From Filing and Fitting to Flexible Manufacturing

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Ramchandran Jaikumar

(1944-1998)

the essence of knowledge
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FROM ART TO SCIENCE IN MANUFACTURING: THE EVOLUTION OF TECHNOLOGICAL KNOWLEDGE

Roger E. Bohn

Preface

This issue of *Foundations and Trends™ in Technology, Information and Operations Management* presents a classic but previously unpublished monograph by Ramchandran 'Jai' Jaikumar (1944–1998) on the history of manufacturing. The development of mass manufacturing ranks as one of the most important contributions to human welfare ever – of the same magnitude as agriculture and modern medicine. Many authors have addressed seminal changes in manufacturing history, such as the Industrial Revolutions, but this monograph takes a longer perspective. It follows the development of manufacturing from the Renaissance to 1985, and shows how manufacturing underwent multiple conceptual transformations, in which changes in technology led to shifts in the nature of work itself. These epochal transformations are emphasized by following the progress of a single industry – firearms – and single company – Beretta – over the entire period. Since the essence of the product changed little over the entire period studied – a chemical explosive pushes a projectile through a metal cylinder – firearms manufacture is an unusually clear opportunity to study changes in hard and soft manufacturing technologies. The most far-reaching changes were in process control, from the use of dimensional measurements around 1800 to the introduction of unmanned machining around 1980.

Each such shift required new ways of organizing work and a different ethos of management. Machinery, organization, scale, product line, and many other factors all had to change in concert to properly exploit the new concepts. And each new epoch represented an intellectual watershed in how people thought about manufacturing.

Prof. Jaikumar wrote the original monograph in the late 1980s while he was on the faculty of the Harvard Business School. [21] Although in that pre-Internet era it was available only as a hard-copy working paper, it became widely known and cited. Professor Jaikumar intended to publish it eventually, paired with a similar longitudinal examination of a continuous process industry. But other projects intervened, and it was never published. Professor Jaikumar died tragically in 1998, leaving behind a legacy of published and unpublished research. When Professor Uday Karmarkar of UCLA approached me for contributions to his new journal, I immediately suggested this piece.

I have made few changes to the main text – primarily clarifications. I have not attempted to incorporate research on manufacturing history done in the last 15 years, and the results are inevitably incomplete. I apologize for the errors and omissions. In partial recompense, I solicit comments and supplements to this monograph, and will undertake to add them to the Web version. I am especially interested in short essays that comment on the evolution of manufacturing in the last 20 years. For example, is the final epoch in the text, the Computer Integrated Manufacturing/FMS epoch, still the last word, or can we distinguish a new epoch, one based on computer networking? How should we think about process control extending across entire supply chains?

In conjunction with Prof. Jaikumar's original monograph I have written a new paper developing one of his themes in more detail: the transformation from art to science in manufacturing. [7] By taking advantage of concepts we developed jointly subsequent to his original monograph, I attempt a more precise and thorough treatment of this topic. Our hypothesis was that the shift from art towards science corresponds to changes in both knowledge about and process control of the physical technology. We developed a framework for describing technological knowledge that makes it possible to track changes in knowledge in great detail, identify gaps in knowledge, and describe trajectories of change. Firearms manufacture provides an excellent case study for testing these ideas using historical evidence. This paper will be published in a separate issue of *Foundations and Trends*; they will be merged in the book version. I have also included a short biography of Ramchandran Jaikumar, who had a unique range of interests and passions.

The passage of time and my own ignorance make it impossible to thank everyone who contributed to this research, but I know Jai would have singled out a few in particular. Beretta's management made this unique longitudinal research possible by providing assistance and access to the company archives. John Simon, who edited many of Jai's works, provided critical assistance with writing and research of both the original monograph and this version. The Harvard Business School and its Division of Research provided financial support. Baker Library and the Library of Congress provided access to rare illustrations from the 18th century. And Jai's wife Mrinalini and sons Nikhil and Arjun provided constant support. My own thanks to Uday Karmarkar and Zachary Rolnik for their support of this project, and to the Alfred P. Sloan Foundation for financial support.

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San Diego, California
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Introduction[1]

Process control is the coordination of machines, human labor, and the organization of work to effect the manufacture of a product. It involves the specification and monitoring of machine setups and operating parameters, formulation of rules and procedures to govern operator–machine interactions, and decisions about the utilization of, and sequencing of, operations on a line. Although the details of process control can be quite different in different industries, a common theme that emerges from its study is the *evolution of manufacturing from an art to a science*. Inasmuch as the long-term viability and manufacturing competence of a firm is intrinsically tied to how one manages this evolution, it is important to understand the factors that drive it.

Manufacturing technology is, in essence, the technology of process control. Because one finds in the metalworking industry a great variety of processes being practiced at any time, and because the industry is large and has a long history, it is a useful base from which to study evolving patterns of process control in the mosaic of machines, labor, and the organization of work. Because aggregate data at the level of

[1] This monograph by Professor Ramchandran Jaikumar is being published posthumously. Details are provided in the Preface – Roger Bohn, editor.

the industry does not lend sufficient relief to the shifts in this picture, we take, as our unit of analysis, a single firm and category of products.

Within the firm we study the evolution of process control from the perspective of the work station – the locus at which technology and work come together and manufacturing takes place. Because we are interested in a particular aspect of technology and work, namely manufacturing's shift from art to science, we also examine the thinking behind the ideas that have shaped process control and the cognitive components of work.

We focus specifically on the segment of the metal fabricating industry engaged in the manufacture of firearms. A number of major manufacturing innovations have had their seeds in this industry: development of machine tools at the Woolwich Arsenal; interchangeability of parts at the Whitney and Colt factories; Taylorism at the Watertown Arsenal. Considerable scholarship has been devoted to the study of this industry, and we are also aided by the existence of a single firm, Beretta (*Fabbrica D'armi Pietro Beretta SpA*), whose history includes the assimilation of each of these manufacturing innovations.

Based in the city of Gardone in what is now northern Italy, and controlled by the same family for fourteen generations since 1492, Beretta has been engaged in the manufacture of firearms for five hundred years. Whereas functionally the product has remained much the same, and manufacturing is still based on fabricating precise metal parts, the detailed processes by which it is manufactured have changed considerably over time. Thus, the firm provides as ideal a natural experiment as one could have. Although it originated none of the major metal fabricating innovations, Beretta was quick to adopt every one of them.

To illustrate how the transformation in manufacturing technology has come about, we visit the arsenals in which the various innovations originated – the Woolwich Arsenal in England and the Colt factory and Watertown Arsenal in the United States – and review the works of the originators. What these individuals thought about and did is the story of the evolution of process control in the metalworking industry.

1.1. The Case for "Epochal" Change in Manufacturing

It will become apparent as the story unfolds that process control has evolved in a succession of epochs, each characterized by a fundamental shift, or "revolution," in manufacturing technology, the organization of work, and the nature of the firm. The story is related from the perspective of the individual at a machine, where process control is effected and the changes can be seen most vividly.

Six epochs of manufacturing process control can be delineated, preceded by a pre-manufacturing epoch in which products were made but not manufactured.

(1) The **Craft System** (circa 1500)
(2) The invention of machine tools and the **English System of Manufacture** (circa 1800)
(3) Special purpose machine tools and interchangeability of components in the **American System of Manufacture** (circa 1830)
(4) Scientific Management and the engineering of work in the **Taylor System** (circa 1900)
(5) **Statistical process control** (SPC) in an increasingly dynamic manufacturing environment (circa 1950)
(6) Information processing and the era of **Numerical Control** (NC, circa 1965)
(7) Flexible manufacturing and **Computer-Integrated Manufacturing** (CIM/FMS, circa 1985)

The first change in the technology of manufacturing firearms came some 300 years after Beretta started making guns. It was the English System of Manufacture, which was introduced at Beretta after the Napoleonic conquest of the Venetian Republic and the establishment of a state-run arms factory near Beretta's location. Much of our understanding of how the English System changed the nature of work comes from a visit to the shop of Henry Maudslay. Sufficient records of this founder of the machine-tool industry exist to form a picture of workshops of the late 18th and early 19th centuries.

The next era, the "American System," is illuminated by a visit to the Colt Armory. It brought to a high state of refinement a system of manufacture based on the notion of interchangeability of parts and the development and use of special purpose machinery. This system was showcased at the Crystal Palace Exhibition in 1851, and within 20 years had been adopted in whole or in part by most of the armories in Europe. Beretta adopted the entire system, contracting with the American firm Pratt and Whitney to build a complete factory at its headquarters in Gardone. The third epoch was the Taylor System, which perhaps even more than the first two revolutionized manufacturing far beyond the firearms industry. Taylorism was the basis of the vast expansion in firearms and other metalworking during World War II. Because company records at Beretta are incomplete for this period, we turn to Hugh Aitken's detailed explication of the introduction of the Taylor System at the Watertown (Massachusetts) Arsenal around 1900.

The first three epochs – those characterized by the English, American, and Taylor systems of manufacturing – related to the material world of mechanization. Each saw the manufacturing world as a place of increasing efficiency and control, substitution of capital for labor, and progress through economies of scale. These objectives were obtained through an engineering focus on machines and what could be done with them. The role of labor was increasingly seen as one of adapting to the machines and the contingencies of the environment – ultimately, of being yet another machine. Concurrently, the machines themselves became more elaborate, capable of ever greater precision and control. Underlying these developments was the principle of *increasing mechanical constraint.*

Abbot Usher, a historian of technology, observes that

> some of the impressive improvement of machines consists of refinement of design and execution. The parts of the machine are more and more elaborately connected so that the possibility of any but the desired motion is progressively eliminated. As the process of constraint becomes more complete, the machine becomes

> more perfect mechanically … The general line of advance takes the form of substitution of the more intense for the less intense forces, grading up through a long sequence that begins with types of human muscular activity … There is a steady increase in potential (energy): we have to deal with a transition for machinery worked at a very low potential to machinery run at very high potential. The change in potential itself requires more and more careful constraint of motion because these highly intense concentrations of energy could not be applied to mechanisms until adequate control was possible. [34, p 116]

This world of mechanization reached its zenith in the 1950s. Already one could hear rumblings of a brave new world. In 1946 Brown and Leaver laid out, in a *Fortune* magazine article entitled "Machines Without Men," a blueprint for a new industrial order.[2] They had made the intellectual leap from mechanization to information processing. Norbert Weiner, in his prescient analysis of the power of information processing, gave credence to Brown and Leaver's world-view. Though it would be another forty years before we would see the first automated, workerless factories, the seeds for the emergence of a new paradigm were planted.

It is appropriate that James Bright completed his landmark study, *Automation and Management*, in 1958, for that year marks the end of the era of mechanization. Bright observed that

> the average manufacturing system of 1956 … can be regarded as no more than a crude assemblage of unintegrated bits of mechanism. These mechanisms themselves may reflect the utmost in the mechanical art of our times. Still, when collected under one roof and directed toward a particular production end, they are anything but a machine-like whole.
>
> A hundred years from now the average factory of our day may be regarded as having been no different in philosophical concept from the factory of 1850 … (Process) "design" has meant

[2] Cited in [29, p 68-70].

> the collection of equipment for a production sequence – not the synthesis of a master machine. [8, p 16]

The glue that makes a collection of machines a manufacturing system is people processing information. The lack of integration Bright speaks of, and the intelligence needed to make machines function, were the focus of the three post-War epochs. The fourth epoch – the Statistical Process Control era – began in the 1930s in the electrical equipment industry, but in the 1950s Beretta was a leader in its implementation in arms manufacture. The fifth epoch grew out of numerical control, while the sixth and final epoch is the world of computer-integrated manufacturing and flexible manufacturing systems. Beretta was an enthusiastic adopter of all three and the discussion of these epochs therefore focuses on its experiences.

Collectively, these three epochs constitute a fundamental shift in the paradigm of production – from a world-view of managing *material transformation* to one of managing *intelligence*. This shift heralds a radical departure in the way we conceive of manufacturing. It is in promoting an understanding of the nature and impact of this transformation that this paper makes its principal contribution. In the dynamic world characterized by statistical process control, numerical control, and computer integrated manufacturing, we see a reversal of the trends of mechanization: increasing versatility and intelligence; substitution of intelligence for capital; and economies of scope rather than scale. Machines are increasingly seen as extensions of the mind meant to enhance the cognitive capabilities of the human being.

1.2. The Long View

An incontrovertible trend we see through the six epochs of process control is the evolution of manufacturing from an art to a science. As we shall see, each epoch represented an attempt to achieve a particular goal in the management of system variation, namely: accuracy, precision, reproducibility, stability, versatility, and adaptability. In the early epochs Beretta and its industry developed measures of the product, then gained control of the process. Next it mastered variability, first in the machine, then in the human. Finally, it studied, and then controlled, contingencies in the process until it was able to extract general principles and technologies that apply in a variety of domains. In short, it achieved *versatility*. It will become apparent that the ethos of process control required to manage each of these is quite different. It is extremely difficult for a firm to manage the conflicting demands of two successive process control paradigms. Therefore, the management of technology required a quick transition from one to the other.

There is a consistency in these six epoch shifts as they were experienced by Beretta.

- Each epochal change represented an intellectual watershed as to how people thought about manufacturing and its key activities.
- Each epoch entailed the introduction of a new system of manufacture; machines, the nature of work, and the organization all had to change in concert to meet a new technological challenge.
- The technological change of each epoch focused on the solution of a new process control problem, but in all six cases this problem revolved around controlling variation.
- Most of the gains in productivity, quality, and process control achieved by Beretta over its 500-year history were realized during the assimilation of the six epochal changes and very little in between.
- It took about ten years to assimilate the change incurred by each epoch.
- All of the changes were triggered by technology developed outside the firm.

Clearly, each of these epochal changes could affect all metal fabricating industries, and they did. But by examining these changes at the level of the work station in a single firm concerned with the manufacture of a single type of product, the firearm, we can see their impact in sharpest relief and observe a consistency that suggests powerful lessons for the management of technology. Our objective in scrutinizing a variety of historical records is not to trace the origin of ideas in process control, or even the full impact of those ideas on manufacturing, but rather to analyze how they have changed the *nature of manufacturing*, effectively moving manufacturing from an art towards a science.

Table 1.1 summarizes some of our findings about the six epochs along dimensions that provide insight into the nature of these epochal shifts.

1.3. Plan of the Monograph

The balance of this introduction discusses the fundamental technical problem of manufacturing, namely controlling the variation inherent in any physical process. Section 2 describes the way firearms were made before the development of manufacturing, by individual master craftsmen. Sections 3 through 8 describe the six manufacturing epochs, in chronological sequence. Beretta's own experiences are discussed, as well as the historical origins of each epoch. In each case, the radical nature of the transformation from the previous epoch is emphasized.

Section 9 concludes the monograph by pointing out how in some ways the nature of manufacturing today resembles that of 200 years ago. A few dozen expert workers with high discretion produce a wide variety of products. Yet other aspects have changed beyond recognition. Human muscle power is irrelevant, output per worker is up 500-fold, and rework is virtually zero.

This monograph is intended to be read in conjunction with additional material. The Preface introduces the monograph and explains its origins. A biography of the author appears at the end. A companion article extends the theme of "manufacturing moving from art to science." It provides a precise model of what this means. The level of detail of technological knowledge increases over time, approaching but never reaching comprehensive scientific "first principles" models of all key phenomena. This permits more decisions to be made according to programmed procedures, without human discretion, as described in the current monograph. These two dimensions, of knowledge and control, tend to grow in concert. When technologically disruptive innovations arrive, however, they step backwards because the detailed knowledge

		English System	American System	Taylor System	Statistical Process Control	Numerical Control (NC)	Computer Integrated Manufacturing
Size Trends	**Introduced at Beretta** (world)	1810 (1800)	1860 (1830)	1928 (1900)	1950 (1930)	1976 (1960)	1987
	# of People (Min. Scale)	40	150	300	300	100	30
	Number of Machines	3	50	150	150	50	30
	Productivity Increase *	4:1	3:1	3:1	3:2	3:1	3:1
	Number of Products	Infinite	3	10	15	100	Infinite
Nature of work	**Standards for Work**	Absolute product	Relative product	Work standards	Process standards	Functional standards	Technology standards
	Work Ethos	"Perfection"	"Satisfice"	"Reproduce"	"Monitor"	"Control"	"Develop"
	Worker Skills Required	Mechanical craft	Repetitive	Repetitive	Diagnostic	Experimental	Learn/ generalize/ abstract
	Control of Work	Inspection of work	Tight supervision of work	Loose of work/ tight of contingencies	Loose supervision of contingencies	No supervision of work	No supervision of work
	Organizational Change	Break-up of guilds	Staff-line separation	Functional specialization	Problem-solving teams	Cellular control	Product/Process/ Program
	Staff/Line Ratio	0:40	20:130	60:240	100:200	50:50	20:10
	Line Workers per Machine	15	3	1.6	1.3	1	0.3
Technology Keys	**Process Focus**	Accuracy	Precision: Repeatability (of machines)	Precision: Reproducibility (of processes)	Precision: Stability (over time)	Adaptability	Versatility
	Focus of Control	Product functionality	Product conformance	Process conformance	Process capability	Product/ process integration	Process intelligence
	Instrument of Control	Micrometer	Go/No-Go gauges	Stop watch	Control chart	Electronic gauges	Professional workstations
	Rework**	.8	.5	.25	.08	.02	.005
	* Over previous epoch * *As fraction of total work						

Table 1.1 Summary of manufacturing epochs

underlying the innovation must be developed. The current state of knowledge and its evolution can be captured by directed graphs showing current knowledge about the technology.

1.4. Control of Variation

Historical studies of manufacturing evolution typically emphasize issues related to scale and energy, such as the evolution of power sources from human/animal power, to water power, to steam, to electricity. Superficially, the increasing intensity of energy use enabled the long-term manufacturing trends of increasing speed and scale – machines that go faster and make more at a time. But in technological terms power is secondary. Crudely applying more force has been feasible, at least since the invention of steam engines, just by building bigger mechanisms. But with no corresponding progress in control, a bigger process will only make junk more rapidly. Therefore the key to progress has been gaining better *control* over manufacturing processes, which permits simultaneous increases in both precision and force.

Consider a product that comprises two or more metal components that must be joined together. The manufacture of such a product entails two types of processes: *fabrication* processes by which individual components are formed, and *assembly* processes that marry the discrete components into subsystems and a final system. For our purposes, it is sufficient to say of the latter that it comprises a sequence of operations whereby the constituent pieces of a product are selected, located, fitted, and bonded. It is with the former set of processes – those that govern metal fabrication – that we are primarily concerned in tracing the evolution of process control.

The purpose of a metal-fabricating process is to create, according to precisely prescribed specifications, the form, physical characteristics, and finish of a metal component (part). The process is executed by a set of people, machines, and procedures, and a measure of their effectiveness is the ability to produce correct and specific parts. Inasmuch as a process never performs identically each time, some variation in the parts produced is inevitable. Sources of variation lie in people, machines, and procedures, as well as in the object being fabricated. A measure of the effectiveness of process control is the degree to which variation is minimized. The goal of process control is to limit such variation, and *the study of process control is the study of the kinds of variation that can occur, their sources, and the means by which they can be managed.*

Proper functioning of the finished product depends on multiple characteristics of each component, such as physical dimensions, strength, and surface finish. The desired level of each characteristic is its *target specification.* For example, consider two metal parts which are intended to fit together by having a cylindrical peg on one part that fits into a round hole on the other, such that they can rotate relative to each other. Obviously, the diameter of the peg must be no greater than that of the hole, else they won't mate. But if the peg is too much smaller than the hole the parts will rattle against each other, and the mechanism will work poorly or not at all. The product designer deals with this by specifying a target diameter for the peg and the hole such that they will fit properly, and a range of allowable variation around the targets. Such targets are called *specifications*, and the ranges are called *tolerances.*

But the realized characteristics of components produced by a particular process are not identical to the target specification or to each other, so their behavior must be described by frequency distributions. The difference between the achieved mean dimension and the target specification is the *accuracy* of the process. The variation of the distribution around its mean tells us to what degree the process is capable of achieving the desired performance; the smaller the dispersion around the process mean the more capable the process. The reciprocal of the variance is the process *precision*, which measures the ability of a machine to execute identical performances and the ability of people and procedures to direct the machine.

Variation arises from a multitude of sources. To overcome variance attributable to machines we strive for *repeatability*; to overcome variance attributable to people and procedures we strive for *reproducibility.* If we measure, for a single component and dimension, the means for sequential lots we would find that over time the mean of the process changes. The standard deviation over time of the process mean, defined as the *stability* of the process, is a measure of how well it performs over time. *System variance* is the net variance due to accuracy, repeatability, reproducibility, and stability.

The above measures of variance assume that we have not made any adjustments to the process. In practice, we always make adjustments to a process when something goes wrong and a process that accommodates such adjustments is obviously desirable. Accuracy, as noted earlier, is the systematic bias in a process, stability the manner in which that bias shifts over time. To the extent that we can adjust the process we can correct the bias and bring it closer to the desired standard. The capability of a process to make dynamic adjustments and correct for bias is termed *adaptability*.

The requirement for adaptability is quite different depending on whether we want to make one component or a large number of identical components. To be adaptable with a sample of a single component a process must have a high degree of accuracy. More important in a process for producing large quantities are precision and stability, as we can almost always compensate for inaccuracy by making adjustments. The greater the stability of a process, the less frequently it will have to be adjusted.

Before proceeding with our discussion of the evolution of process control we need to define a further notion, that of *versatility*. Versatility is the ability of a process to accommodate variety in product specifications. It is quite different from the notions discussed above, yet it has important implications for process control. As greater versatility usually reflects greater complexity in a task, the sources of variation can be expected to increase when versatility increases, if no other changes are made.

Process control is central to manufacturing because better control reduces variation, which enables a number of benefits: higher production rates, lower rework, tighter tolerances, and less raw material. In turn these improve characteristics that end-users care about: cost, product variety, and product quality. For firearms, product quality measures enhanced by reduced variation include weight, power, durability, and shooting accuracy. The benefits are taken as some combination of these attributes depending on market preferences, such as the orders of magnitude improvements in both firearms manufacturing productivity and product performance over two centuries. In the end a seemingly manufacturing-specific issue, process variability and its control, is at the center of the technological and economic revolutions of the last centuries.

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