THE ROUTLEDGE COMPANION TO PRODUCTION AND OPERATIONS MANAGEMENT

Edited by Martin K. Starr, Sushil K. Gupta

Chapter 37
The Evolutionary Trends of POM Research in Manufacturing

Tinglong Dai, Johns Hopkins University
Sridhar Tayur, Carnegie Mellon University

July 2016

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1 Introduction: Creating Wealth and Happiness, Massively

What are we talking about when we speak of “manufacturing”? The U.S. Census Bureau defines the manufacturing sector as the collection of “establishments engaged in the mechanical, physical, or chemical transformation of materials, substances, or components into new products,” which does not seem satisfying to readers who wonder: What exactly is the *purpose* of manufacturing? Manufacturing has created wealth and happiness in a massive way, and has been responsible for achieving a global improvement in the quality of human life. In his "Report on Manufactures" (1791, p. 240), Alexander Hamilton wrote that:

> Not only the wealth; but the independence and security of a Country, appear to be materially connected with the prosperity of manufactures. Every nation, with a view to those great objects, ought to endeavour to possess within itself all the essentials of national supply. These comprise the means of subsistence, habitation, clothing, and defence.

The simultaneously complementary and substitutive relationship between manufacturing, technology, labor, and capital complicates the situation. The manufacturing sector contributed to just 11% of the value added to U.S. GDP in 2012, a significant decline from 25% in 1970. The decline in the importance of the manufacturing sector is global: it contributed to 16% of the value added to the world’s GDP in 2012, down from 27% in 1970. However, we should not underrate the importance of manufacturing to the economy and society for at least two reasons. First, the manufacturing sector has been a traditional source of abundant middle-class jobs. In the case of the United States, the sector is credited with providing steady income to millions of households, allowing them to afford decent living standards, support children's education, and, collectively, form the largest consumer market in the world, which is crucial to the continued prosperity of the manufacturing sector. Second, the manufacturing sector sustains and regenerates itself through technological advances: shaped by technology, manufacturing drives technological innovations through, among other means, investing in research and development activities. Combining both aspects, we see a virtuous cycle in which technology drives the refinement and expansion of the manufacturing sector, which creates jobs, enables better lives for many, and propels more innovative technology.

Will this virtuous cycle sustain? At this crossroad of history, we do not have the answer, but the past offers some definitive signs of hope. Edmund Phelps, in the book *Mass Flourishing: How Grassroots Innovation Created Jobs, Challenge, and Change* (2013, p. 1), concludes, "Over most of human existence, the actors in a society's economy seldom did anything that expanded what may be called their economic knowledge—knowledge of how to produce and what to produce." Figure 1 shows a population-weighted economic and human history of the past two thousand years. It provides visual evidence of the dramatic effect of the flourishing of manufacturing: prior to the Industrial Revolution, the wealth created or the number of years people lived remained stable for centuries. The world began to change dramatically at a rapid pace only after the inception of manufacturing in the 18^{th} century.

< Figure – 37 - 1>

Figure 1 Worldwide productivity and longevity in history. The *y*-axis shows the percentage that each century's population-weighted history accounts for the entire human history. Source: Economist (2011)

In this chapter, we seek to provide a targeted view of the manufacturing sector—with a focus on massively produced consumable goods such as chemicals, consumer packaged goods (CPG), automobiles, industrial machinery/components, pharmaceuticals, medical devices—and the sector's relationship with POM, which inevitably involves discussing technology. Indeed, the influence of POM over manufacturing is largely through its mastery and command of technology. We are interested in examining the way that manufacturing creates massive wealth and happiness, and are therefore mindful of whether the development of manufacturing improves or impairs social welfare.

In the rest of the chapter, we will move on to discussing the role of technological innovation in manufacturing, distribution, and logistics, as well as how POM orchestrates technologies in improving and transforming the manufacturing sector. We then outline practical problems in operations management (PPOMs) in the manufacturing sector, which allows us to trace POM in the evolution of the manufacturing sector. Lastly, we weigh the labor versus capital tensions, and close with thoughts on the impact of POM on society and global trade, and relevant research opportunities for young scholars.

2 Modern Manufacturing: An Orchestration of Technologies

The word "manufacture," coined in the 1560s from Latin *manu* (hand), originally referred to handcrafted products. By this definition, many notions associated with modern manufacturing no longer apply: specialization is rare, collaboration is seldom required, knowledge sharing is almost non-existent, and economy of scale is lacking. In fact, diseconomy of scale may be the norm in the case of handcrafted production, because excessive unorganized manual labor often leads to fatigue and boredom.

The past four and a half centuries have witnessed the "ecological extinction or near extinction" of handcrafted production in the manufacturing sector (Fraser 2015). Most saliently, this is due to technological advances that include the invention of steam engines, availability of long-distance mass-transportation tools, electrification of industries and households, invention of the computer, not to mention the development of telecommunication, Internet, and mobile devices in recent years. What is not as salient in the pathway leading to modern manufacturing, however, is the changes in the *operations*. An early identification of such changes is in *Capital, Volume I* (Marx 1912, p. 371), which involves two aspects: increased scale of labor ("the union of various independent handicrafts, which become stripped of their independence and specialized to such an extent as to be reduced to mere supplementary partial processes in the production of one particular commodity"), and specialization of and isolation among job functions ("An artificer, who performs one after another the various fractional operations in the production of a finished article, must at one time change his place, at another his tools…. These gaps close up so soon as he is tied to one and the same operation all day long").

We have witnessed the historical and inevitable shift from handcrafted production to an automated, massive production that has become the principal way that our society creates products crucial to its citizens' wealth and happiness. Yet our materialistic abundance, in certain cases, may lead to "excess and a lack of taste, a trend exemplified by living in custom built, faux French mansions, and driving Hummers, civilian version of a military assault vehicle" (Smil 2013, p. 2). The ongoing "maker movement" (Morozov 2014), a response to the banal aspect of modern manufacturing that may feel ironic to historians, emphasizes handcrafted and individualistic products. Will the word "manufacturing" ever return to its original root? We do not know the answer, but one thing we are certain of is that the renaissance of individual, handcrafted production—if materialized—will be empowered by technology (specifically, additive technologies such as 3D printing).

But what *is* technology? In *The Nature of Technology*, Arthur (2009, p. 53) characterizes the essence of technology as "a programming of phenomena for a purpose… an orchestration of phenomena to our use." Arthur continues, saying that, "more than anything else technology creates our world. It creates our wealth, our economy, our very way of being." In other words, the purpose of manufacturing is no different from the function of technology, and is achieved essentially through an orchestration of technologies.

Consider how technologies such as the steam engine, electric power transmission, computers and programming languages, the Internet, the iPhone, wearable devices, and 3D Printers shaped the manufacturing sector. Technology, when orchestrated for the purpose of manufacturing, permanently transforms the latter, and then dictates the evolution of trade flows and work patterns. But what tool does a manufacturing manager have in orchestrating technology?

3 What Is Orchestrating Technology?

Technological revolutions do not simply change the way people make products. They also call for, and inevitably are followed by, changes in the way that physical, financial, information, and human resources are organized and managed. Such changes need an orchestrator, that is, operational innovations (hereafter, production and operations management as represented by POM). Even the least attentive historian would be cognizant of the fact that with every tide of technology innovations, *operational* innovations emerge. Examples include, Newton's seminal industrial engineering initiatives, Frederick Taylor's Scientific Management (albeit questioned by historians, e.g., Lepore 2009), Ford's invention of the assembly line system, Toyota Production Systems, the invention of operations research, W. Edwards Deming's quality control movement, the emergence of supply chain management, and the contemporary Enterprise Inventory Optimization software.

But what is "operation"? The Random House Dictionary defines "operation" as the "power to act." This definition precisely captures the relationship between operational innovation and technology innovation: POM provides the *power* necessary for technology to transform manufacturing to meet the needs of end consumers. What gives modern capitalism its dynamism that separates it from the early mercantile capitalism? The answer, according to Phelps (2013), is strikingly simple: ideas. The field of knowledge known as POM, provides and *is made up of*, ideas for organizing manufacturing activities. POM is full of ideas for creating and updating a firm's business model to act on ever-shifting risk curves (Girotra and Netessine 2014).

POM's tendency to *act* has shaped the trajectory of the evolution of its theory and practice: for most of its history, the practice of POM has been far ahead of its theoretical foundations and academic formulations. Consider, for example, the kanban practice that the Japanese manufacturing sector started experimenting with in 1947, two years before the founding of the Graduate School of Industrial Administration (GSIA) of the Carnegie Institute of Technology, a major birthplace of systematic, quantitative approaches to addressing real business problems, a.k.a., management science (Khurana 2010). The practice didn't begin to draw worldwide attention and mimicry until the 1980s. Only at that time did rigorous, theoretic studies—including Deleersnyder et al. (1989); Mitra and Mitrani (1990); Tayur (1992, 1993); Veatch and Wein (1994)—start flourishing in major POM theory outlets.

POM textbooks contain a great deal of information about operational innovations before the 1990s. Knowledge or consensus regarding what has happened since that time, however, has been scant. Paul Krugman (2015) attributes "the big productivity gains of the period from 1995 to 2005" to "things like inventory control." The same period marks the inception and development of the enterprise of inventory optimization *software*. Therefore, a significant portion of the rest of the chapter will be devoted to the practical impacts of inventory control, among other problems related to product portfolio choice, planning for flexibility and responsiveness, production planning, and logistics of manufacturing companies.

4 Operational Innovations and PPOMs

We now discuss a number of fundamental PPOMs, as listed in Table 1, which are motivated by operational innovations, and verifiably address manufacturing executives' concerns. These problems may be issues inside the factory, outside the factory, or at interfaces between the inside and outside of the factory.

<Table 37 – 1>

Table 1: Practical Problems in Operations Management (PPOMs)

We wish to emphasize that the eight PPOMs identified herein are by no means exhaustive of the whole range of problems that POM encounters in its role as it influences and transforms the manufacturing sector. Rather, these eight PPOMs represent part of the best efforts made by the POM community to understand the complex and fascinating operational details in the manufacturing sector and to implement some of the most intellectually exciting and practically applicable ideas. Other important areas where PPOMs exist, such as quality control and standardization, are not covered here, but will be detailed in other chapters of the volume. Likewise, due to space limits, we are not able to cover the following topics: (1) sustainability-related issues, such as remanufacturing, reverse logistics, and carbon footprint; (2) ethical and political issues, such as counterfeiting, child labor, conflict minerals, and supply-base issues; and (3) planned obsolescence and the associated innovations leading to shorter shelf life and fast fashion alterations. In addition, we do not consider largely strategic-level considerations such as (1) capacity options, (2) quantity discounts, and (3) contracting and incentive design. Lastly, because we have a contemporary, managerial focus, we refrain from referring to the earliest production and inventory models (e.g., Harris 1915) in discussing the PPOMs.

4.1 POM inside the Factory

Massive production, empowered by the uses of standardized components (invented in the late 19th century) and moving assembly lines (invented in the early 20th century), introduced formidable managerial challenges that did not exist during the preceding centuries dominated by handcrafted production. Any plant manager in a modern manufacturing firm naturally faces three basic and practical problems: (1) when and at what rate to produce and store inventory; (2) how to hire, fire, and deploy workers; and (3) how to coordinate various production stages.

These practical problems correspond to three areas of POM applications, namely, PPOM-1 (production and inventory control), PPOM-2 (employment planning), and PPOM-3 (management of kanban-controlled systems). In fact, Warren Buffett, arguably the foremost capitalist of our time, may be said to be a master of addressing these PPOMs (at least the first two), according to his biographer Alice Schroeder (2008, pp. 213-216). In early 1962, Buffett acquired the rights of control of Dempster Mill Manufacturing Company based in Beatrice, Nebraska. Buffett coached Lee Dimon, a former purchasing manager who accumulated such an excessive amount of windmill-parts inventory that "the company's bank prepared to seize the inventory as security for its loan, then grew alarmed enough to make noises about shutting Dempster down." Buffett and his partners "swept through the place like a swarm of boll weevils and slashed inventory, sold off equipment, closed five branches, raised prices for repair parts, and shut down unprofitable product lines. They laid off a hundred people." The results were impressive: by year-end 1962, Dempster became profitable, and "the bank was happy."

Undoubtedly, PPOM-1 dominated much of POM theory from 1950s until the 2000s, not only for its apparent relevance to practice, but also for its irresistible intellectual appeal. Nobel winners Kenneth Arrow and Herbert Simon were among the founding fathers of the production and inventory theory, and established what is well known as the base-stock policy that much of today's production and inventory control practice still uses today. Interestingly, until the early 1990s, almost four decades after the birth of the production and inventory theory, a practically efficient method to compute the optimal base-stock level for industry-level problems still did not exist. The necessity drove another level of academic excitement, represented by the application of infinitesimal perturbation analysis (IPA) to design efficient recursive methods that allow industry-scale applications (Glasserman and Tayur 1995).

A major concept in addressing PPOM-1 is flexibility—the ability of a factory or production line to manufacture multiple products, which allows maximum utilization of limited production capacity. The corresponding POM practice, namely, flexible manufacturing systems (FMSs), started in the late 1970s. A few years later, Stecke (1983) identified five production-planning problems, including (1) part-type selection problem, (2) machine-grouping problem, (3) production-ratio problem, (4) resource-allocation problem, and (5) loading problem. To show POM was actually helpful in guiding the then-brand-new practice of FMSs, Stecke (1983) applied her algorithms to a production facility at Caterpillar Tractor Company in Illinois.

Jordon and Graves (1995) examine the flexibility of making products at different plants or lines from a different angle: "How much process flexibility is needed?" More specifically, "Can the benefits of total flexibility be achieved with something less than total flexibility?" Their approach, even by today's standards, was radically refreshing. Jordan and Graves (1995, p. 578) wrote that:

> We have not developed an optimization model… Complex models have their place, especially for guiding specific decisions. However, simple models—if focused on the right questions—can often reveal new principles that can greatly improve management decision-making.

In their own writing, Anupindi and Tayur (1998) expressed the same view, writing that, "A crucial aspect of our approach is that we insist on a systematic way of managing the critical stage: a cyclic schedule… We recognize that our production strategy may not be optimal. However, it is simple and can be implemented easily on the shop floor." Conceptually relevant to this flexibility is the so-called stochastic economic lot scheduling problem (SELSP), which arises when a single machine can make multiple types of products (i.e., satisfy multiple types of demand) but has to make one type at a time. The demand for each type of product arrives in a random fashion, and each switch of product type incurs a setup time.

The SELSP problem is among the most technically challenging topics in PPOM-1. The exact optimal solution to SELSP is intractable due to its large state space. Nevertheless, POM researchers have studied it using various creative approaches. For example, Bowman and Muckstadt (1993) used a Markov chain approach and considered a finite number of schedules. A more practical cyclic scheduling strategy, however, involves a fixed production sequence. Anupindi and Tayur (1998) focused on the case of a fixed production sequence and derived the cyclic schedule under which the switch to each product was triggered by its own inventory level only. Markowitz et al. (2000) developed a heavy-traffic approximation to obtain the optimal fixed production sequence in which the switching decision depends on the inventory levels of all the products.

Although fears of a jobless future in which automated robots rather than humans operate manufacturing have long existed (Ford 2015), manufacturing simply cannot function without some level of human involvement. PPOM-2 (employment planning) addresses the issue of hiring workers and scheduling them according to the needs of production. One fundamental difference separating this decision from production and inventory control is that human beings, unlike machines, are inherently flawed and need to rest at a certain point in time. Frederick Taylor (1914) was not the first to understand and formalize human limits, but he was certainly the first to attempt to systematically address them. Taylor contends that workers need to overcome the tendency to work below their capacity ("soldiering") to become "first-class men." Irrespective of whether Taylor indeed "fudged his data, lied to his clients, and inflated the record of his success" (Lepore 2009), his stopwatch system brought him global fame. It led to what may have possibly been the only U.S. legislation effort to endorse and publicize POM theory, and made him and his theory an indispensable part of business education. All these accolades, unfortunately, did little to help change capitalism's reputation of cruelty and heartlessness.

Consider a factory facing seasonable demand and that would thus have fluctuating inventory and capacity utilization throughout a year. Assuming a fixed workforce size, PPOM-1 helps optimize the production and inventory decisions. PPOM-2, on the other hand, addresses the issue of employment planning in one two ways: First, make hiring and firing decisions dynamically. According to *laissez-faire* capitalism, the factory can hire and fire workers flexibly depending on the needs of production over time: hire more to meet increased demand, and lay off workers to meet decreased demand. Yet, in the real world, hiring, and particularly firing, can be very costly, time-consuming, and distressing. Thus, sophisticated planning is in order. Second, maintain a largely fixed workforce size, but absorb demand fluctuations with overtime work and possibly part-time workers. Holt et al. (1955) contend, “Order fluctuations should, in general, be absorbed partly by inventory, partly by overtime, and partly by hiring and layoffs, and the best allocation among these parts will depend upon the costs in each particular factory.”

Jointly, PPOM-1 and PPOM-2 aid in a factory’s production, inventory, and employment management. A sizable factory often consists of multiple production stages (cells), and coordination between these stages can be a major challenge; failure to coordinate leads to frequent blocking and starving at various stages, requiring (sometimes excessive) inventory buffering.

Assuming some uncertainty in the production process, achieving “just-in-time” production in a literal sense is impossible. Is there a practical way to partially achieve it? The kanban approach, developed in 1947 in Japan by Taiichi Ohno in the Toyota Motor Corporation, provides an answer (Monden 2011). A kanban is simply a card, and each production unit has a fixed number of kanbans. The circulation of kanbans provides an informative signal regarding each unit’s inventory status; each machine will remain idle, even with all the necessary parts, until the next machine is ready to receive the next batch of parts. Kanban provides a revolutionary “pull” alternative to the more traditional “push” manufacturing system, in that it insists customer demands drive production, and each cell’s production is driven by the downstream cell’s requirements. The “pull” approach minimizes human-made interruptions and delays, and enables a smooth production process in which materials flow through the entire sequence smoothly following customer orders.

The kanban system has been highly successful and has found numerous applications in manufacturing firms worldwide. Tayur (2000) tells of four employees of an Ohio laminate plant who approached him in the summer of 1992 to help them implement a kanban system in their plant. When he asked them why they wanted a kanban system, they answered simply and firmly, “It will make us profitable again.” In a separate episode, Steve Jobs, in 1986, insisted on following the kanban system in designing the product line for the NeXT computers. According to Isaacson (2011, p. 225):

> [Jobs] insisted on building his own fully automated and futuristic factory, just as he had for the Macintosh... He insisted that the machinery on the 165- foot assembly line be configured to move the circuit boards from right to left as they got built, so that the process would look better to visitors who watched from the viewing gallery. Empty circuit boards were fed in at one end and twenty minutes later, untouched by humans, came out the other end as completed boards.

The transition from “push” to “pull” not only challenges traditional managerial thinking, but also defies the classical queuing network models, in which each stage of a tandem queue is often triggered by its preceding stage. The classical sample path techniques become unreasonably cumbersome, and a new technique is needed. Tayur (1992, p. 298) joyously announced, “Fortunately, such a technique has recently become available.”

4.2 POM outside the Factory

A factory never exists for its own purpose. Adam Smith recognizes this fact in *The Wealth of Nations* (1776, Chapter V), writing that,"If [an item] was produced spontaneously, it would be of no value in exchange, and could add nothing to the wealth of the society". Although large-scale production was made possible by the invention of automated assembly lines, its existence was driven by modern freight transportation networks. These networks overcame geographic disconnections between different markets and generated sizable factory orders, making large-scale production a necessity.

PPOM-4 (network design and flexibility) aims to address the following question: What are the best locations for suppliers, production sites, assembly lines, and distribution centers to satisfy customer demand? In other words, what is the best configuration of a firm's supply chain network? The solution to PPOM-4 often requires a network way of thinking.

Lee and Billington (1993) study the problem of managing material flows at the Hewlett-Packard Company (HP). They recognize that inventories stored at different locations have different cost structures and abilities to meet customer orders. Hence, HP needs to control inventories "along the chain while maximizing customer service performance." A more treacherous challenge, however, is the decentralization in decision-making, because many firms "have intentionally decentralized operational control of their business units or function," which makes information flows "restricted or costly so that complete centralized control of material flows may not be feasible."

Among POM researchers' efforts to facilitate the implementation of centralized model outputs in decentralized, multi-agent settings, Tayur (2013, p. 6851) coined the term "management mechanics," a comprehensive modeling method building on "staged optimization":

> A modeling framework and solution proposal should allow for partial changes in the decisions in a sub-network holding the rest somewhat constant, and then, increase the range and scope of decisions being changed. What is needed is a comprehensive model that allows for what I call "staged optimization" deliberately restricting some variables to be within a certain range for the time being. That is, a controlled release in concert with the organization's capacity to absorb change, in rhythm with their existing processes and compatible with their IT systems.

Another vexing operational challenge outside the factory is the logistics network planning under *non-stationary* demand (a.k.a. seasonal demand) (PPOM-5). Bradley and Arntzen (1999) report "severe end-of-quarter demand spikes" at an electronic firm, and refer to the demand pattern as "the hockey-stick pattern." Similar to PPOM-2 (employment planning), an obvious tradeoff exists between capacity expansion and inventory buffering. Interestingly, regarding the actual decision-making mechanisms at the firm, different entities manage these two levers. To be able to influence the firm's capacity decision-making, Bradley and Arntzen (1999) wrote that, "It was crucial that our analysis convinces managers responsible for capacity decisions that the implications of our model regarding capacity investment were appropriate."

One approach to handling non-stationary demand is to model the demand process as a Markov-modulated Poisson demand process, and find optimal safety stock levels at various inventory nodes (e.g., Chen and Song 2001). Graves and Willems (2008), on the other hand, develop a discrete-time model with several key assumptions, and show that a constant-service-time policy is near optimal and "has obvious implementation advantages." Tardif et al. (2012) solve PPOM-5 by redesigning Deere & Company's outbound distribution network to better serve its extensive distribution network consisting of 2,500 independent dealers. To keep the logistics costs low and maintain service requirements for Deere's highly seasonable products, the company deployed different tactics during the peak and off-peak selling and shipping seasons. While recognizing the value of formally treating the "trade-offs between transportation, warehousing, and inventory replenishment decision."

4.3 Interface between the Inside and the Outside of the Factory

The activities inside and outside the factory are inherently connected and interact. Therefore, when making operational decisions, a modern manufacturing manager should not pretend those decisions are isolated. PPOM-6 (inventory management with service-level requirements) significantly extends the scope of PPOM-1 (production and inventory control) in that it deviates from the hidden critical assumption that the demand is outside the firm's control. Instead, PPOM-6 aims to directly incorporate and influence product availability through improving the production, inventory, and distribution decisions.

An industry-scale implementation at Caterpillar (Keene et al. 2006), which has a complex product line and faces competition in a global marketplace, aims to increase the firm's product availability. This goal entails answering the following questions: (1) "What product availability is possible and at what cost and inventory levels?" (2) "What inventory reduction is possible?" (3) "What mix and deployment of inventory will enable BCPD (the Building Construction Products Division) to improve and stabilize product availability while minimizing total chain inventory?" (4) "Does BCPD have the data and systems it needs to optimize inventory and meet its product availability objectives?" The outcome of the project demonstrates the power of POM in manufacturing: the standard deviation of product availability was halved, whereas the mean lead times shrank by 20%.

Among the POM researchers and practitioners' efforts in bridging the inside of the factory with the outside, PPOM-7 (product design) reflects a radical way of thinking: the lever here is not simply inventory, capacity, or network configuration. Rather, it aims to fundamentally change the design of the product in order to serve customers better at lower costs. As with several PPOMs mentioned previously, this problem emerges only because today's factories face a multitude of demands from aspiring customers. Lee (1992) states that, "product proliferation creates a major operational challenge to managers of a manufacturing enterprise. It's difficult to forecast demands accurately, leading to high inventory investment and poor customer service."

Specifically, what is the best way to avoid inventory wastage due to product proliferation? The answers may involve PPOM-4, PPOM-5, and PPOM-6, as well as changing the manufacturing process itself. Lee and Tang (1998) formalize the concept of delayed differentiation according to which managers would not commit work-in-process (inside the factory) to a particular custom option until a later point, so that the firm can gain better demand information (from outside the factory). The so-called "vanilla boxes" (i.e., an assembly process using semi-finished products) idea, emerging out of IBM's product-development practice, and studied by Swaminathan and Tayur (1998), proposes planning inventories in advance to react to market demand responsively, while maintaining an array of customer options.

Lastly, PPOM-8 (lead-time quotation, i.e., providing customers with quotes of lead times for make-to-order operations, also called "due-date setting") is relevant to the Internet age in which customers desire more product choices shipped at a faster pace. This requirement would naturally influence what is happening inside the factory. Keskinocak et al. (2001) consider a factory making orders of customized tools for steel mini-mills to produce specialty steel. Because little uncertainty exists in the actual production process for each family of products, the authors argue that "the key challenge in managing this business is thus not in manufacturing, but rather in the interface between manufacturing and customer service representatives (CSRs), the functional group that accepts orders and guarantees lead times to the customers who demand customized rolls and whose order process is not easily predictable." This consideration needs to be directly factored into the factory's objective function because the revenues decrease the quoted lead-time.

In general, the manufacturer can quote multiple lead times for differentially patient customers. Palmbeck (2004) observes that among BMW customers, those in Germany can often wait for one or two months, whereas those in the United States and Europe are reluctant to wait for more than one week. Thus, the factory's problem goes beyond production scheduling, and entails capacity and pricing decisions.

5 Capital versus Labor

Consider the following encounter between PPOM-2 and PPOM-3 (Isaacson 2011, p. 184): the "Cuba-admiring wife of France's socialist president François Mitterrand" Danielle's visit to Apple factory, accompanied by Steve Jobs:

> [Mitterrand] asked a lot of questions, through her translator, about the working conditions, while Jobs… kept trying to explain the advanced robotics and technology. After Jobs talked about the just-in-time production schedules, she asked about overtime pay. He was annoyed, so he described how automation helped him keep down labor costs, a subject he knew would not delight her. "Is it hard work?" she asked. "How much vacation time do they get?" Jobs couldn't contain himself. "If she's so interested in their welfare," he said to her translator, "tell her she can come work here any time."

One can fairly say the tension between labor and capital has *always* been a focal point of the manufacturing sector over its course of evolution. Inherently, according to Karl Marx (1973, p. 325), "Capital and labour relate to each other here like money and commodity; the former is the general form of wealth, the other only the substance destined for immediate consumption. Capital's ceaseless striving towards the general form of wealth drives labour beyond the limits of its natural paltriness…"

Industrial capitalism—as opposed to *merchant capitalism* from the 1550s to1800s: "someone with wealth might become a merchant, investing in wagons or boats to transport goods to places where price were higher" (Phelps 2013, p. 2)—started around the early 18th century, and reached its peak in the late 19th century. Mark Twain coined the term "the gilded age" to refer to the period around 1870-1900 that featured an unprecedented level of wealth in a society that was driven largely by "*Beautiful credit! The foundation of modern society*."

Ironically, almost two centuries later, the fact that we are now living in "the second gilded age" is striking (Fraser 2015). The increasing level of economic inequality—more low- and high-income individuals in the population but fewer in the middle-income range—is disconcerting. Why does inequality matter to the future of manufacturing? The prosperity of manufacturing creates a solid base of middle-class consumers who, in return, drive the demand for more and better products. This virtuous loop that has powered the manufacturing sector for more than a century will lose its magic without a sufficiently large proportion of the workforce having solid earning powers.

As we previously discussed in PPOM-2, managing a workforce has traditionally involved no more than hiring, firing, and deploying. In the past decades, robotics has significantly enhanced automation and reduced the need for blue-collar workers. Another technology significantly influencing today's labor practice is real-time productivity monitoring, the technology underlying which is enormously attractive for its newness, as stated by David Cozzens, the CEO of Telogis, a company specializing in providing telematics to commercial trucking fleets (Kaplan 2015). Cozzens wrote that, "it was big data. It was the Internet of things. It was cloud computing; it was mobile; it was really a new market, with low penetration."

Firms are leveraging real-time productivity-monitoring tools to track their employees' performance on an hourly or more frequent basis, which, ironically, has driven the emergence of a new oxymoron—permanent part-time jobs.

The so-called "sharing economy," epitomized by Uber, has also led to dramatic changes in the form of labor, which may be phrased as "uber-ized" workers. Although this solution seems novel, it does not come with benefits such as health insurance or social security that are crucial in maintaining a middle-class lifestyle. In addition, much of the sharing economy reduces demand for durable products, which in itself is not good news for the manufacturing sector. The technology and operational innovations may look fancy, but, Fraser (2015, p. 326) wrote that, "How odd this fancy seems. Our new system of flexible global capitalism, including the American branch, is increasingly a sweatshop economy."

Before making any attempt to address economic inequality, we need to weigh the following question: Will the ever-increasing economic inequality jeopardize the future of manufacturing? Economists and political philosophers agree that excessive economic inequality is simply a symptom, and directly tackling the symptom may backfire (Allen 2015). Increased economic inequality is often either transitory or even beneficial to society. On one hand, Simon Kuznets (1955) famously proposed an inverted-U curve outlining the relationship between productivity and economic inequality: increased income per capita in a society initially leads to higher economic inequality. Once the income hits a threshold, the opposite is true. John Rawls (2009), on the other hand, contends that management practices widening economic inequality are moral if they benefit (or do not harm) the least advantageous group in absolute terms. These insights are helpful as we evaluate the social welfare implications of various technological and operational developments in the manufacturing sector.

6 Implications for Managers

Undoubtedly, managers have always been eager learners of well-known POM practices—as we have illustrated in the cases of Steve Jobs' just-in-time experiments at Apple, and Warren Buffett's inventory-management efforts at Dempster. Yet, managers often undervalue POM theory for at least two reasons. One, as mentioned previously, the theoretic development of POM often trails POM practice. Therefore, a significant proportion of POM studies, although truthfully reflective of POM practice, do not contain sufficiently refreshing "new news."

The good news is that the academic field of POM, by observing and improving practice while also keeping a healthy distance, can attract some of the most intelligent minds. "The price to be paid for keeping good scientists," as Simon (1976, p. 347) points out, is that "a certain part of their activity will simply result in good science, not particularly relevant to the specific concerns of business." In our view, the price is perfectly reasonable and provides managers with the advantage of a never-ending stream of first-class researchers who, from time to time, make important breakthroughs (e.g., stochastic inventory models and computational techniques) influencing worldwide practice.

For instance, the rise of private equity (PE) funds has made the role of POM more visible, because POM can be effectively utilized to orchestrate technologies to improve a manufacturing firm's profitability and thus return on assets. In an interview (Camm and Tayur 2010, p. 449), Tayur provides an example of a capital-driven, POM-empowered bailout effort of a dying factory:

> One particular company was an amazing experience in which we repurposed a foundry that was making parts for the automotive industry … into making parts for wind energy. Our investment of $3 million in 2002 returned over $34 million in 2008. Nearly half of this return can be tied to OM projects—which improved capacity flexibility, reduced scrap, and institutionalized lean practices—and strong inventory-control techniques.

The future of manufacturing will crucially depend on practitioners' and researchers' co-creation of POM theory and practice: a rigorous academic discipline attracts the best and brightest minds to advance the theory, while the close collaboration between practitioners and researchers ensures the manufacturing sector continues to shape and enrich the discipline, which, in return, helps manufacturing regenerate itself and flourish.

7. Conclusion: The Future of POM and Manufacturing

A manufacturing revolution is underway due to major technological advances. In this section, we outline several new patterns in the future of manufacturing and their implications on POM research.

First, additive manufacturing technologies (e.g., 3D printing) and direct-to-consumer distribution through the Internet will change the work patterns of manufacturing organizations, such as healthcare manufacturers (Rifkin 2014). These technologies may fundamentally change the global landscape of the manufacturing sector. For example, 3D printing will mean a reduced need for outsourcing small, complex specialty products to suppliers in developing countries, which provides dual advantages in that (1) the manufacturer can function with *zero* finished-product inventory, and (2) the manufacturer can produce close to where demand exists. For POM researchers, this paradigm shift calls for not only a new set of quantitative modeling tools, but also empirical studies identifying effective managerial practices.

Additive manufacturing technologies, due to their unprecedented and ever-increasing affordability, will also empower the marker movement, a.k.a. the "third industrial revolution," that promotes "good taste and self-fulfillment through the creation and the appreciation of beautiful objects" (Morozov 2014, p. 69). To use Maslow's theory of a hierarchy of needs, this movement will facilitate a transition from producing abundant generic products satisfying customers' basic needs (physiological and safety) to empowering "prosumers" (as opposed to customers) who create and manufacture, driven by their own needs for belongingness/love, esteem, self-actualization, and self-transcendence. The purpose is not to substitute higher-level needs with industry products, but rather to complement, enrich, and elevate an individual's pursuit of such needs. Can POM go beyond firms' profit maximization and help individuals reach their personal goals? In addition to journal and conference publications, can POM researchers publicize their intellectual findings in more tangible and accessible ways, such as mobile applications and software from which consumers can readily benefit?

Second, the Internet of Things (IoT), the formation of an interconnected computer network of machines and locations through wide availability of affordable sensors, will be a major shaper of the future of manufacturing. Thanks to the popularity of smartphones, wearable devices (e.g., Apple Watch, Google Glasses, activity trackers), and RFID, IoT has been available even in some of the least materialistically rich countries. IoT makes the world of manufacturing more tractable and transparent, and has potential applications to manufacturing operations such as quality control. IoT also provides the *ubiquitous computing* capability that may alter the workings of the enterprise inventory optimization system. POM researchers may start revisiting some of the commonly made assumptions, especially those regarding information-sharing mechanisms between firms: Are the traditionally accepted principal-agent theory, and more broadly, informational economics models applicable to new realities?

Third, an increasingly robotized manufacturing sector kills traditional blue-collar jobs that previously had to be performed by human beings, but creates middle-class jobs that never existed before. With skyrocketing labor costs in China and the continued lack of sophisticated infrastructure in much of the underdeveloped world necessary for global manufacturing, the trend will become global. Today, major manufacturing firms in China's Pearl River Delta Region, which makes the majority of the world's apparel, electronic, and high-tech products, have switched to fully or partially automated facilities. This will contribute to widespread structural unemployment over many parts of the world, at least for the foreseeable future. Does POM have a role in shaping a better future for manufacturing by helping to provide abundant and well-paid manufacturing jobs? Extensive studies allude to conditional positive answers in the retail sector, and some of the ideas may be applicable to manufacturing (Zeynep 2014). POM researchers can participate in the public discourse on speeding up automation in manufacturing by helping to craft operational strategies that make structural unemployment, as the society transitions to a more knowledge-intensive economy, less painful.

Fourth, after being leapfrogged by emerging economies in various technological and operational frontiers, the United States and Europe are set to become the "new emerging economy" (Zweig 2013), with better infrastructure, rule of law, and globally competitive human costs, leading to the booming of backshoring. This transition is largely driven by technological innovations and will drive the need for operational innovations, in both theory and practice.

Today's economy, to quote Arthur (2009, p. 209), "is becoming generative. Its focus is shifting from optimizing fixed operations into creating new combinations, new configurable offerings." POM should continue to play the role of orchestrating technologies in building a better future for manufacturing. We echo the sentiments of Ovid at the end of this chapter, "Let others praise ancient times; I am glad I was born in these."

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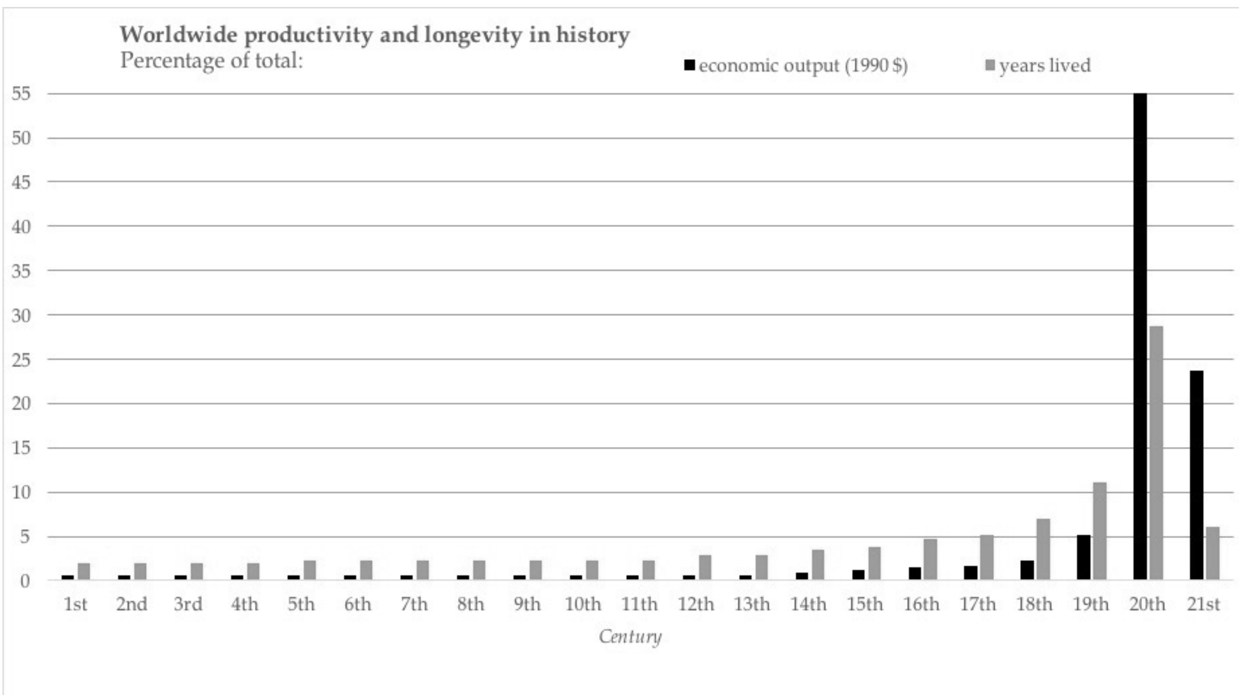

Figure 2 Worldwide productivity and longevity in history.
The *y*-axis shows the percentage that each century's population-weighted history accounts for the entire human history. Adapted from The Economist (2011)

Table 1 Practical Problems in Operations Management (PPOMs)

Category	Application Areas	Selected POM Contributions
Inside the factory	PPOM-1: Production and inventory control	Simon (1952), Wagner and Whitin (1958); Stecke (1983), Roundy (1985), Bowman and Muckstadt (1993), Glasserman and Tayur (1995), Jordan and Graves (1995), Anupindi and Tayur (1998), Kapuscinski and Tayur (1998), Markowitz et al. (2000), Levi et al. (2006)
	PPOM-2: Employment planning	Holt et al. (1955), Schild (1959), Hanssmann and Hess (1960), Buffa (1967)
	PPOM-3: Management of kanban-controlled systems	Deleersnyder et al. (1989), Mitra and Mitrani (1990), Tayur (1992, 1993), Veatch and Wein (1994)
Outside the factory	PPOM-4: Network design and flexibility	Lee and Billington (1993), Huchzermeier and Cohen (1996), Rao et al. (2000), Graves and Willems (2000, 2005)
	PPOM-5: Inventory placement and logistics with non-stationary demand	Bradley and Arntzen (1999), Chen and Song (2001), Graves and Willems (2008), Tardif et al. (2010)

	PPOM-6: Inventory management with service-level requirements	Gerchak et al. (1988), Glasserman and Tayur (1995), Ettl et al. (2000), Troyer et al. (2005), Keene et al. (2006)
Interface between the Inside and the Outside of the Factory	PPOM-7: Product design	Lee (1996), Lee and Tang (1997), Swaminathan and Tayur (1998), Yunes et al. (2007)
	PPOM-8: Lead-time quotation	Duenyas and Hopp (1995), Anupindi and Tayur (1998), Tayur (2000), Keskinocak et al. (2001), Plambeck (2004), Kapuscinski and Tayur (2007)