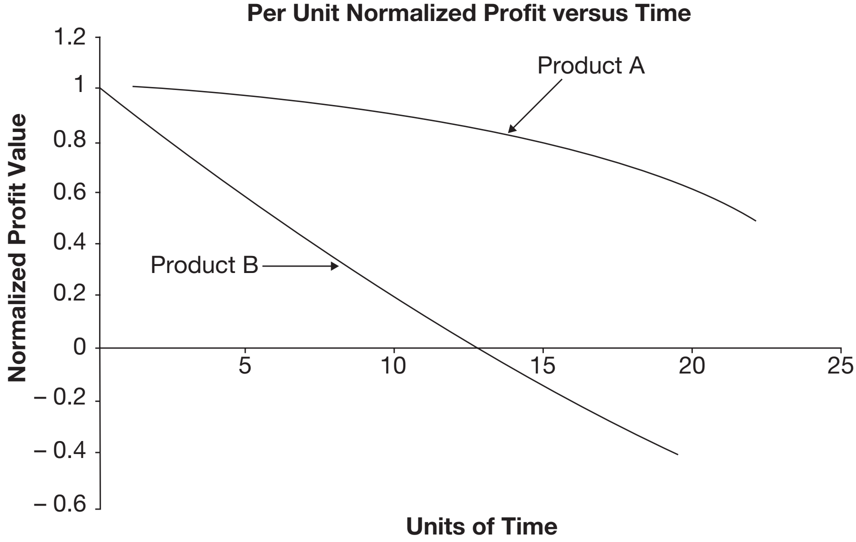
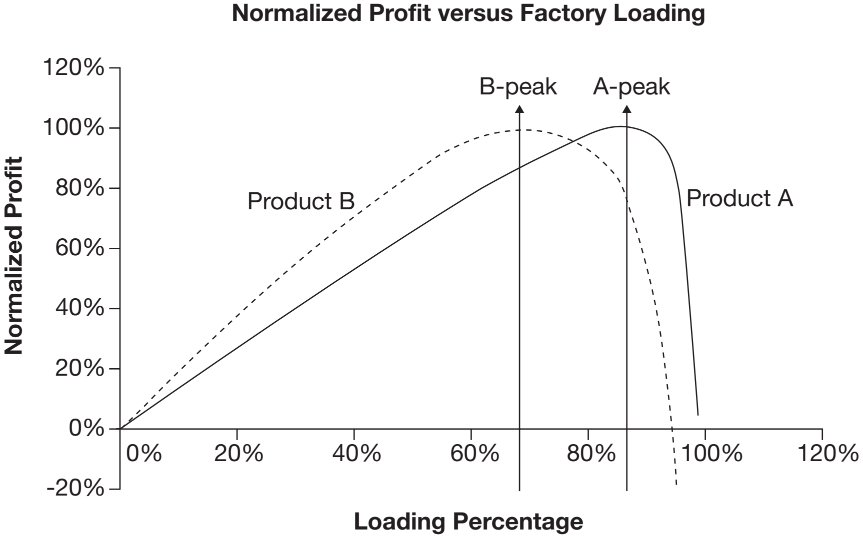


FIGURE 7.13

Factory profit curves for factories A and B.



From Figure 7.13 we see that factory A should operate at about 88 percent of its upper bound on capacity. Factory B, on the other hand, should operate at roughly only 67 percent of its upper bound on capacity. In short, if the goal is to maximize profit, a factory might, depending on its profit function, best achieve this goal by underloading the factory—a decision that may be considered blasphemous by some factory managers.

CHAPTER SUMMARY

In this chapter, three holistic factory performance curves have been presented. (These metrics are holistic in that they attempt to evaluate the entire factory system rather than its parts.) The first, the factory operating curve, has received previous attention elsewhere in the literature (Aurand and Miller, 1997). The other two, the factory load-adjusted cycle-time curves and factory profit curves, have not been published previously in the open literature (Ignizio, 1997). When these curves, particularly the factory load-adjusted cycle-time and factory profit curves, are introduced into real-world factories, management is provided with the information necessary to direct resources and effort toward the most productive efforts in terms of improving factory performance. This is in marked contrast to the performance measures used by some firms.

In Chapter 8, a number of other, somewhat lower-level factory performance metrics will be presented. In addition, the limitations of some commonly employed metrics (e.g., moves, utilization, inventory turns, work-in-progress turns, etc.) will be discussed.

CASE STUDY 7: IN THE HOT SEAT

Tommy Jenkins shifts his weight on the rock-hard chair. He desperately hopes that his anxiety isn't evident. He truly hates whoever the fiend might be who designed the straight-backed chair in which he is sitting. Marvin Muddle, his eyes as cold as those of a great white shark, stares at him from across his massive desk, waiting for a response.

"I'm confident," says Tommy without any confidence whatsoever, "that my factory is competitive with any other Muddle factory anywhere. We're well along with the *LEAN* Forward program, and I'm positive that this quarter's figures will show that we've reduced costs."

Marvin thumbs through the latest report on Muddle factory performance. Pointing his finger at a graph of cycle-time comparisons, he answers, "Tommy, this graph indicates that your factory has the worst cycle time of any of our factories. Your customers are complaining about how long it's taking for delivery of their orders. These graphs don't lie, Tommy, so how can you still say everything is fine?"

* * *

Ben Arnold and Donna Garcia shift uncomfortably in their chairs. Tommy Jenkins' face is tomato red, and the veins on his forehead seem ready to pop out of his skull.

"I want to know," Tommy hisses, "just why I've not been told the truth about our situation. I don't ever, ever want to be chewed out by our CEO like I was yesterday. Now, which one of you is going to level with me?"

Ben Arnold clears his throat and responds, "Tommy, you've seen the before and after photos of our factory's workplaces. The CANDOs performed on our workspaces have reduced clutter. Pictures don't lie. And, by cleaning up those areas, we've reduced recordable injuries. Maybe our cycle time hasn't been reduced as of yet, but I'm told that it's bound to be shortened within the next six weeks."

"I don't care what you've been told, Ben. I want you to promise me that our factory cycle time will be the best in the company. Can you do that?"

"Tommy," Ben replies, "I can't promise you that. I can only tell you that is what I've been told. I've …"

Donna Garcia interrupts, "Tommy, I can promise you that our cycle time will be the best in the firm. But it will require you to make a change in our factory starts."

Ben's eyes narrow. Tommy replies, "Why should I change our factory starts? You need to give me a damn good reason for that."

"Just give me a moment," says Donna, as she opens her laptop computer and places it on Tommy's desk. "I've got a copy of the slides that Professor Leonidas presented to the *LEAN* Forward team. I think you'll find one of them particularly interesting."

"How in the world did you get a copy of that man's slides?" asks Tommy. "Besides, you told me that his presentation was rubbish and that he spent the day bashing me and this company. So why should I even look at his slides?"

"First of all," replies Donna, "I had Ed, our safety and ergo director, divert the professor's attention before his presentation began. While Ed had his attention, I made a copy of the professor's slides on the conference room computer."

That's the girl, thinks Tommy. Our most recent slogan may be "*LEAN* Forward," but Donna realizes that our real slogan is "*Aufero absque dedecus*."

"Second," Donna continues, "while the professor did indeed bash Muddle, and you in particular, he did make a few interesting points." Advancing the slides, Donna stops at one labeled, "Factory Operating Curve."

"How did your name get on those slides?" Tommy asks. "I expected to see the professor's name on them and even a copyright notice."

"I had one of the nerds in IT unlock the protection on the slides. He removed the copyright notice and the professor's name," says Donna. "I thought you'd approve."

"Good girl," says Tommy. Ben nods his head in agreement.

"Getting back to this slide," Donna continues, "notice that you can reduce factory cycle time by a significant amount by means of only a slight reduction in factory loading—at least if your factory is operating as poorly as ours. So, as I see it, the best way to reduce cycle time is for us to reduce factory starts."

"But," Tommy replies, "how can I convince headquarters to allow a reduction in factory loading? We've already told them that our capacity is 10,000 units per week. And even that is probably an underestimate."

"I think I can answer that," says Ben. "Just tell them that the figures provided to us on the capacity of our factory constraint workstation were wrong. Tell them that our true capacity is only 9,000 units per week. I'd also recommend that we put the blame for this error on one of the junior people in the Factory 7 capacity group and fire him or her."

"What about you, Donna?" Tommy replies. "Do you think Ben's plan will work?"

"I agree with Ben. Based on what the professor said, I believe that we can wind up with the best factory cycle time in the entire firm within six weeks. There's also something else we might want to consider—the matter of Winston Smith."

"Winston Smith?" asks Tommy. "I thought we had got rid of that problem a long time ago. What does he have to do with our dilemma with cycle time?"

"If you recall," Donna replies, "we promised Julia Austen that we wouldn't fire Winston if she accepted the Muddle Fellow appointment. Of course, we also promised Winston that we wouldn't fire Julia if he stayed on and kept his mouth shut. Winston has kept his side of the bargain, but for the past few years he's been sending his ideas and recommendations for factory performance improvement to your office. I've seen copies of his e-mails, and some of his ideas should, I think, at least be looked into."

"I have no idea of what you are talking about, Donna," says Tommy. "I've never seen any correspondence from Winston. What about that, Ben?"

"As your technical assistant, I filter out your e-mails, particularly those sent by such riff-raff as Winston Smith. Frankly, I didn't see anything of interest in the garbage he's been sending," says Ben, defensively.

"I disagree," says Donna.

"Okay, so you two disagree on Smith's input," Tommy replies. "Let's leave it at that for now. What I want, though, is to follow through with *my* plan for reducing factory starts. Ben, have someone in the capacity group take the blame for the overestimate, and have the poor sap fired. However, if we haven't achieved the best cycle time in the company within six weeks, I just may have to think about getting a new technical assistant—and a new factory operations department head. Do I make myself clear?"

"Clear, boss," says Donna and Ben in unison. "But," Donna adds, "what about the ideas Winston Smith has been sending in? Shouldn't someone at least look into those?"

"Have your people read his memos," says Tommy. "I also want you to keep an eye on that man. Mark my words, you should never trust an Englishman."

With the meeting concluded, Tommy turns his back on Donna and Ben. As a consequence, he misses the wink that Ben gives Donna.

* * *

When he hears the door of his office close, Tommy Jenkins swings his chair about and gazes out his corner office window. He's learned a few things in his time at Muddle, one of which is not to trust anyone. This might explain why he asked, months ago, that Ben keep tabs on Donna. He followed that up with a confidential meeting with Donna, asking her to keep her eye on Ben.

You can never, Tommy thinks, be too careful. Now, he thinks, I should make up a list of potential candidates to replace those two, should they not come up with some way, any way, to reduce our cycle time.

* * *

Two days later, Jenny Chen, a junior member of the factory capacity group, enters the security gate of the office complex at a Muddle factory campus. Her arrival time is 7:30 a.m., precisely 30 minutes early, as has been her habit for the two years she has been dutifully employed by Muddle. Jenny is taken aback to find that the security gate will not accept her badge and further surprised when an alarm sounds. And she is even more concerned when a half-dozen security personnel rush to the gate.

"Ms. Chen," says a security officer, "it is my duty to inform you that you are no longer an employee of the Muddle Corporation. You'll find your belongings in that cardboard box over there," he adds, pointing to a box outside the entranceway.

"But why?" asks Jenny. "What could have possibly happened to cause my firing? Can't I please speak to my manager? There must have been some terrible mistake."

Before Jenny can ask another question, two members of the security team forcibly escort her from the building. As heads turn, wondering just what all the commotion is about, Ben Arnold arrives. A few seconds later, he is on the elevator, feeling no remorse whatsoever about his role in the firing of Jenny Chen. This is, he thinks, what he gets paid for—and why he loves coming to work.

CHAPTER 7 EXERCISES

1. The total process time of a factory is 10 days. Its average factory cycle time is 30 days. What is its cycle-time efficiency?
2. The manager of the factory in Exercise 1 claims that among all the factories in the firm, her factory's velocity is the fastest (i.e., its cycle time is the lowest). Provide a response, in 25 words or less, that might serve to change her confidence in that statement.
3. Explain, in 25 words or less, why the comparison of factories on the basis of point estimates of their *LACTE* values is incorrect.
4. The factory manager of factory B (with regard to Figure 7.13) believes that his factory should be loaded at the same rate (i.e., 88 percent) as factory A. Which one of the seven wastes of lean manufacturing is he exhibiting?