FACTORY PHYSICS FOR MANAGERS

How Leaders Improve Performance in a Post–Lean Six Sigma World

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To Meg, my one and only, Zachary, Madeline,
and Audrey—epiphanies to me. Every breath is a blessing.
May the Peace of Christ that passes all understanding keep your hearts
and minds in the knowledge and love of God.
—Edward S. Pound

To my wife, Julia; my parents; and the team at Arc Precision.
—Jeffrey H. Bell

To my wife, Blair, who for thirty years now has picked me up when I was low, has kept me humble when I was haughty, and has loved me always. And to my children, who have blessed me and taught me more than I have taught them: Jacob, William, and Rebekah; and to my grandchildren, a wonderful blessing, Alana, and Jake. And to the only wise God be glory forevermore through Jesus Christ! Amen.
—Mark L. Spearman

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FACTORY PHYSICS FOR MANAGERS

Prologue

THE BOOK IN BRIEF

How can executives and managers of manufacturing and supply-chain companies predictably achieve high cash flow, low cost, and excellent customer service? This book describes how forward-thinking managers use Factory Physics science to cut through the clutter and confusion of competing options. Typical management efforts currently lack any comprehensive, practical science and are almost always hit or miss. Managers commonly move from one initiative one year, such as "Reduce inventory!" to another the next year, such as "Improve customer service!" because they don't have a practical understanding of the underlying natural behavior of the operations they are trying to manage. Meanwhile, software companies are ever touting the next big initiative in software, such as materials requirements planning (MRP), enterprise resources planning (ERP), advanced planning and optimization (APO), cloud computing, and big data, to chronologically name a few, as if more advanced technology is the solution to whatever ails a company. Using *Factory Physics for Managers*, leaders will advance management practice and performance because Factory Physics science objectively describes what will work for them and what will not. The practical Factory Physics approach helps managers decide whether and when to use the excellent Lean, Six Sigma, and Theory of Constraints operations tools to drive company business strategy implementation while predictably and repeatedly achieving their business goals. Managers innovatively use Factory Physics science to drive higher performance using existing ERP or legacy information technology (IT)—no major IT investments required.

With *Factory Physics for Managers*, Ed Pound and Jeff Bell, executives each with over 20 years of experience in operations, and Dr. Mark Spearman, with over 30 years of experience in research and consulting and coauthor with Wallace Hopp of the world-renowned, award-winning textbook *Factory Physics* (Long Grove, IL: Waveland Press, 2008), describe the manufacturing and supply-chain management summit: a comprehensive, practical, and scientific approach to managing manufacturing and supply-chain operations. This approach directly addresses the inherent variability and risk in business. Typically, executives apply some bundle of popular initiatives, mathematics, and software—the results are unpredictable and often disappointing. This book provides a fundamental science in a very practical framework that will immediately improve executives' and managers' intuition, change how they view their world, and enable them to lead their organizations much more effectively.

WHY IS THIS BOOK NEEDED?

There is widespread confusion about what works and what doesn't work in manufacturing and supply-chain operations. As a result, operations strategies and plans often do not achieve what they promise. Software companies sell applications that just perpetuate what clients already do—regardless of whether or not the software does what the client needs. Lean proponents promote the Toyota Production System and its tenets in the vein of an operations theology. Six Sigma proponents insist on the rigorous statistical analysis required to identify and root out variability. Theory-of-Constraint adherents continue to focus exclusively on bottlenecks. In response to the uneven success of these efforts, Lean and Six Sigma proponents simply concatenate those two initiatives (Lean Six Sigma) in a continuing search for a comprehensive solution to achieve business results. Meanwhile, the academic community, and industrial engineering in particular, has lost its way. Many curricula teach the Lean and Six Sigma approaches but are following industry rather than leading. All this creates enormous confusion. What are executives or managers of manufacturing, service, or supply-chain companies to do in determining how to best lead their companies to achieve marketing and financial goals?

Wally Hopp and Mark Spearman, both with degrees in physics, had a firm grounding in the scientific method when they started as assistant professors in industrial engineering at Northwestern University in the 1980s. They surveyed the state of the field and wondered about a basic applied science and mathematical framework to describe operations. Most of the field was too deep and technical—operations research—or too unstructured and smacking of folklore—continuous-improvement zealotry—to be of good, sustainable use to manufacturing, service, and supply-chain executives. They set out to describe a fundamental, practical science of operations in a manner that would be useful to executives leading operations in support of a business's marketing and financial goals. One executive attending a nascent training session observed, "This is like physics of the factory," and the name Factory Physics stuck.

Messrs. Bell and Pound were students of Spearman and Hopp in Northwestern's MMM program in the early 1990s when the book *Factory Physics* was written. In 2001, Dr. Spearman left academia and devoted his time exclusively to industry and perfecting the science in practice. The authors have applied the principles relentlessly in companies large and small and have advanced the science to elegant leadership practices—both simple and effective. The result is the Factory Physics framework.

This framework shows that vague strategies such as "Eliminate waste" and "Reduce variability" are so general as to be nearly useless—except for companies that have done little or nothing for operations improvement. In the case of companies just starting their journey to systematically improve performance, there's usually so much waste and variability that merely focusing an organization's attention on those issues will generate good results. Beyond initial efforts, limited practical understanding of the Factory Physics science of operations often produces tremendous wasted effort and uneven results. Sound Lean and Six Sigma methodologies are often misapplied. Moreover, most manufacturing and supply-chain operations have high complexity as a result of product mix, process intricacies, and demand variability. This complexity cannot be handled effectively with simple Lean techniques such as value-stream mapping or 5S. Using simple techniques to handle complexity is like paying a financial advisor to tell you to "buy low and sell high." In addition, how does copying another company's best practices provide a *unique* competitive advantage? While the Toyota Production System works very well for Toyota and similar operations, there are better approaches for running a chemical plant or a job shop.

The Factory Physics framework enables managers to calculate risk and act decisively. They make operational decisions that are tuned to and inform their company's business strategy to ensure success in operations leadership. The strength of the Factory Physics approach is that it is based in science. It is not "initiative by imitation" or something managers think they might try because a friend, or colleague, or an industry analyst said that it worked somewhere else. Executives and managers reading this book will be inoculated against the lull of bland slogans through an improved knowledge of operations behavior from the practical science learned. The book will explore that science in a plain and uncomplicated fashion. It will discuss some of the math behind the science at a basic level (those interested can refer to *Factory Physics* for a more mathematical discussion). *Factory Physics for Managers* will take the concepts and apply them to the task of designing and executing operations control to achieve a company's business goals. The closed-loop control approach described for operations strategy and execution is fundamentally different from most, if not all, contemporary approaches. It will fundamentally transform a company's information technology practices from transaction tracking "financial ERP" to an integrated control system connecting executive strategy to day-to-day execution. Additionally, the book addresses the change-management challenges that every executive faces. After reading this book, executives and managers will be much better prepared to lead. They will have much improved intuition and be able to apply practical science to translate business strategies into operations tactics and controls—tactics and controls that can be executed with confidence to achieve a company's marketing and financial goals.

CHAPTER 1

Science—Use It or Lose

There is nothing more practical than a good theory.

—Kurt Lewin

"Oh, that is just a theory!" When we hear this, it usually means that the speaker thinks that the theory in question is not true and not useful. Indeed, the word *theoretical* has come to mean an idea that is not practical. The U.S. National Academy of Sciences' definition of *theory*, however, addresses this issue:

> *The formal scientific definition of theory is quite different from the everyday meaning of the word. It refers to a comprehensive explanation of some aspect of nature that is supported by a vast body of evidence. Many scientific theories are so well established that no new evidence is likely to alter them substantially. For example, no new evidence will demonstrate that the Earth does not orbit around the sun (heliocentric theory). . . . One of the most useful properties of scientific theories is that they can be used to make predictions about natural events or phenomena that have not yet been observed.*[1]

Interestingly, almost everything people do is based on some kind of theory—most aspects of which are intuitive. People intuitively believe that the floor will remain solid when they walk on it—that is a theory. Drivers intuitively believe that the car will slow down when they hit the brakes—another theory. If the brakes are broken, the theory is wrong, and the consequences can be severe. As the U.S. Academy of Sciences says, "The most useful property of a theory is *the ability to make predictions about natural events . . . that have not yet been observed*" [emphasis added].

But not all theories are good. Some are simply false. For instance, the theory that the Sun moves around the Earth is not true; instead, it is the other way round. Other theories may be true but really tell us nothing. These are known as *tautologies.* For instance, "All time in a factory is either value-added time or non-value-added time." This is just as valid as the statement, "All time in a factory is either spent in the cafeteria or not spent in the cafeteria." Because the truth of the statement is contained in the statement itself, it tells us nothing about the real world.

OF THEORIES AND BUZZWORDS

There are many theories about production management. However, managers usually don't argue about theories per se because they do not want to sound too theoretical; instead, managers often argue about *buzzwords*. Merriam-Webster online defines a *buzzword* as "an important-sounding usually technical word or phrase often of little meaning used chiefly to impress laymen."

However, some truly remarkable innovations occurred at the beginning of the twentieth century, before buzzwords became common. *Mass production* was developed by Henry Ford. *Scientific management* was pioneered by Frederick Taylor and Frank and Lillian Gilbreth. And by the 1930s, *quality control* became important with the invention by Walter Shewhart of the control chart. Interestingly, many of these innovations morphed into buzzwords once the use of the computer began to take off in the 1960s. The first was as manufacturing requirements planning (MRP), followed quickly by the more encompassing manufacturing resources planning II (MRP II), business resources planning (BRP), and others. The 1980s introduced just in time (JIT), total quality management (TQM), business process reengineering (BPR), flexible manufacturing system (FMS), and a host of other three-letter acronyms (TLAs) (see Table 1-1). In the 1990s, a new TLA appeared: the all-encompassing enterprise resources planning (ERP) system. The 1990s also introduced two new buzzwords that were not TLAs and, given that they are still on the scene today, have had great endurance—*Lean* and *Six Sigma*. Indeed, given the success of Lean and Six Sigma, they are more like the historic initiatives of the early twentieth century than like the buzzwords of the 1980s and 1990s. What makes them different?

Lean took the best of JIT and combined it with practical methods such as value stream mapping (VSM) and 5S. Numerous "how-to-do-Lean" books made Lean more than a buzzword—it became a

TABLE 1-1. Examples of Three-Letter Acronyms

TLA	Full Phrase	Description
MRP	Materials Requirements Planning	Computer software for production planning and control
MRP II	Manufacturing Resources Planning	Next generation MRP
BRP	Business Requirements Planning	Another extended version of MRP
FMS	Flexible Manufacturing Systems	Highly automated production system that can switch to different products quickly
BPR	Business Process Reengineering	An approach for redesigning work processes
JIT	Just In time	A production management approach for quick delivery
TQM	Total Quality Management	Management approach to improve quality of products and processes

phenomenon. Today, Lean is being applied in everything from factories to offices and even hospitals; the participating organizations perform scores, if not hundreds, of *kaizen* events (improvement projects) each year.

The other methodology with staying power has been Six Sigma. A common saying before Six Sigma was "KISS—Keep it simple, stupid!" But Six Sigma dismissed this axiom, recognizing that manufacturing systems are anything but simple and sometimes require a more sophisticated approach. That Six Sigma unapologetically applies extremely sophisticated statistical methods shows how far management has moved from KISS. Like Lean, Six Sigma has become almost universal, with most companies having trained numerous *black belts* (a more captivating name than "statistics expert") and performing hundreds of Six Sigma projects each year. The fact that Lean Six Sigma is now being used by the U.S. Department of Defense and other government agencies indicates how ubiquitous it has become.

If you are looking for the next great buzzword, this book is not for you. If you are looking for a book that will tell you when and why Lean and Six Sigma work well as well as when and why they will not work, then read on. If you are looking for a book that allows you to understand the basic principles of production and supply chain so that you can design a management system that may or may not look like Toyota or Apple but is uniquely suited for *your* particular business environment, read on.

While we appreciate and strongly support the appropriate use of Lean and Six Sigma techniques, no matter the label, we have found that Lean and Six Sigma approaches do not provide a *comprehensive* theory for managers to use in charting a course for business performance. Additionally, there are some principles of Lean and Six Sigma theory that consider neither the reality of the business environment nor the natural behavior of production/inventory systems. Very often, Lean practitioners consider the Toyota production system with its focus on achieving one-piece flow as the *end* rather than as a *means* to the ultimate end which is long-term profitability. Likewise, Six Sigma will assert that all variability is "evil" and that it should always be as low as possible. History shows us that this is not always a good approach.

Compare the strategies of Henry Ford and Alfred P. Sloan. Ford produced a single model of automobile (Model T from 1908 to 1927) offered to the customer in "any color he wants so long as it is black."[2] Ford was a fanatic about driving variability out of production. In 1921, GM had been a distant second to Ford with 12.3 percent of the market compared to Ford's 55.7 percent. Sloan became president and CEO of GM in 1923 and set a goal to provide "a car for every purse and purpose" thereby greatly increasing the variability in the GM supply chain. But the strategy worked, and by 1929 GM had eclipsed Ford in the market, later becoming one of the largest corporations in the world.[3]

Unfortunately, the methods that enabled Sloan to create one of the world's largest corporations sowed the seeds of its own destruction. GM's centralized management and focus on finance made it appear profitable when it was not. Moreover, the strict requirement for a positive return on investment (ROI) prevented GM managers from seeing the need to implement changes that would be required to exist in a market that offered better cars for less money. In this case, the return on investment was necessary for survival. But after years of increasing profits and market share, hubris set in, and the question of survival was never raised.

Moreover, it is not because GM did not embrace Lean that it failed. Indeed, GM not only embraced Lean, but, in a somewhat ironic twist of fate, is listed as an example of "Lean Manufacturing and Environment" under the "Case Studies and Best Practices" website of the U.S. Environmental Protection Agency.[4] Nonetheless, on June 1, 2009, after almost 101 years, Alfred P. Sloan's GM ceased to exist. GM declared bankruptcy, and all shareholders were essentially wiped out. The new GM was owned by creditors, the largest being the U.S. government. Today, the "new" GM is back on its feet after the U.S. Treasury sold its last remaining shares in December 2013. Whether it withers or flourishes will depend on how well its management understands the underlying principles of automobile production and marketing.

One problem facing the new GM and most managers in any large corporation is a constant need for action. This need breeds new "initiatives" whether they are appropriate or not and leads to a flurry of activity. The new activity often diverts attention from the fundamental problems rotting a company's financial core. The Factory Physics approach avoids such activities by focusing only on those that are directly related to cash flow, customer service, and long-term profitability and by considering the tradeoffs among these.

Continuous improvement programs can be quite powerful, but simply having activities labeled as "continuous improvement" does not make a company successful. Next we consider one of the most successful (and long) continuous improvement programs in history—the Toyota production system. A scientific analysis of the Toyota production system provides a peek behind the curtains of folklore that have been laid over the secrets of Toyota's success.

TOYOTA AND SCIENCE

Toyota is the archetype of Lean. In the 1960s and 1970s, Toyota was a car company that competed by producing inexpensive cars. However, quality was not a strong point. In a 2007 article in *Automotive News*, Max Jamiesson, a Toyota executive in the 1970s and 1980s, provided the following assessment:

> *"Back then, the car was a piece of junk." When he left Ford Motor Co. for Toyota, his Detroit colleagues made jokes about Toyota being little more than recycled beer cans. They weren't far from wrong, Jamiesson admits.*
>
> *He recalls that Toyota engines back then would "grenade" at 50,000 miles, and the brake pedal would "fold into the floor." At high altitudes, Toyota carburetors needed to be propped open with Popsicle sticks,*

or the engine would starve from insufficient air-fuel delivery. But the exterior fit and finish was [sic] *good.*

"The outside of the car was like a show car," Jamiesson says. "All the lines and tolerances were perfect, so that when the salesman showed the car, it was beautiful. And the interiors were great, too. So we told Japan, 'This is great; it shows we can make a quality car. Now make the rest of the car like that.' The rest of the things need to function."[5]

From this inauspicious beginning, Toyota transformed itself into one of the most successful companies in the world and has offered one of the best-selling cars in America, the Camry, for nearly three decades. Those of us old enough may remember the saying from that earlier time, "Cheap stuff . . . made in Japan." Toyota played a huge role in changing that perception.

How Toyota Did It

So how did Toyota do it? One of the first things was to take a scientific approach and recognize that the manufacturing environment itself was not a static given but could be *changed*. Like Einstein, who rejected the notion of a fixed space and time, Taiichi Ohno and Shigeo Shingo rejected the notion that the mass-production practices of their day were the best practices possible. Instead of seeking to find the optimal lot size for a given setup time, they sought to reduce setup times until the optimal size was *one*! Indeed, "one-piece flow" became a hallmark of the Toyota Production System (TPS). This idea of focusing on the details of the environment was applied to such an extent that Toyota's 5S process for making an operation clean and organized became an important part of TPS implementation. Toyota recognized that controlling work in process (WIP) with supermarkets (i.e., *kanbans*) and measuring output (i.e., *takt* time) worked better than trying to control output with a schedule and measuring WIP. Toyota also recognized the precedence of quality before production. An operator could stop the line if bad parts were being produced. "If you do not have time to do it right the first time, when will you find time to do it over" is a pithy aphorism that hits at the heart of this concept (and the basic concept of Six Sigma as well). Finally, Toyota empowered its employees to redesign workplaces over and over again until they found the most efficient configuration for the given task.

While these steps sound simple, and perhaps even obvious in hindsight, it is important to realize that while Toyota was perfecting its production system, equally "obvious" and *opposite* steps were being pursued in the United States. Ohno began developing Toyota's system in the late 1940s and continued to perfect it into the 1970s. Thus, while Toyota considered *overproduction* to be a key waste, Detroit was happily pursuing mass production as the key to reducing costs. Long runs of millions of automobiles were produced by U.S. automakers in the belief that if the inventory did not sell when produced, it would eventually move when discounted at the end of the model year.

Given the results, it seems clear that although Ohno and Shingo never described the TPS in *scientific* terms, they understood the behavior of production systems at a very basic level. Shingo described practices in extremely poetic and flowery terms, for example, "The Toyota Production System wrings water out of towels that are already dry."[6] This description is catchy but difficult to implement.

Many managers read about the almost miraculous results obtained by Toyota and are eager to put in a similar system and reap the rewards. They are often disappointed when they cannot achieve the same results in a few months. What they do not realize is that Toyota perfected its system over a period of more than 25 years. Of course, with the plethora of Lean literature available, one should expect results more quickly than that. Even so, it is likely that the journey will require a sojourn through the desert before reaching the Promised Land. For instance, if the production environment produces poor-quality products, the line will stop quite frequently as a manager begins to implement the TPS practice of stopping the line whenever there is a defect. This means that a defect that causes a problem for one station in a 10-station assembly line stops the *entire line* for some period of time. This can amount to a great deal of downtime.

Obviously, any lost time to address quality problems must be made up. One way Toyota did this was to schedule 10 hours' production into a 12-hour time slot. In this way, an extra 2 hours were available, if needed, for stopping the line, and yet the line could nearly always achieve its daily requirement needed to meet demand. Stopping the line was not costless. Toyota paid for its quality focus by paying for more capacity than it actually used. In contemporary parlance, this is called "undercapacity scheduling."[7]

While this sounds like a great deal of extra time, a 2-hour makeup period for a 10-station line absorbs relatively few stoppages. If each station had only one problem per hour and this problem could be remedied, on average, in 1 minute, the time lost on a 10-station line would be 2 hours for every 12 hours of production. This is exactly the makeup period that was described in Schonberger's best-seller of the 1980s, *World Class Manufacturing* (New York: Free Press, 1986). Producing for 10 out of every 12 hours yields a capacity utilization of 83 percent. If one line could not meet demand working 83 percent of the time, another line or overtime (with all the attendant expenses) would be required. But Toyota recognized that by allowing line stoppages for quality problems, the tension created would motivate people to eliminate the root causes of the line stoppages and thereby require fewer shutdowns and less makeup time. For a company just beginning its Lean journey, we would expect to see more issues per hour, and most would take more than 1 minute to resolve. Thus 2 out of every 12 hours represented world-class performance, which is why Schonberger reported it in his book.

The other hallmark of the Toyota Production System, one-piece flow, also comes with a cost. While one-piece flow results in minimum WIP and minimum cycle time for a given output rate set by the *takt* time, it requires additional makeup time. (We use the term *cycle time* to indicate the time required to produce a part from raw stock until completion. Other authors may use cycle time to indicate the process time on a machine. We prefer to call this *process time* and recognize that other authors may use such terms as *production time*, *throughput time*, *flow time*, and even *sojourn time* to mean what we are calling *cycle time*.) Indeed, if one watches an automotive assembly line operate for any length of time, one will typically see workers complete their tasks and have time to stand back and wait for the next vehicle. Unlike the two extra hours of makeup time used to accommodate line stoppages as a result of quality defects, these few seconds of makeup time are used to accommodate the variation in the task times.

For example, suppose that the demand for the Camry is 600,000 units per 250-day year. This translates to 2,400 units per day or 1,200 units per 12-hour shift. For a manager scheduling the line to work 10 hours each shift, the *takt* time will be 30 seconds ([10 h × 3,600 s/h]/1,200 = 30 s). This means that the time available at each workstation is 30 seconds. However, if the line's manager adds enough workers to the line so that the *average* task time is 30 seconds, there will be trouble. If the average task time is equal to the *takt* time, a station worker will be able to complete the task within *takt* only 50 percent of the time. This means that as the line continues moving, the worker will have to continue working into the next workstation, thereby disrupting that worker's work.

There are two ways to avoid such problems: (1) stop the line every time a worker faces a task that takes longer than the average or (2) set the *takt* time to be somewhat longer than the average task time. Thus, in the first case, the line will move at the pace of the slowest worker and will stop from time to time. However, if a manager uses the second option and sets the *takt* time to be somewhat longer than the average, some extra time is allowed for each station, thereby providing a very regular output for the entire line.

Now consider the histogram of task times in Figure 1-1 showing the distribution of times for tasks on an assembly line. About 5 percent of tasks take less than 20 seconds, 45 percent take from 20 to 25 seconds, another 45 percent take from 25 to 30 seconds, and the last 5 percent take more than 30 seconds. The average is 25 seconds, and the standard deviation is 3 seconds. Therefore, if the *takt* time of the line were set to 30 seconds, 95 percent of tasks would be completed in the time allotted. The workers should be able to deal with the 5 percent of occurrences that take longer than 30 seconds as long as they do not all happen at the same time.

While 5 seconds does not sound like much, the extra time adds up. Moreover, performing a 25-second task in a 30-second *takt* time is equivalent to having an extra 2 hours available for each 10 hours

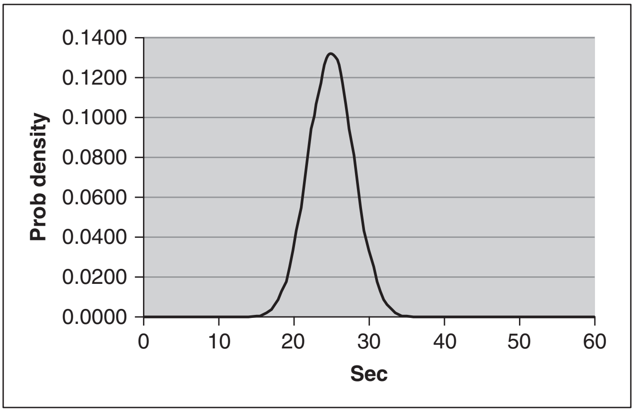

FIGURE 1-1. Histogram of task times

of production because 25/30 = 10/12 = 83.3 percent. And since managers commonly employ the first method for long disruptions and the second for variations in task times, this results in useful production time from less than 70 percent of the scheduled production time ($0.833 \times 0.833 = 0.694$). This means that for a 12-hour shift, a manager gets around 8 hours and 20 minutes of productive time, not including lunches, breaks, and shift changes. In this case, if the manager scheduled workers to cover lunches and so on, the result would be around 1,200 parts produced per shift, the amount needed to cover demand.

Batch and Queue Production

On the other hand if a manager uses a different line control approach by decoupling the line and allowing WIP to flow freely and accumulate between processes, the system would run at the rate of the slowest process, that is, one part every 25 seconds (plus the extra minute once per hour). In this case, however, when one station had a problem, other stations could continue to run as long as there was WIP. Now, what about those disruptions? Recall the 10-station assembly line having, on average, a single 1-minute disruption per hour. Over a 12-hour period, this would add up to 2 hours of disruption time (2 h = 10 stations × 12 disruptions each × 1 h/60 min), and this is what was planned. However, if the stations of the line have been decoupled, each station only "sees" its own disruptions. The production time now would be 11 hours and 48 minutes (losing only 1 minute per hour per station), and the production rate would become around 1,700 parts every 12 hours. This means that the decoupled line produces 41 percent more than the line with one-piece flow.

But, again, there is a cost! The extra production was achieved by allowing a great deal of extra WIP above what would be required for one-piece flow. The extra WIP entails a longer cycle time to get through the line. The one-piece flow line takes 5 minutes to produce a part (10 stations with 30 seconds per station). If the decoupled line has 5 units of WIP for each station, the cycle time grows from 5 to 25 minutes. If the WIP required were 15 units, the cycle time would be 75 minutes. The problem with all this WIP is that it hides problems. The line can happily run *with* the problems, and there is no need (much less urgency) to eliminate them. Moreover, if bad parts start being produced at the first station and they are not discovered until the last station, then the line has just produced 150 units of *scrap* or *rework.* A line with such a high scrap (or rework) rate can easily end up with productivity levels below that for one-piece flow despite all its makeup time.

A Balanced Approach

Fortunately, one-piece-flow and unlimited WIP are not the only options. There is a middle way. If a manager limits the WIP at each station, the decoupled line's productivity is only *slightly* reduced while retaining the ability to quickly detect problems when they occur. What should this WIP limit be? As usual, "It depends!"

It depends on how much *variability* there is in the system. Variability will be an important concept in this book and will be discussed in more detail later. Any variability in production time or part quality will have a negative impact on productivity. This doesn't mean that all variability is bad—more on this later. However, a little extra WIP can greatly buffer variability, thereby increasing productivity without overtly increasing cycle times or substantially hampering defect detection. The key is to understand how throughput is related to WIP and variability—and this is one of the major insights of Factory Physics science.

THE TRACK RECORD: LEAN AND SIX SIGMA

While Lean and Six Sigma have seen tremendous success in reducing waste and improving profits in many companies, success is not always ensured. Indeed, a recent *Wall Street Journal* article indicated that 60 percent of Six Sigma projects did not yield the expected benefits.[8] The record for Lean is worse, with only 2 percent of projects achieving their anticipated results.[9] The low hit rate for Lean projects may be due, in part, to the huge number of *kaizen* events (i.e., improvement projects) that are attempted by many companies. Another reason is that Lean promotes improvement by imitation. "This is what Toyota did, so this is how you must also do it!" Managers do not understand how the TPS works, only that it worked for Toyota. Then they apply it to a business very different from Toyota's, and it does not always fit.

A CONFUSED LANDSCAPE

While many people understand the basic relations of accounting and finance, too few similarly understand basic relations found in production and the supply chain. Everyone understands that if revenue increases with no increase in costs, profits will rise. When we ask our seminar participants to describe the basic relation between the time it takes a part to move through a factory and the number of parts within that factory, less than 1 percent have been able to do so correctly. We have observed a similarly low percentage among university researchers, the analysts (e.g., Gartner, Forrester, Solomon, and others) and the vast majority of consultants. Why is this? It is certainly not because these people are stupid. It is because these relations are seldom taught either in universities (that have not adopted *Factory Physics*) or in short courses. *Factory Physics for Managers* seeks to remedy this deficiency.

This lack of basic understanding results in much confusion. We call it *Newton's third law of experts*: For every expert, there is an equal and opposite expert. For every Lean consultant espousing the benefits of level production, there is an information technology (IT) salesman pitching advanced planning and scheduling (APS). Even among Lean experts, there is little agreement on how the science of the TPS works. Ask a room full of Lean masters to describe what makes a pull system a pull system, and you will get a room full of different answers. Even the definitions given by the Lean Enterprise Institute (LEI) and the American Production and Inventory Control Society (APICS) do not agree—nor do they make sense. The classic definition is given by the founder of LEI, James Womack, and spelled out in his book with Dan Jones, *Lean Thinking* (New York: Free Press, 1996).

> Pull *in simplest terms means that no one upstream should produce a good or service until the customer downstream asks for it.*

But this definition is quite different from that offered by the dictionary produced by APICS:

> *Pull: (1) In production, the production of items only as demanded for use or to replace those taken for use. (2) In material control, the withdrawal of inventory as demanded by the using operations. Material is not issued until a signal comes from the user.*[10]

The Womack definition implies that pull systems are essentially make-to-order systems. The APICS (production) definition is vague. The first phrase, "productions of items only as demanded," is similar to Womack's definition (i.e., make to order), whereas "replace those taken for use" suggests a supermarket or a make-to-stock system. Meanwhile, the APICS material definition is rather tautological because "issuing material" inventory and "withdrawing inventory" are essentially the same. That the definitions by the two expert organizations in the field are so different is very troubling in and of itself. More troubling is the fact that if managers were to choose one or the other, they are faced with the question, "What is the big deal?" Make to order and make to stock have been around for more than 60 years.

In our opinion, a bigger deal is that both organizations appear confused regarding the science underlying what they label as a pull system. Otherwise, they would not describe it using the same terms as those used to describe make-to-stock and make-to-order systems, which have been around for many years, because the pull concept *is essentially different* from both make to order and make to stock.

In Chapter 3 we will show that WIP control provides a way to achieve minimum cycle time with maximum throughput, regardless of its label. Neither of the preceding definitions discusses WIP control as a way to control performance. Both definitions state that producing or using only what is demanded is the defining characteristic of a pull system. If a million customers asked for a part at once, either definition requires an attempt to produce all 1 million parts at once. The classic pull implementation known as *kanban* does limit the amount of WIP of each part to the number of production cards (be they physical cards or electronic ones). The benefits are shorter cycle time, less WIP, and a stable flow. While *kanban* is the best-known method, the limiting of WIP can be done in many ways. After we describe the dynamics of production systems, it will become clear that classic *kanban* (the original pull system) is overly restrictive, and we will describe a way that is much simpler and more applicable to complex environments such as those with low volume and a high (and changing) mix. Finally, the use of a pull system often becomes an end in itself in many Lean implementations. This loses sight of the fact that the goal for a business is to sustain high profitability over the long term, not implement pull.

Many more things are confused besides the definition and purpose of pull. For instance, many people believe that increasing capacity at bottlenecks will result in greater output of the factory (not always true). Others believe that reducing cycle time will increase output (not true). Line balancing is the idea of setting up all stations in a line so that they have the same levels of capacity, and many believe that line balancing will minimize costs (also usually untrue). It is not surprising that such beliefs are held—production *seems* relatively simple, and these assertions *seem* intuitively true.

The problem is that most people's manufacturing, service, and supply-chain intuition is based on what happens *on average.* People understand mean effects. But when variability becomes the issue, their intuition is much worse. Why is this? *Because there has never been an adequate science of operations* or, in other words, a *theory* of operations that managers can use to reliably predict the results of actions before the actions are taken. Factory Physics science provides a remedy to this problem by providing a practical set of theories that have been tested and validated through relentless analysis and practice.

We believe that basic knowledge of the way production and inventory systems behave should be a prerequisite for anyone seeking to design, control, or manage such a system. This does not mean that the manager or vice president needs to have a Ph.D. in industrial engineering or logistics, only a keen intuition about how such systems behave. Managers should know the relationships between WIP, cycle time, throughput, variability, and capacity in an intuitive way. They should appreciate the importance of using a computer to model the process because it is better to experiment with a model. With a valid model, many options can be tried quickly to see which works best. Conversely when experimenting with the actual production of service operations or a supply chain, mistakes are frequently career-limiting. The purpose of this book is to teach managers and executives these basic relationships so that they can make better decisions. If you remain unconvinced, consider what happens when a large company attempts innovation by imitation—setting a huge project into motion because that is the way Toyota did it.

Boeing's Moving Assembly Line

Boeing's creation of a directly coupled moving assembly line to produce its 777 jet airliner was a huge mistake. This view may be a bit controversial. Boeing has made presentations around the country extolling its accomplishment of this impressive *technological* feat. Our contention is that although it is technically impressive, it did not make business sense, and the results obtained were available using much less flashy and *much less* expensive methods. Moreover, by blindly copying Toyota, Boeing not only spent a great deal of money but also was shut down for long periods of time during a period of peak demand. While we are big admirers of Boeing as one of the world's leading aerospace companies, this particular decision was ill-advised. Executives at large companies such as Boeing make decisions with big and expensive consequences. The 777 moving assembly line story provides an example of why a solid, fundamental understanding of the science behind operations is vital—especially for executives.

We begin in March 2007, when two of the authors attended a conference where the keynote speaker was from Boeing. His talk, "Transformation of a Factory—The 777 Moving Line," had created quite a buzz. How would such a line work? Planes are not cars. One might roll a car off an assembly line every 30 or 45 seconds, but the *takt* time for an airplane is three days.

Of course, putting a 777 on a moving assembly line was not easy, but then the Japanese consultants Boeing had hired never said that it would be easy. They only said that, "It must be!" because their contention was that a company could not be lean without a moving assembly line. Boeing management was not only going to make Boeing lean, but Boeing was also going to be a Lean leader. Already Boeing was teaching its suppliers to become leaner. Ohno had defined seven forms of waste (or *muda* in Japanese), and Womack and Jones had added one more to make it eight. By 2001, Boeing had defined ten. The search to eliminate waste became a way of life, and much waste had been discovered and eliminated, leading to great productivity increases.

The implementation cost for the 777 moving assembly line turned out to be around $250 million (from 2006 to 2007), plus the lost revenue in shutting down the plant several times for a number of weeks. It was also not easy. The first attempt was in 2006, but there were problems. A moving stand had to be created for access. Standard heights had to be established and implemented. Several plant modifications later, the line began moving in 2007, just in time for the conference. Boeing provided the following explanation on its website for why moving assembly lines are a good idea for planes.

> *Moving assembly lines, and the accompanying Lean techniques, enable a smooth, continuous production flow, enhancing the quality and efficiency of production processes. The line is stopped when an abnormal condition occurs. Stopping the line is the visual that tells us an abnormal condition exists and needs to be quickly addressed. In addition to reducing flow time and production costs, moving assembly lines also create an environment that makes it easier for employees to do their jobs. All the tools, parts, plans and work instructions are delivered to employees so they have everything they need where and when they need it.*

The only problem with this explanation is that the line moves at an average rate of 1.8 inches per minute. In practice, it was not a continuous movement, but the line was periodically pulled forward. This meant that no one would notice for quite a while if the line were stopped. Thus one of the key benefits of a moving assembly line was lost from the beginning.

One of the key results reported at the conference was a reduction of square footage of 72 percent. But then there was a question from the audience—by how much time was the 777 assembly cycle time reduced? "It used to take 50 days to complete one 777—we have reduced that to 48 days." It was clear that divulging a meager two-day cycle-time savings was an awkward moment for the speaker. On a break, we were chatting with the speaker and asked for additional information in an attempt to further understand the tradeoffs of the endeavor. We said, "Our understanding is that the greatest variability in process time for plane assembly is due to the type of seats that are installed. A plane for a budget carrier having basic seats will take much less time to install than one for a plane with first class, business class, and basic seats. What did you use for the *takt* time?" The speaker replied, "Well, we tried to use the average but, as you might expect, that did not work too well. So we ended up using the longest *takt* time."

So an evaluation of the implementation's effectiveness must include

- Cost of $250 million to modify the plant
- Lost revenue while the plant was shut down
- Reduced throughput to enforce the longest *takt* time required for the most complex of the 777 models

This was an example of what one wag calls, "Type III error—solving the wrong problem." Cycle-time reduction was not the issue.

More throughput—making more planes—was the issue. By installing a moving assembly line that had to accommodate complicated planes as well as simple ones, Boeing reduced the output of the 777 plant. While it is impossible to correlate directly, during 2007, the company's total backlog grew from $250 billion to $327 billion, the largest increase since the company began reporting the statistic.[11] Coincidental or not, implementation of the moving assembly line occurred at a time when demand was very high for Boeing.

This was 2007. By 2009, Boeing was reporting better results[12]:

- Factory build-time reduction: 24 percent
- Factory unit hours: 34 percent
- Inventory turn rate: 71 percent
- Lost-workday case rate: 37 percent

We are not sure how they went from a 4 percent reduction in cycle time to a 24 percent reduction, but, again, cycle time is not the point, and the 2009 description provided no indication of an increase in throughput. The *takt* time remained at one plane every three days.

More recently, Boeing has made improvements to the line and has significantly reduced the *takt* time to 2.5 days and thereby increased throughput by 20 percent. How did Boeing do this? A 2012 blog on the *Aviation Week* website described the following changes:

1. Made process improvements such as automated "flex track systems" that fit on the airplane and drill holes more accurately and faster than a human worker can do
2. Prebundled and preinstalled the wires in a stand that goes directly into the cockpit instead of installing individual wires on the assembly line
3. Changed the design to allow wiring subassemblies to be made offline and then inserted in a fraction of the time required previously[13]

Perhaps it was necessary to have the plane moving on an assembly line to highlight the need for these improvements, but we think not. Preparing subassemblies offline essentially removes tasks from the critical path by doing them in a parallel operation. Another benefit publicized by Boeing at a 2013 conference, which two of the authors of this book attended, was that installing a moving assembly line enforced the production discipline needed to be more productive. Again, enforcing good management practices does not require a moving assembly line. Interestingly, Boeing had already been extremely successful using decoupled assembly lines and offline subassembly to increase the rate of B17 production back in World War II.[14]

The fact that it took six years to implement the 777 moving assembly line, not to mention the huge cost of implementation, shows how important it is to perform improvements based on a theory that can "make predictions about phenomena that have yet to be observed" and not because "that is the way Toyota does it."

Remarkably, Boeing is not using a moving assembly line to build the new 787 Dreamliner.

LOOKING AHEAD

This book is about increasing your knowledge and, more importantly, your intuition. Consequently, Factory Physics should not be a buzzword although that will not prevent some from trying to make it so. Indeed, that is a danger that we often warn our clients about. We recommend against using the classic company-wide rollout of a Factory Physics "initiative." Not everyone in the company needs to master Factory Physics science. Certainly the concepts should be taught at an appropriate level when implementing design changes to production or inventory control processes. Those involved in changes identified through application of the science should have at least a cursory understanding of why the changes are being made and an opportunity to provide feedback. The great thing about this approach is that it's highly objective. Combined with a genuine appeal to the intelligence of the average worker, the Factory Physics approach works well because people like doing things that make sense. If someone can objectively show that one of the concepts does not make sense, something has been learned and the science advances. Factory Physics science is not the "next best thing." It represents the underlying principles of whatever "best thing" you are currently using and is the knowledge of the next best thing you create for your particular business.

The remainder of this book will describe Factory Physics science as a comprehensive, practical science of operations for managers. Using this science will enable managers to design, implement, and control a production or service system uniquely suited to their particular business—while avoiding the pitfalls of initiatives by imitation, buzzwords, and poorly defined or bad theories. To do this, we begin with the most basic business goal—to make money now and in the future. The goal should be achieved through moral means and to noble ends, but if a company does not make money now and in the future, it jeopardizes any noble ends its owners and employees desire. We will describe the inherent conflicts between sales and operations that arise in most businesses in pursuit of the most basic goal. We seek to resolve these conflicts not by making them go away (because they will not) but by providing a means to establish an integrated *strategy*. By *strategy*, we mean to plan where to operate in the cost, inventory, and customer service constraint space that makes the most money. We will develop this strategy definition as we introduce new concepts. We then will describe how to translate such a strategy into real-world *tactics* that achieve the strategy. Finally, we will describe a groundbreaking approach to execution that establishes *controls* and *measures* to show when the business is in control and when it is out of control. Only when it is out of control do managers need to make adjustments. The result is a much more stable operations system that achieves its strategic objectives in the face of demand variability, production complexity, and product complexity *and* is easier to manage than most contemporary approaches.

In later chapters we address leadership and change-management issues. Throughout this book, we provide examples from a number of different industries and from large and small companies. Finally, we provide a recommended approach for readers to use in implementing the Factory Physics framework in their particular companies and examples of companies that already have implemented the Factory Physics framework. Using the recommended approach and studying these examples will give any manager the ability to (1) design a production and supply-chain management system uniquely suited to his or her particular business and (2) drive predictable, significantly improved performance.