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Beyond Lean: Production and Inventory Policy for the Old Economy

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ABSTRACT

Lean manufacturing has fundamentally changed the way business leaders think about the production of manufactured goods and services. Over the past three decades, firms have dedicated considerable resources to reducing production setup times, shrinking inventories, and organizing work into cellular flows. Discrete parts manufacturing has benefited from production planning schemes that smooth production and level-load the plant to reduce idle time and overtime. But in the process industries, where production occurs 24 hours a day, seven days a week, what does it mean to level-load the production facility? In those industries, capacity stabilization is defined as creating production cycles that are predictable, and level-loading consists of stabilizing manufacturing lead times. In this article, we describe the differences between what we call inventory-centric versus capacity-centric modes of production and inventory control, and we present data collected from a large chemical plant operation that illustrates a mismatch between inventory policy and capacity characteristics. We also describe policies appropriate for old economy firms in the face of increasing consolidation and pressures to reduce costs and increase responsiveness.

Keywords: lean, inventory management, process industries

INTRODUCTION

The art and science of industrial manufacturing has changed dramatically over the past 70 years. In the early 1950s, innovations in operations research, carried forward from solving the operational and logistics problems of World War II, came to U.S. factories (Morse 1977, Kirby 2000). Japanese industrialists studied Ford's River Rouge facility and, combining it with the ideas of foreign scientists and intellectuals, forged new ways of producing and competing (Johnson and Bröms 2000). Perhaps the most notable outcome of the post-war industrial progress was the transformation of the Japanese and U.S. automobile industries. Beginning in the 1970s, and continuing through the present, significant advances were made in manufacturing production and inventory management philosophies. This transformation was driven largely by the management, process, and control innovations introduced by such notable figures as W. Edwards Deming, Kaoru Ishikawa, Masaaki Imai, Joseph Juran, and Taiichi Ohno. The entire episode, and its industrial and economic significance, was chronicled by Womack, et al. (1991), who introduced the term lean manufacturing to differentiate the new industrialism from Fordist mass production.

The lean manufacturing philosophy is marked by a radical shift away from workers performing finite, repetitive tasks that produced large lots of identical items and instead toward reorganizing more flexible capital equipment, using adaptable processes, synchronizing work, aligning performance measures, and cross-training employees into teams and cells that produce customized products on a single-item basis. Since the 1980s, discrete parts manufacturers in a variety of industries have capitalized on the success of automakers by mimicking or replicating their practices to reduce cost and gain efficiency. In recent years, off-the-shelf improvement doctrines such as "lean six sigma" emerged, and many of the largest multinational corporations have been feverishly implementing them. These new, accessible process improvement rubrics have successfully distilled the cost-focused, control aspects of lean production into highly deployable management tools. Supporting the process management revolution, and aiding in organizational cost control, have been rapid and explosive innovations in information technology. These innovations have given birth to electronic data interchange (EDI), enterprise resource planning (ERP), and radio frequency identification (RFID)—technologies that have provided management the opportunity to know and understand more about their operations than ever before. With the advent of organizational disintegration that typically takes the form of outsourcing, offshoring, or both, many firms can no longer invest in information technology to achieve competitive advantage (Porter 1980). These technologies have become operational necessities.

EMERGENCE OF THE NEW ECONOMY

Coincident with new approaches to manufacturing has been the adjustment of the United States' economic and educational engines to support the new economy. The new economy that emerged in the 1990s has been thought to have entirely different economic rules, fueled by advances in technology and telecommunications that enable producers of goods, services, and ideas to compete on a high-speed, large-scale, global basis. This new economy is characterized by the commingling of banking and insurance, consumer electronics, biotechnology, and "big box" retailing with its dependence on cheap foreign goods and inexpensive labor. The new economy has been enabled by highly efficient, information-rich logistics networks and Internet-based commerce that has served to bridge organizational and geographic boundaries of multiple firms with shared economic goals and interests. There is no better evidence of the shift in economic emphasis toward the new economy than in the replacement of four old economy stocks (Bethlehem Steel, Texaco, Westinghouse Electric and Woolworth) with four new economy stocks (Johnson & Johnson, Hewlett-Packard, Travelers Group and Wal-Mart) in the Dow Jones Industrial Index in 1997.

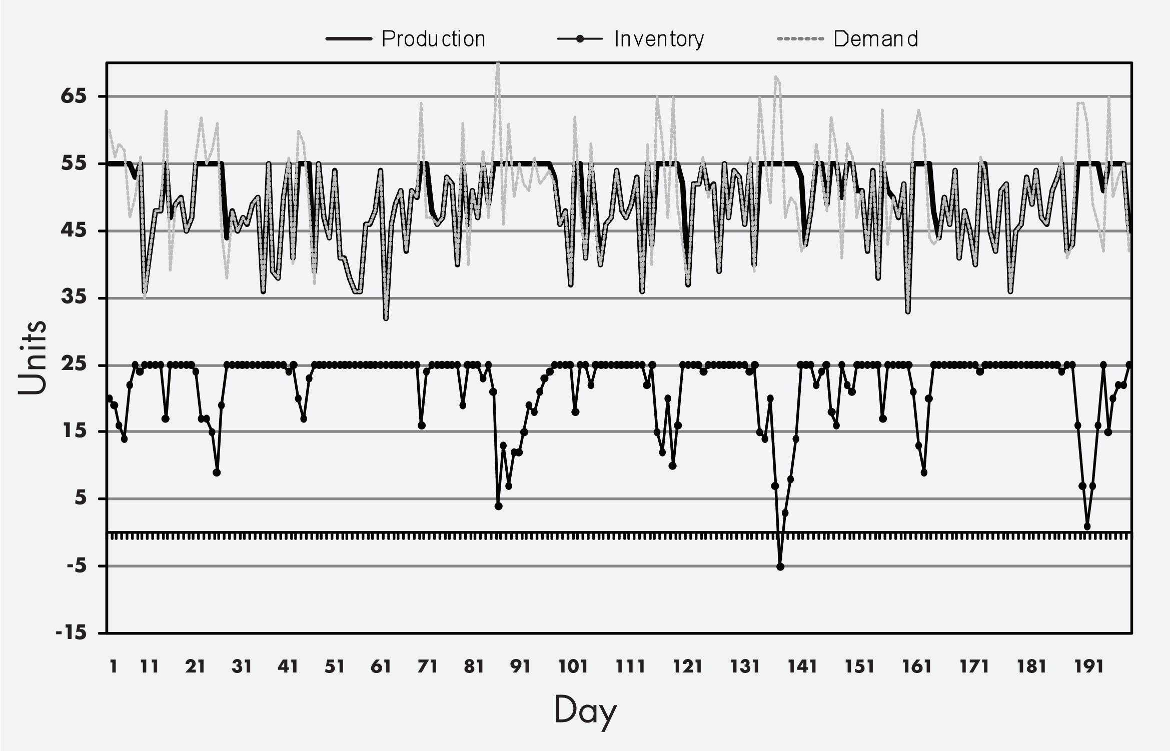
While business leaders continue to focus on the new economy and its implications—both good and bad—demand for the old economy's products has grown at explosive rates (WTO 2005, Farmer 2006). The petroleum and chemical industry alone provide critical raw material feedstocks to industries such as pharmaceuticals, plastics, agriculture, paints and dyes, detergents, beverages, and auto parts. As demand for chemicals has grown, changes in the regulatory environment as well as increasing energy costs have driven executives to shutter domestic production and build new facilities offshore (Friscia and O'Marah 2007). These offshore facilities are often designed to serve large geographic regions—in some cases, hemispheres—with multiple markets across many national borders. Paper mills and "big iron" printing press operations face similar competitive and regulatory conditions as petroleum and chemicals, and as these industries consolidate production or move productive assets offshore, new supply chain management challenges emerge.

Historically, finished goods inventories in old economy firms have been stored at the production site in silos, tanks, or warehouses. If there were off-site depots or distribution points, the decision of where to locate them was not trivial and was guided by the desire to locate near large customer operations and existing transportation infrastructure. Now, with longer and less predictable transit times (a natural outcome of offshore strategies), process industries are faced with more complicated production and logistics decisions in addition to inventory placement decisions. These decisions affect the timing of replenishing products to serve manifold customer segments subject to demand, lead time, and production uncertainty. The result of increased operational uncertainty in turn drives uncertainty in financial performance. Despite millions of dollars of investment in information technology and enterprise resource planning systems, many old economy firms have failed to transform their strategic expectations into operational realities (Dey, et al. 2010).

LEAN MANUFACTURING: AN INVENTORY-CENTRIC APPROACH REQUIRING FLEXIBLE CAPACITY

Lean manufacturing is grounded in what we call an inventory-centric view of production and inventory control: Inventory targets are set, and production capacity is scaled to be flexible to respond to customer requirements. For example, Figure 1 is a numerical illustration showing the evolution of the inventory and production quantities in an environment where the average demand is normally

FIGURE 1: An Inventory-Centric Approach with a Target Inventory Level of 25 Units



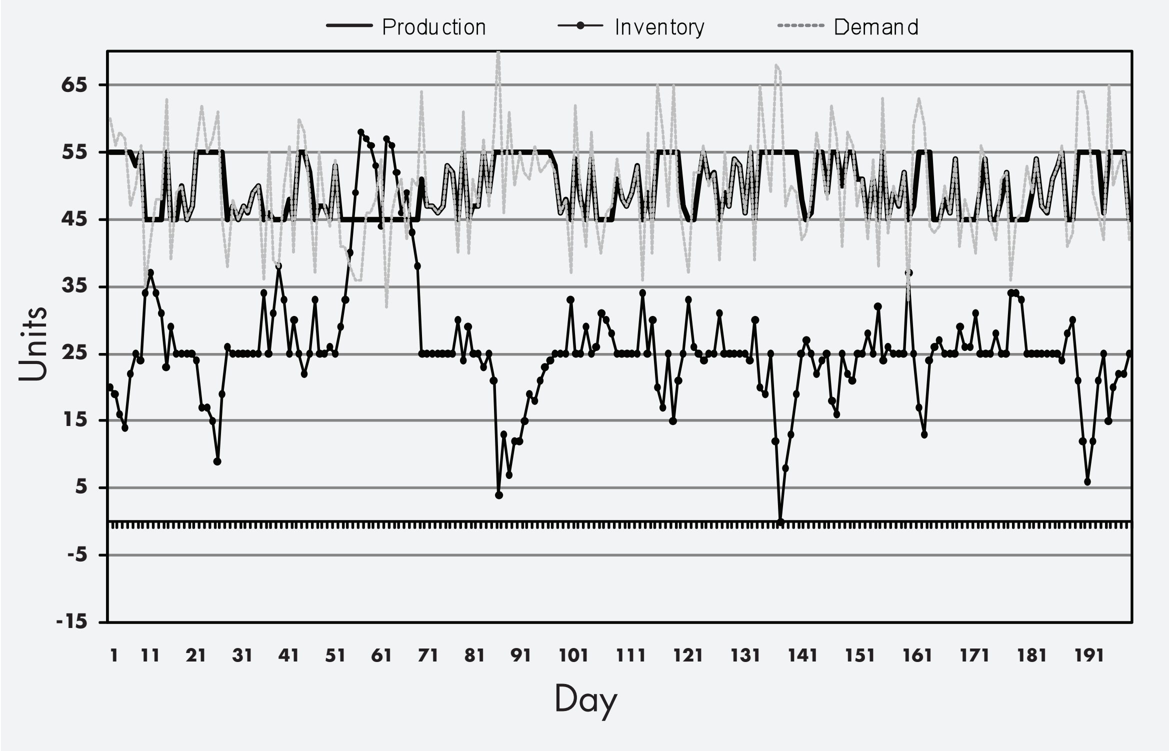
distributed and has a mean of 50 units, and the standard deviation of the demand is seven units. In this example, a target inventory level of 25 units is used to achieve a 100 percent customer service level, and the daily production capacity is 55 units. Each day, orders are received and then satisfied with finished goods inventory, with production capacity responding to meet the target inventory level of 25 units.

One can see that over time, the target inventory level of 25 units is fairly stable, and production responds in a flexible manner (a minimum of 31 units to the maximum of 55 units) to absorb the shocks of the random demand. This type of inventory-centric philosophy is most appropriate after significant investments have been made to reduce production changeover times, customer demand has been stabilized (both the volume and mix of items), and the labor force has been cross-trained to redeploy to various operations according to need. Discrete manufacturing firms—particularly in the automobile industry—have concentrated on the dramatic reduction and control of inventories within their plants. They do this through pull production and kanban systems that rely on flexible capacity to meet inventory levels targeted to satisfy customer demand.

Researchers and practitioners, however, acknowledge fundamental differences between discrete part and process manufacturing (Fransoo and Rutten 1994). Process industries typically have fewer direct customers, fewer stock keeping units (SKUs), specialized and inflexible production capacity whose schedules are dictated by inflexible technology, capital (versus labor) intensity (Taylor et al. 1981), high energy usage, long production run lengths, high levels of automation, and a focus on high capacity utilization and a minimal number of setups relative to discrete part production. These firms fundamentally sell time (capacity) on their equipment to their customers. Additionally, many process industries are constrained by product transformation times that cannot be negotiated—chemical or biological reactions cannot be hastened without compromising the end product—and changeover times of 12 to 24 hours are common.

Finished goods in process industries are often produced in a predetermined sequence based on

FIGURE 2: A Capacity-Centric Approach with a Target Production Cycle Between 45 and 55 Units



engineering and equipment considerations, such as sequence-dependent setup times or contamination factors. The production sequence is typically established to minimize the total setup time spent on the equipment over an entire cycle while respecting any sequence dependency. This type of production sequence is sometimes referred to as a product wheel or a pure rotation schedule, which is a special type of cyclic schedule. The circumference of the product wheel is the length of the cycle, measured in time.

Because changeovers between products tend to be long, variable, and therefore expensive, they are produced in large "campaigns" that make up an overall production cycle. These production cycles tend to have some degree of variability associated with them due to unplanned maintenance, "warmup" times (the time in which production must run before on-spec product is produced), or fluctuations in demand that might require either shortening or lengthening the planned production run of a particular product. Large production campaigns necessitate supporting inventories to satisfy demand over the production cycle horizon (cycle stock), as well as to protect the system against shortages due to demand uncertainty (safety stock). This type of production and inventory philosophy, whereby production capacity is stabilized and scaled only to minimize changeovers while inventories are used to absorb demand uncertainty, is what we refer to as capacity-centric.

In a capacity-centric production and inventory environment, there are capacity targets—upper and lower bounds set on the production cycles—and inventory is used to absorb fluctuations in demand. In Figure 2, we return to our previous numerical example where demand is still 50 units on average with a standard deviation of 7 units, and the capacity is 55 units. But we have now set a production cycle target to produce no fewer than 45 units in any production run. By stabilizing the production cycles between 45 and 55 units, the inventory must now fluctuate considerably to take up the random shocks in demand.

The questions of interest in capacity-centric production environments: In what quantities, and in which specific products, should inventory be carried to achieve the lowest cost and highest customer service while keeping production stable?

Discrete parts manufacturing has benefited from production planning schemes that level-load the plant to reduce idle time and overtime. Lean practitioners call this heijunka, which refers to leveling (Womack and Jones 2003). But in the process industries, where production takes place 24 hours a day, seven days a week, what does it mean to level-load the production facility? To our knowledge, there has been no definition of level-loading for process manufacturers in the academic or practitioner literature. We define capacity stabilization in the process industries as creating production cycles that are predictable, and level-loading in these continuous operations consists of stabilizing the manufacturing lead times. In the types of continuous and large batch production environments we have witnessed, changeover times can range from 12 to 24 hours with significant waste and off-specification material resulting from the changeover process. From a practical and financial perspective, it is imperative that the production capacity in these environments be stabilized to minimize unanticipated changeovers, unpredictable yields, and less than planned output, as well as to reduce the length and variability of manufacturing lead times to satisfy customer requirements. Production plans must be robust but emphasize stability and minimize the number of unplanned changeovers that drive costs and contribute to internal process uncertainty (Van Landeghem and Vanmaele 2002).

While the production equipment of process manufacturing firms tends to be inherently inflexible and requires stability to be most efficient, market demand is almost never stable and predictable. Also, the introduction of new products increases the planning and manufacturing complexity. The discrepancy between demand uncertainty and production stability may be resolved through the creation of feasible production schedules and finished goods inventories in the right product at the right time. Failure to accomplish effective inventory management, which in many cases results in inventory levels higher than what might be observed in discrete manufacturing environments, will lead to excessive logistics costs, downward price pressures, or scrapped material.

THE GAP BETWEEN OPERATIONS MANAGEMENT AND "LEAN" THEORY AND PROCESS INDUSTRY PRACTICE

Evidence shows that the competitive environment of process manufacturing firms is becoming more intense. It also shows that consolidation in capacity and the number of enterprises (Labaton 1999, Stout 2000, Weston and Johnson 1999), combined with the expansion into new markets (Freeman 1999, Swift 1999), has created pressure on process manufacturing firms to aggressively control operating costs while expanding or guarding their traditional markets. In the context of all of the larger environmental and competitive change, a great deal of confusion remains within industry regarding what constitutes lean, JIT, pull, and push production (Hopp and Spearman 2004). The chemical industry, in particular, is in its infancy with respect to understanding lean (Melton 2005).

Many process and large batch manufacturing firms use material requirements planning (MRP) logic for planning production because it has some planning value. It is well known by the practitioner community that MRP assumes both a fixed manufacturing lead time and infinite production capacity. Maintaining a constant production lead time in this planning environment is difficult precisely because there is a capacity constraint. Operations management theory offers the stochastic economic lot scheduling problem (SELSP) to assist in production scheduling where demand is random and setups are incurred between the manufacture of successive products. (See Federgruen and Katalan 1996, Gallego 1990, and Winands et al. 2010). The stochastic economic lot sizing problem requires production cycles to be changed frequently to achieve a target customer service level (or minimize customer wait times) while minimizing inventory holding costs. For process and large batch manufacturing firms it is undesirable to fluctuate production cycles because it results in increased quantities of off-specification material, reduced effective capacity utilization, or both. Outside of the academic press, popular management literature such as that by Womack and Jones (2003) and Liker (2003) describes lean and the Toyota production system. While this popular management literature

TABLE 1: Process and Large Batch Manufacturing Enterprises Observed Pursuing "Lean"

North American Industry Classification System (NAICS) Title	4-Digit NAICS code	# of Enterprises
Grain and Oilseed Mining	3112	1
Beverages	3121	1
Pulp, Paper, and Paper Board Mills	3221	3
Printing and Related Support Activities	3231	1
Basic Chemical Manufacturing	3251	3
Pharmaceutical and Medicine Manufacturing	3254	3
Plastics Product Manufacturing	3261	2

is compelling and useful for firms producing services or discrete products, it is devoid of examples, applications, or case studies addressing process manufacturing. Both the academic and popular business press emphasize low levels of inventory as a critical component of lean. But because of historical investments in capital and labor, facility location decisions, or both, models developed to support lean manufacturing that target low levels of inventory may be wholly inappropriate for large batch or process manufacturing firms that make up what we call the old economy.

Recently, several site visits were conducted at continuous process and large batch manufacturing firms involved in the production of grain and oilseed milling, beverages, paper, commercial printing, basic chemicals, pharmaceutical and biotechnology products, and plastics. Each of these firms is in either the Fortune or Global 500 list of top companies and are identified by their North American Industry Code (NAIC) in Table 1.

During our site visits, we witnessed experimentation with lean production principles and discovered that each firm we visited was (1) instituting dramatic inventory reduction programs that placed unilateral limits on all products measured in a specified quantity or days of supply, (2) changing production schedules frequently to meet target inventory goals, therefore incurring many unplanned changeovers, (3) generating large quantities of off-specification or waste product and observing increasing costs in raw materials as a result of increased changeovers, and; (4) experiencing reduced customer service levels and less effective capacity utilization.

The inventory reductions and the setting of target inventory levels for each firm were part of companywide lean initiatives based on the executives' reading of the popular business press or at the direction of a hired consultant. These observations cannot simply be dismissed as the foibles of a handful of overzealous or misguided firms, but rather should be viewed as the result of misunderstanding what constitutes lean. This misunderstanding corresponds with the lack of attention the academic community gives to this particular industrial sector.

Many operations management textbooks—for example, Hopp and Spearman (2007)—state that several prerequisites must be satisfied before embarking upon a lean initiative. These imperatives include production smoothing (level-loading or heijunka), establishing capacity buffers, reducing setups and setup times, cross-training workers, improving plant layout, and reducing work in progress.

But when we look closely at these lean imperatives and consider the reality of the operating conditions in process and large batch manufacturing industries, there are obvious gaps in their applicability (see Table 2). Production smoothing (or level-loading) is not defined in the lean literature or operations management textbooks for process industries that run 24 hours a day, seven days a week. Likewise, when production is continuous, the establishment of capacity buffers or "safety capacity" (Hopp et al. 1993) as it is defined in the literature has little meaning for operations that run continuously. Reducing setup times is often impossible in the near term and likely governed by a physical or chemical transformation process that is non-negotiable. For capital-intensive process industries, cross-training workers provides little (if any) return. Changes to plant layout are either infeasible due to multiple parts of the plant feeding other parts whereby they are physically connected by pipes, or the changes are prohibitively expensive because they essentially involve demolition and construction projects that require the plant to be shut down for extended periods. Finally, work in

TABLE 2: Common Lean Imperatives and Process or Large-Batch Industry Realities

Lean Imperative	***Process or Large Batch Industry Reality***
Smooth or "level-load" production (heijunka) — establish production plans that are smooth with respect to volume and product mix	Production smoothing is not defined in the literature for the continuous process of large batch namufacturing industry
Establish capacity buffers — scheduling the factory less than 24 hours per day	Factory runs 24 hours per day, 7 days per week
Reduce setups on equipment — reduce setups, institute single-minute exchange of dies (SMED), convert internal setups to external setups, abolish setups.	Setups are often 12 to 24 hours and are non-negotiable - there are physical and chemical transformation processes that cannot be shortened in the near term
Cross-train workers — because labor is a critical capacity input it is desirable to cultivate a mutli-skilled workforce	Labor is not the primary capacity input and therefore cross-training has little impact on operations
Improve plant layout — adjust plant layout to accommodate less movement of material and employees	The plant is fixed; production is a process that consists of a system of pipes, reactors, and transformation mechanisms that do not lend themselves to reconfiguration
Reduce work in progress	Work in progress is constant due to continuous production; work in process is often determined by the physics of the transformation process

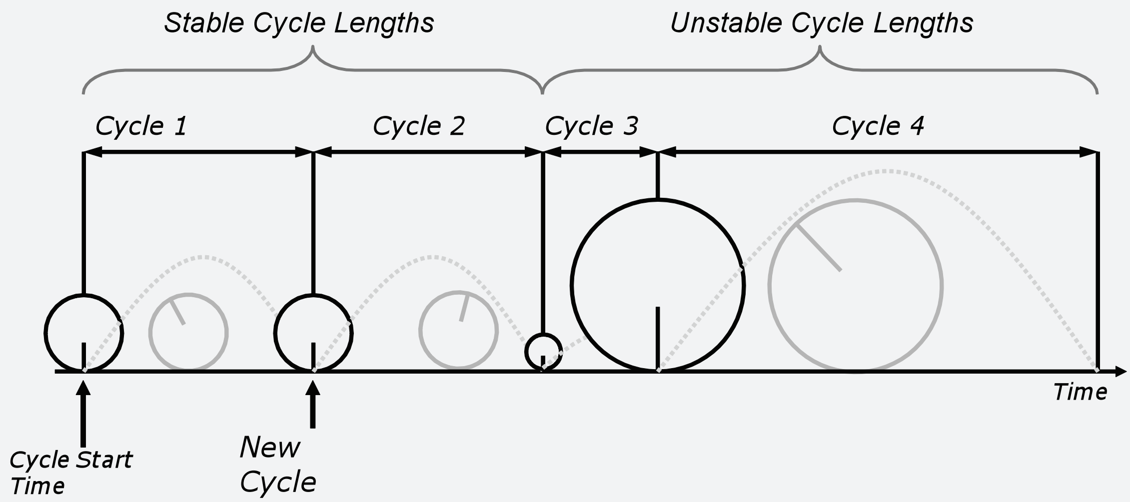
process is often defined by the volume and velocity of product flowing through pipes that are governed by physical properties. In some instances, a change in the velocity of the product flowing through the pipes in a chemical process can result in coagulation or off-specification material.

STABLE AND VARIABLE PRODUCTION CYCLES: A CHEMICAL COMPANY'S NATURAL EXPERIMENT

We will now highlight one particular chemical plant that was aggressively implementing a lean program because its chief executive read a book describing a popular German discount grocer's success. Thinking of the production cycle as a succession of identical cycloids, one may visualize the evolution of the production cycles over time so that the interval between the start times is uniform and therefore predictable. We will refer to this type of evolution of production cycles as stable and could characterize this type of scheduling as level-loading. In cases when the production cycle is not stable—that is, the size of the cycloid changes from period to period to replenish an inventory level or minimize a customer wait time—the length of the production cycles is unpredictable, and the interval between start times is not equal. These types of production cycles are referred to as unstable (see Figure 3).

Figure 4 shows the production for a single product at a process industry plant we examined, varied over a 12-month period in which a policy change occurred. In this particular firm, changeovers lasted between 12 and 24 hours during which off-specification ("off-spec") material was produced which then had to be disposed of as waste or sold at a discount on the secondary market. During the first six months of the year, production was stable and predictable due to a philosophy of stabilizing production cycles. Note that the volume and interval between production runs was fairly uniform, as illustrated in Figure 4 by overlaying cycloids whose circumference is equal to the length of each production run. During the second half of the year, however, executive management instituted an inventory-driven policy requiring no more than 10 days of inventory on-hand for any product. This policy resulted in unpredictable fluctuations in production utilization as a result of having to lengthen and shorten production cycle lengths to meet demand and maintain customer service levels. There was a 70 percent increase in the total number of changeovers in the plant between the first and second half of the year, utilization of the

FIGURE 3: Stable and Unstable Production Cycle Lengths



equipment went down, the length of production campaigns increased as did cycle stock and manufacturing lead times, and customer service went down. Consequently, demand became erratic due to unpredictable service, and customer purchasing managers began hedging to cover their own service levels by padding orders and "gaming" the system—placing large orders and hoping to get some amount of product to keep their own operations running.

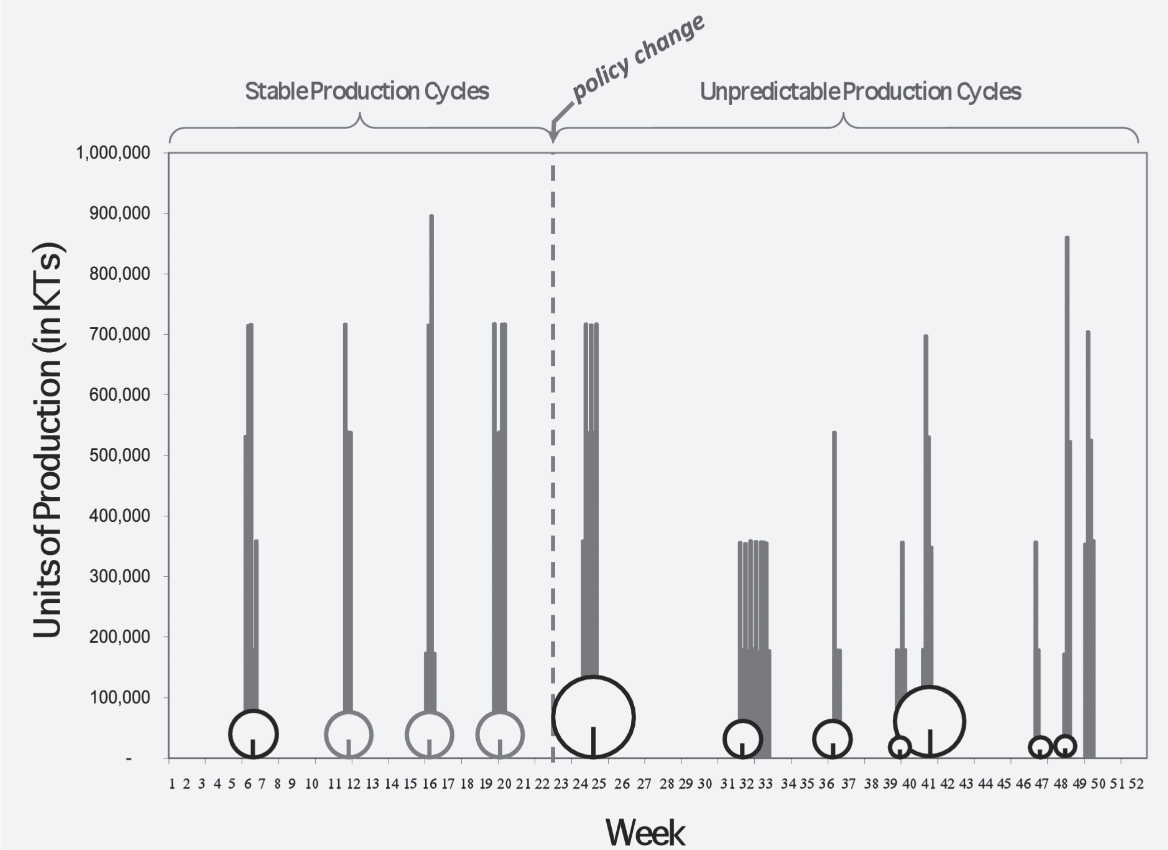
As the predictability of the manufacturing environment deteriorated, a direct and measurable increase in operating costs followed, in the form of lost production time and increased logistics expenses stemming from late deliveries. Eventually, total logistics expenses exceeded total production expenses. Moreover, there were other costs that were not well documented, including the time devoted to creating new production and shipping schedules and the changes in lead times given to customers that consequently disrupted historical demand patterns. While system inventories decreased to meet the "10 days on-hand" target, so did on-time customer delivery performance and total profitability. According to our observations, setting managerial targets without understanding their operational and financial implications often results in higher costs, loss of managerial control, and poor customer service—consistent with results discussed by Litzky et al. (2006).

It is worth recognizing that the stability of the production cycles in the first six months of Figure 2 was due to the experience of the production planner, who long complained of the impact of unplanned changeovers on the plant's operational stability and costs. The production cycles were planned offline in a spreadsheet and later entered into the enterprise resource planning (ERP) system because the planning system was incapable of developing production plans that would explicitly stabilize production cycles. Indeed, the ERP system required the planner to enter in a fixed manufacturing lead time (see Figure 5). Without a stable, predictable production cycle, a fixed manufacturing lead time parameter has no meaning.

USING STABLE, CYCLIC PRODUCTION SCHEDULES TO IMPROVE SUPPLY CHAIN COORDINATION

Simon and Holt (1954) and Modigliani and Hohn (1955) emphasized the need for models that consider the trade-offs between production fluctuations and inventory costs in a dynamic, interactive environment. Holt et al. (1960) conjectured that stabilizing production and "allowing fluctuations in inventory of finished products to serve as a shock absorber in avoiding production fluctuations" could reduce total system costs. Unfortunately, this research did not develop as quickly as inventory-based research, largely due to the limitations of computing technology at the time.

FIGURE 4: Stable and Unpredictable Production Cycles in a Process Industry Plant



Stable, repeatable production cycles can be used to improve supply chain coordination and collaboration. They enable the production facility to provide accurate lead time quotes to customers, and more accurate orders to suppliers for raw material. A stable environment where the uncertainty in lead times is reduced is a necessary condition for establishing stable financial performance. For example, Glasserman and Wang (1998) explicitly show the trade-off between lead time and inventory: When lead times are random, the inventory consequences multiply. Hall (1988) makes a thorough and compelling case for stable, cyclic production schedules and associates such schedules with the elimination of waste, improved quality, decreased lead times, increased labor skill and morale, and decreased costs. Schmidt et al. (2001) provide evidence of significant increases in output as well as cost reductions by introducing cyclic production planning in a make-to-order aluminum-tubing products facility. Based on what we have observed in the field, as well as the prevailing research, we believe that creating predictability and stability between the factory and its customers and suppliers may lower overall supply chain costs.

Stalk and Hout (1990) introduced the idea of time-based competition and stressed the importance of using speed to compete. It has since been widely acknowledged that consistent and accurate lead time quotations are a potential competitive advantage (Hopp and Sturgis 2000, 2001; Hall and Porteus 2000). The importance of keeping delivery promises and attaining high levels of service while keeping inventory levels relatively low has also received attention from Sox, et al. (1997). We maintain that customer service is multidimensional, and one important dimension is a firm's ability to quote consistent and accurate lead times and then keep its promises. This requires a coordinated production and inventory strategy. Determining appropriate inventory levels when demand is uncertain is difficult. But when this is combined with replen-

FIGURE 5: Screenshot from the Microsoft Dynamics GP Enterprise Resource Planning (ERP) System Requiring a *Fixed Manufacturing Lead Time* Parameter

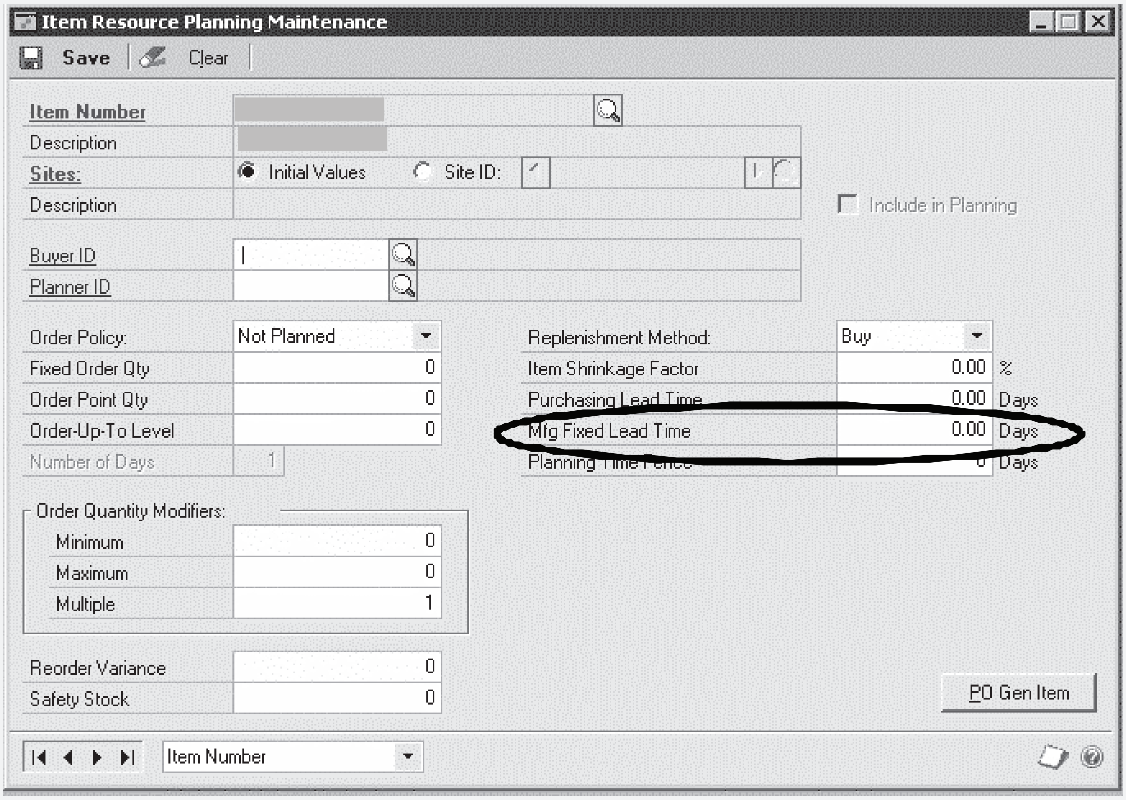
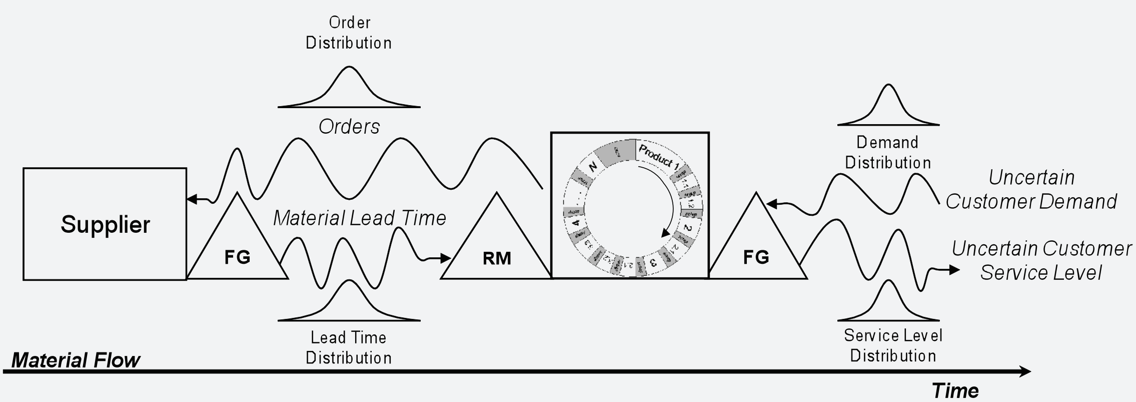


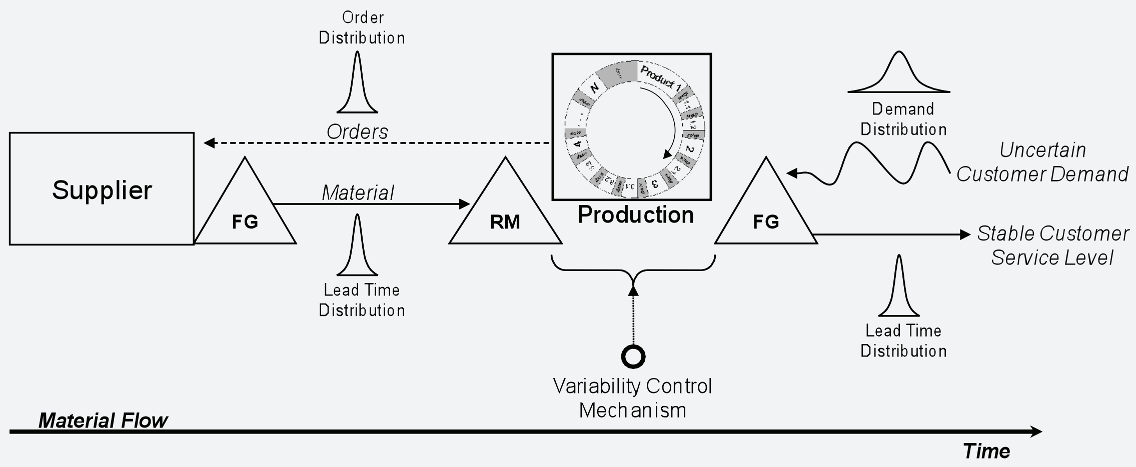
FIGURE 6: Customer Demand Variability Transmitted Through the Supply Chain



ishment uncertainty due to long and variable production cycle lengths, excessive inventories can enter the system quickly and expose the firm to significant financial risk.

Supply chain collaboration schemes and expected outcomes have been studied extensively in the operations research and management science literature (see for example de Kok and Graves 2003). Whether the firm decides to collaborate with its suppliers is a strategic decision; however, it is a simple matter of self interest that motivates our willingness to assist a supplier, whenever feasible, to provide good service in the form of timely delivery of raw materials. If on-time service from

FIGURE 6: Production Policy as a Supply Chain Variability Control



suppliers is highly variable, then higher inventory levels must be kept as a buffer and hedge to ensure the availability of raw material feedstocks to keep production running. By giving stable orders to suppliers, firms can potentially lower raw material safety stock and the operating costs of suppliers. Simply stated, stabilizing a firm's production capacity usage inherently stabilizes the stream of demand requirements placed on its supply base. Figure 6 illustrates a typical serial supply chain with a supplier that provides raw materials for a process manufacturer producing items using a cyclic schedule and then storing finished goods (FG) in a co-located warehouse.

Orders arrive at the production facility randomly and are filled or backordered. Based on the demand for finished goods, the production facility will place random orders to the supplier. Material received from the supplier is stored in the production facility's raw material (RM) inventory until it is used to produce finished goods. It has been shown that random demand transmitted over a random order stream exacerbates the bullwhip effect and consequently erodes supply chain operational and financial performance (Forrester 1958, 1961; Metters 1997).

We maintain that in situations with no collaborative effort, and even when the supplier relationship is at arm's length, the firm should provide suppliers a stable demand stream to reduce costs of excess inventory through the transmission of stable orders. By transmitting stable and predictable orders back to suppliers, the firm may keep costs lower and improve the reliability of the service they receive. Balakrishnan, et al. (2004) show that a process of "order smoothing" alleviates a natural tension between downstream supply chain partners, who wish to propagate full demand variability upstream, and the upstream partners who prefer to reduce variability that increases operating costs. The "order smoothing" is attained through the use of an explicit downstream inventory replenishment policy as a variability control mechanism that reduces upstream order variability.

We propose that process manufacturers stabilize their production environments to stabilize lead times to customers, reduce unplanned changeovers in operations, and buffer the transfer of demand variability back to suppliers by using stable cycles as a "shock absorber" or variability control mechanism (see Figure 7).

As with any set of operations, procedures, or tasks, ones performed routinely tend to improve with practice. When the production cycle length is known in advance, workers can develop routines of activity that make operations cheaper, better, and faster. Rhythms of behavior and routine develop more easily in stable environments. A disruptive or chaotic environment makes learning extremely difficult, and improvement of the system is unlikely to occur (Mukherjee, et al. 1998; Lapré and Van Wassenhove 2003). A constant and stable production cycle length may make the firm more competitive from a customer service perspective while also lowering total supply chain costs. By dampening order variability to upstream suppliers, the firm can create a stable, rhythmic environment for continuous improvement and operational innovation.

In the petrochemical industry, a significant amount of waste or off-specification material is often produced as a result of a changeover. Reducing the number of unplanned changeovers through a deliberate program of cycle stability can reduce the amount of waste and off-specification material. The objective could be adopted as part of the firm's overall sustainability goals, described by Fliedner and Majeske (2010) as "the new lean frontier." Additionally, reducing overall variability in the supply chain makes it easier to forecast financial results—something shareholders and stakeholders agree is desirable.

CONCLUSION

A guiding principle underlying our production philosophy is that short, predictable, and repeatable production cycle lengths are highly desirable because they require less cycle stock, permit fast responses to changing conditions, enable accurate lead time quotations to customers, smooth orders for raw materials to suppliers, and enable the production facility to develop efficiency through repetitive and rhythmic cycles. Stable, predictable processes tend to produce stable, predictable operational and financial outcomes. These predictable outcomes are measured in terms of operating costs, profit forecasts, finished goods inventory levels, and raw material consumption and costs.

A policy of stabilizing production cycles necessitates an inventory policy to absorb random demand and maintain customer service goals. Increasing inventory to maintain a stable production cycle will likely be out of step with popular interpretations of lean (pursuing very low levels of inventory). But process and large batch manufacturing industries must respect the physical limitations of the production equipment and establish production and inventory policies that are feasible and economical. If the production equipment is characterized by long changeover times that are not negotiable, then stabilizing the production cycles should be an explicit operational goal with a complementary inventory policy that will absorb random demand. But if the production environment is characterized by flexible machinery whose setups may be accomplished offline and cross-trained workers that can be redeployed to different stations when necessary, as is often the case in discrete manufacturing environments, then setting low inventory levels and enabling the capacity to absorb the shocks of random demand is advisable.

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