Taylor's Unsung Contribution: Making Interchangeable Parts Practical

John Paxton
Wayne State College

For at least two centuries before they became practical, manufacturers and craftsmen searched for techniques to make identical parts that would exchange quickly and readily between machines of the same type. However, they failed and the solution was not found until the turn of the 20th century. The problem was straightforward, even if its solution was not. This solution is largely unreported in the literature, despite the importance of both the problem and its solution. The idea that the solution came from one of management's giant figures makes this even more difficult to believe, yet it is so.

Frederick Winslow Taylor scarcely needs an introduction. Familiar to any student of management, Taylor is acknowledged as the father of scientific management and the first to bring the scientific method to the study of production and business. His *Principles of Scientific Management* and *The Art of Shop Management* are classics and still available through booksellers, despite being a century old now. Although largely discredited for their (seemingly) narrow focus, they remain as some of the first applications of the scientific method to the art of business, and were largely responsible for the establishment of management as a profession and academic discipline.

Because of this towering reputation, it is often forgotten that Taylor was first educated as a machinist through apprenticeship and later earned a Bachelor's Degree in Mechanical Engineering as a young man. After several other industrial jobs, Taylor came to Bethlehem Steel, where much of his ground-breaking work was done.

This paper is about Taylor's scarcely-acknowledged work relative to part interchangeability and his research that made truly interchangeable parts a practical proposition. The concept of the economical, interchangeable part is the foundational assumption upon which mass production, and thereby modern economies, rests. Without interchangeable parts, there would be no mass production and the quality of modern life would be vastly diminished. Therefore, the very practice of modern management, resting on the accomplishments of Henry Ford (mass production industrial technique) and Alfred Sloan (modern organizational structures and practices, based on high-volume mass production), rests ultimately on the solution to the problems preventing the manufacture of economical interchangeable parts. Frederick Taylor and his team solved these problems.

The literature on "interchangeable parts" stresses the importance of this concept in manufacturing but is strangely silent on the problems; there is simply a vagueness, an ambiguous space in between the failures of Singer and McCormick to move to complete part interchangeability in the late 1880s and 1890s and Ford's move to true part interchangeability with the Model T in 1908. There is an unexplained gap there. This paper will fill in that gap.

Realizing the Need for Parts Interchangeability

The first widely-reported instance of interchangeable parts in Western history was in the mid-fifteenth century, with the advent of Gutenberg's movable type. Actually a segment of a three-part system, movable type contributed markedly to both the Renaissance and the Reformation. Gutenberg's genius was combining the idea of movable type, the use of oil-based ink, and a wooden printing press adapted from olive and fruit presses. In doing so, Gutenberg made printed matter less expensive, just as inexpensive paper was also becoming available. This triggered a surge in literacy as printed material – tracts, pamphlets, and broadsides in addition to books – became more easily and cheaply available. Further, this literacy was not just limited to the upper classes, but was much more widespread throughout the population as well (Burns, 1963). Taylor's work had the same effects on manufacturing that Gutenberg's had on printing – essentially, the creation of a new world culture.

Because of the prevalence of war in Europe between the middle of the 15th century and the end of the 19th century, the arms industry provided the focus for parts interchangeability and mass production during this time frame. Firearms were (1) militarily important, and (2) very expensive - expensive to obtain, expensive to use, and expensive to maintain. It was this confluence of events (military need and scarcity/expense) that made the firearms industry one of the first to launch a concerted search for the "grail of interchangeability." Interchangeable parts would reduce the expense of manufacturing, the expense of use and the expense of repair. As the sizes of the armies increased, this problem became increasingly important.

And this is precisely the problem. Manufacturers had known for some time what needed to be done and also how to do it. It was not replicating identical parts that was the problem. The problem was doing this economically. Parts interchangeability was certainly possible, but it was not the most economical.

The literature on interchangeable parts never states and seldom approaches this critical problem. While the literature talks much about the advantages of parts interchangeability, and the trials of inventors, innovators, and manufacturers in reaching true interchangeability, the closest the literature comes to defining the critical problem is to state that essentially the parts could not be made to fit without hand-filing. Hounshell (1985, p. 23) comes the closest to pinning down the critical technology when he stated:

> The process of hardening parts made interchange impossible because iron always changed its shape during and after this process (parts were worked or machined in a soft state and then hardened for their final use). Even if parts fitted together nicely before hardening, they would not do so after it. They had to be 'restored.' The eminent machine tool builder and master of precision (Joseph Whitworth - this author's note) argued that this could be done 'only by hand labour [sic].'

Simply put, machine-tool cutting edges simply were not hard enough to process previously-hardened steel. The choice then was binary: Leave the steel as "mild steel" in which case it would be too soft to properly perform its function, or "hand fit" the part after hardening (requiring lengthy filing by expert craft masters). In the only reference seen that stated this explicitly, Womack, Jones and Roos (1990, p. 27) stated, "The warping that occurred as machined parts were being hardened had been the bane of previous attempts to standardize parts."

Therefore, the primary problem definition is this: To achieve parts interchangeability, manufacturers need to have the capability to machine parts *after* they have been hardened. Womack et al. (1990, p. 35) further refined this definition: "The key to interchangeable parts . . . lay in designing new tools that could cut hardened metal . . . with absolute precision. But the key to *inexpensive* interchangeable parts would be found in tools that could do this job at high volume with low or no set-up costs between pieces." This latter statement acknowledges the pressure toward incipient mass production at the turn of the century.

This then brings into focus three problems that needed to be solved simultaneously in order to make interchangeable parts a reality. Machine tools had to not only cut hardened steel, but had to do it precisely (Nelson, 1980), and with little setup cost (Smith, 1973). The technology already existed to ensure little setup cost by using "pantograph followers," machine tools which could copy a "master piece" faithfully. For the precision aspect, machine tools just needed a simple redesign to make them heavier and more rigid, a simple fix. But the problem with cutting hardened steel had been, so far, insolvable.

Taylor's Primary Professional Background and Motivations

Brown (2000) cogently argued that Taylor and other mechanical engineers of the time were intimately involved with establishing the engineering profession as the final arbiter of both product design and process design, i.e., the product itself and the processes, materials, sequences, and machining required for its production. Until this time, the engineer "roughed out a sketch" for a product, even those as large as railroad locomotives, then the engineers and the production foremen worked iteratively to make the product. In essence, then, craft production made each product unique. "Men such as William Sellers, Henry Towne, and Frederick Taylor sought this control to aggrandize their own individual power, to achieve autonomy for the engineering profession, and to increase business profits" (Brown, 2000, p. 218). While this may somewhat overstate the case, it is true that, during this time frame, engineering was establishing itself as a profession and was anxious to gain the respect of the manufacturing community.

By employing detailed working drawings, with specifications attached, Brown said, " . . . working drawings represented a substantial managerial incursion into craft workers' autonomy, suggesting a de-skilling motive . . . In particular detailed shop plans shifted two attributes of skill, planning and resourcefulness, out of the workers' control and into the charge of engineers and designers" (Brown, 2000, p. 218).

Further, Brown stated, "The higher cost of skilled labor, arising from the relative scarcity of craft-trained workers in the United States, gave American employers a powerful incentive to routinize tasks " (Brown, 2000, p. 226). Further, "By 1900 or so, collegiate training had become the primary route of entry into American engineering" and "in developing their drafting systems, engineers such as Towne and Frederick Ball were motivated by the control imperative that grew within the professional culture of American mechanical engineering by the 1880s" (Brown, 2000, pp. 228-232). One cannot but help noting that Taylor received his mechanical engineering degree in 1883. Therefore, *control of the shop* and *high efficiency* were part and parcel of the professional lifeblood taught to Taylor in pursuit of his degree.

The Solution

To achieve this control of the shop, Taylor knew that he had to standardize both processes and operations throughput. This meant more precise control of the machines, better planning and standardization of operations, and tighter control of the production process. All of these things though meant eliminating variation within the shop. Until the machines could be made less variable and more precise in operation, shop control was beyond Taylor's (and the profession's) reach.

By the 1890s, then, there were two problems unsolved: the cutting tools and the precision speed control. Taylor solved both of these. Taylor became involved in both the search for better tool steel and in *scientific management* (increasing the reliability and validity of managerial decisions by the use of the scientific method) as a result of his training and education. Brown (2000) makes a strong case for the argument that American engineers were largely focused on control of the production process and control of costs. In his degree program and his shop experience, Taylor was inculcated with these motivations as a professional.

The tool steel used to make cutting tools of the time had been developed in 1868 by Robert Mushet in Scotland. It was a steel alloy containing 2% carbon, 2.5% manganese, and 7% tungsten. However, it dulled quickly when applied to hardened steel and was thus unsatisfactory from both Taylor's perspective and from the perspective of interchangeable parts, which, in order to be uniform enough for interchangeability, had to be machined *after* they were hardened.

In 1894, Taylor began a series of experiments on cutting tools in the Cramp shipbuilding firm (Nelson, 1980). In 1898, he continued his investigation at Bethlehem Steel, still aimed at finding a better cutting-tool-steel-making process from which cutters could be made (Nelson, 1980; Taylor, 1914). The problem with Mushet steel was that cutters made from it heated as they cut and consequently lost both their temper (hardness) and their edge; a steel more tolerant of heat was needed. A new hire, J. Maunsell White III, joined Bethlehem Steel and was assigned to Taylor as an assistant in these experiments. The two complemented each other well and as Neck and

Bedeian, (1996, p. 22) described, "Just eight days after White joined the experiments (23 October 1898), discovery of the high-speed steel techniques, which later produced the Taylor-White patents, occurred." Essentially, these experiments proved that heating the alloys, such as Mushet steel, to a much higher point [300º- 400º F higher (Nelson, 1980); around 1890º F (Neck & Bedeian, 1996)] than previously used, coupled with a liquid-lead bath annealing process, produced a much harder steel (Misa, 1999). In essence, the cutter became harder the faster it cut (i.e., the higher the feed rate was), just the reverse of Mushet steel (Kirby et al., 1996). Kirby et al. (1996, p. 511) went on to say that, "Machine-tool practice was thus revolutionized, and speeds were doubled, tripled, and even quadrupled." Wikipedia (High Speed Steel, p. 1) states, "The Taylor-White process was patented and created a revolution in the machining industries, in fact necessitating whole new, heavier machine tool designs so the new steel could be used to its fullest advantage." In other words, the machine tools themselves became even heavier (i.e., no wooden components) (Smith, 1973; Gordon, 1989) and more rigid), allowing for greater accuracy and greater precision when machining parts (Hounshell, 1985; Gordon, 1989). Further, the new steel allowed cutting previously-hardened parts. This means that parts could be machined after heat-treatment, negating any warping, on machines that performed with greater accuracy and precision. In a contemporary (1900) article in *Railroad Master Mechanic*, an anonymous staff writer reported that a cutter made of Taylor-White steel alloy on a lathe took sixteen minutes at an increased feed rate, used dry (i.e., no cutting lubricant) to form a certain test piece and at the end of this trial, the cutter was unimpaired and still sharp. A cutter of Mushet steel used in the same trial took twenty three seconds to burn out completely (*Railroad Master Mechanic*, 1900). Another contemporary account may be found in *The Metallographist* (1903). More recent accounts may be found in Boothroyd and Knight (1989) and Sheldrake (2003).

Misa (1999, p. 193) presented the following data:

> Under the experimental conditions, tools made of [Mushet] steel could withstand cutting speeds running from 20 to 30 feet per minute. When treated by the new process, these same tools could be run at 60 feet per minute . . . The new cutting power erased the long-standing production bottleneck at the No. 3 ingot lathe. From December 1898 to June 1899, monthly production at the lathe nearly tripled, while the hours of lathe time fell by almost one-third . . . the new steel increased the cutting speed of round-nose tools by 183 percent, their depth of cut by 40 percent, and the pounds of metal they removed per hour by 340 percent.

Further, upon development of the cutting-tool steel, more experimentation by Taylor and his team of subordinates – a mathematician named Knox, Henry Gantt (of "Gantt Chart" fame), and Carl Barth – resulted in the invention and manufacture of slide rules for calculating lathe feed rates and "improved procedures" for setting up and accomplishing lathe work in June of 1899, which increased process reliability and reduced variability (Nelson, 1980, p. 88). In Nelson's words, Taylor and his team:

> ... devised an improved procedure for calculating the appropriate speed, feed, power, and machine times for machine tool operations. By the end of the year he had prepared slide rules for thirteen of the largest lathes in Machine Shop No. 2. Taylor was ecstatic. At last he had a way to determine proper machine tool methods. Control of the metal-cutting machinery, the most elusive element in the machine shop environment, was within his grasp (Nelson, 1980, p. 88).

Between vastly improved shop drawings that included tolerance specifications (i.e., modern drafting practices) and the improvement of process practices noted above, shop control and cost reduction was well within the reach of practicing mechanical engineers, thanks to Taylor and White.

However, this accomplishment was neither fast nor easy. Misa (1999) clearly documents experiments beginning in 1881 and stretching to 1898, in four separate companies. In 1898 at Bethlehem alone, the critical experiments took 16,000 iterations, consumed eight to nine months, and cost (estimated) between $50,000 and $125,000 at Bethlehem Steel. From a scientific perspective, the reason for so many experiments was failure to gain positive results and failure to assure replication. The perfection of the Taylor-White high-speed cutting steel took immense dedication, faith, and will.

Taylor was, at the same time, active in mechanical engineering circles (e.g., President of the American Society of Mechanical Engineers (ASME), 1906-1907), publicizing the Taylor-White process. Taylor and White were awarded the Elliott Cresson Medal by the Franklin Institute in 1902. Taylor was given an award for the same accomplishment at the Exposition Universelle Internationale in Paris in 1900 (Neck & Bedeian, 1996). All of these helped increase the visibility of the Taylor-White process, and spread the word about the new "high-speed cutting steel."

The first of the keys to interchangeable parts was present at last. The second and final part quickly followed. At this time (circa 1900), machine tools were driven by a central power source, usually a steam engine. The steam engine turned a large, central drive line, equipped at regular intervals with large pulleys. These pulleys were in turn connected to the machine tools by a wide leather or canvas belt. This system is known as a "line-shaft, belt-drive" system. Biggs (1996, p. 84) showed a particularly interesting photo of such a machine shop in her work. Devine (1983, p. 352) described speed control on such a system: " To run any particular machine, the operator activated a clutch or shifted the belt from an idler pulley to a drive pulley using a lever attached to the countershaft. Multiple pulleys offered speed and power changes."

Obviously, such a system was variable only in discrete increments, as one changed from a larger to a smaller pulley or vice versa. Intermediate speeds were impossible, except by the addition of more pulleys. Such a system negated some of the advantages of Taylor's research on optimum speed and feed rates. In addition, the belts, made of canvas or leather, tended to stretch and wear over time, making speed control even less reliable. Taylor was one of the first, if not the first, to equip an experimental lathe with an electric-motor drive (Misa, 1999), making him a pioneer of what is now common practice through the machine-shop world; "unit drive" and precision speed control via electric motor. Precision speed control was easily achieved on these motors by known technology (e.g., variable resistors or potentiometers) (Devine 1983). Thus was the second major consideration solved.

By 1901, both the cutting tool and precision machining problems were solved, both solutions courtesy of Frederick Winslow Taylor and his subordinates. Taylor had solved the major problems preventing the manufacture of interchangeable parts and thus dissolved the stumbling block holding back mass production. Arguably, this is the most significant of Taylor's many notable accomplishments.

The Effects: Short-Tterm

The effect of Taylor-White tool steel in essence established the practicability of interchangeable parts. For the first time, steel parts could be hardened and then machined precisely, preventing the warping that had, for decades, delayed the realization of machine-made, precision interchangeable parts. For the first time, the reality of ". . . inexpensive interchangeable parts would be found in tools that could do this job at high volume with low or no set-up costs between pieces" could be realized (Womack, Jones & Roos, 1990, p. 35).

In addition, and in tandem with the new cutting tool experimentation, the additional research guided by Taylor, on optimum feed and cutting rates did two things: (1) it showed that scientific calculations for particular machines were possible and desirable, and (2) it showed dramatically the effects of making and using such calculations. Hounshell (1985, p. 232) commented,

> In Chapter 2 [sic] the question was raised of whether in the 1870s and 1880s high-volume, economical production of accurate parts was technologically possible. By 1913, when Colvin wrote the series in the *American Machinist* and when Ford initiated line assembly techniques, the machine tool industry was capable - perhaps for the first time - of manufacturing machines that could turn out large amounts of consistently accurate work.

In other words, the work of Taylor and White concerned with producing high-speed tool steel capable of machining hardened steel parts was critical to the production of interchangeable parts; it was the key which had been missing for some 200 years.

Longer-range effects and conclusion

Interchangeable parts were key to the evolution of high-volume mass production (HVMP). Hounshell (1985) relates these advances as directly applied to Ford's Model T design, plant layout, and production.

Table 1: *Total automobile production at Ford by year*

1903=1700	1904=1695	1905=1599	1906=2798
1907=6775	1908=6015	1909= 10660	1910=18942
1911=34610	1912=66640		

The total climbed rapidly after that as the Model T production, started in 1908, took hold and the production system evolved (Gunnell, 2002, pp. 20-28).

It is obvious that something revolutionary began happening at Ford between 1906 and 1912. The production totals show traditional "craftsman" manufacture between 1903 and 1906. But in 1907 and beyond, the production totals show the beginning of an exponential rise. Something significant had happened. That "something significant" here was the Model T. Design of the Model T began in 1906, and the design was predicated on interchangeable parts and ease of economical manufacture. Without the contribution of Taylor and White (the mechanical engineers, not the managers), neither of these would have been possible.

The success of the Model T – and the underlying development of modern industrial technique triggered by Taylor-White high-speed cutting steel tools – catalyzed the entire automobile industry. In response to Ford's commanding position in the auto industry, Alfred Sloan began redesigning General Motors and the Chevrolet Division in particular to compete with Ford Motors. This redesign, taking until 1928, was the birth of the modern corporation (Paxton, 2009). Included were modern cost accounting, strategic planning, marketing, finance, and organizational structure. Both the industrial techniques and the corporate structure – the bedrock foundations of modern management – survive today and both were directly triggered by Taylor, White, and their experiments which resulted in high-speed cutting tool steel.

By 1928, HVMP (high-volume mass production) and the modern corporation had reached maturity (Paxton, 2009); both were realities throughout the United States. These essentially rebuilt the culture and society of the nation (Gordon, 2004). Both Taylor and White died prior to 1916, White in 1912 (Neck & Bedeian, 1996) and Taylor in 1915 (NY Times obituary). But by scientifically pursuing the research that invented high-speed cutting tool steel, thereby making interchangeable parts possible, both Taylor and White contributed greatly to the Allied victories in both World War I and World War II, for in both of these wars, the United States was the only national economy based on a mature system of high-volume manufacture (World War I) and that had the only mature high-volume mass production economy in the world (World War II) (Paxton, 2009). Beyond this, their technology proved instrumental in improving the quality of life across the globe in the second half of the 20th century. Quite a contribution, unsung and largely unrecognized as it is.

References

The Metallographist.Volume 6, Number 2: 130 (April, 1903), p.130. Accessed at http://books.google.com/books?id=1voCAAAAYAAJ&pg=PA130&lpg=PA130&dq=the+metallographist+and+the+taylorwhite+process&source=bl&ots=6Acb46iId7&sig=oD4Bzx0NORa94buysmBP6xvbFgc&hl=en&ei=NWBsS6vbEZT4sQOepOWxDQ&sa=X&oi=book_result&ct=result&resnum=1&ved=0CAcQ6AEwAA#v=onepage&q=&f=false on February 5, 2010.

Obituary: F. W. Taylor. *New York Times*, March 22, 1915. Retrieved from http://www.nytimes.com/learning/general/onthisday/bday/0320.html on February 5, 2010.

Railroad Master Mechanic, Volume 24: 527. (1900), p.527. Accessed at http://

books.google.com/books?id=YSU2AAAAIAAJ&pg=PA527&lpg=PA527&dq=Railroad+Master+Mechanic,+1900+and+the+taylor-white+source=bl&ots=W0o7FtQz6A&sig=LVi4KAF_7QEsFLn7F0g58XCMCGA&hl=en&ei=7WFsS_mpBor-tAP21OWyDQ&sa=X&oi=book_result&ct=result&resnum=1&ved=0CAcQ6AEwAA#v=onepage&q=&f=false, February 5, 2010.

Biggs, L. (1996). *The Rational Factory: architecture, technology and work in America's age of mass production*. Baltimore, MD: The Johns Hopkins University Press.

Boothroyd, G. & Knight, W. A. (1989). *Fundamentals of Machining and Machine Tools*. New York: McGraw-Hill, Inc.

Brown, J. K (2000). Design plans, working drawings, national styles: engineering practice in Great Britain and the United States. *Technology and Culture, 41*(2).

Burns, E.M. (1963). *Western Civilizations: their history and culture* (6th ed). New York, NY: W. W. Norton and Company.

Devine, W.D. Jr (1983). From shafts to wires: historical perspective on electrification. *The Journal of Economic History, 43* (2): 347-372.

Gordon, J.S. (2004). An empire of wealth: the epic history of American economic power. New York, NY: Harper Perennial.

Gordon, R.B. (1989). Simeon North, John Hall, and Mechanized Manufacturing. *Technology and Culture, 30* (1): 179-188.

Gunnell, J. (2002). *Standard Catalog of Ford, 1903-2003* (3rd ed). Iola, WI: Krause Publications.

High Speed Steel. (n.d.) http://en.wikipedia.org/wiki/

Hounshell, D.A. (1985). *From the American System of Mass Production, 1800-1932*. Baltimore, MD: The Johns Hopkins University Press.

Kirby, R. S., Withington, A. B., Darling, A. B. & Kilgour, F. G. (1956). *Engineering in History*: 511. New York, NY: McGraw-Hill, Inc.

Misa, T.J. (1999). *A Nation of Steel: the Making of Modern America, 1865-1925*. Baltimore, MD: the Johns Hopkins University Press.

Neck, C.P. &. Bedeian, A.G. (1996). Frederick W. Taylor, J. Maunsell White III, and the Matthew Effect: the rest of the story. *Journal of Management History, 2* (2): 20-25.

Nelson, D. (1980). *Frederick W. Taylor and the Rise of Scientific Management*. Madison, WI: The University of Wisconsin Press.

Paxton, J. (2009). Engineering, management, and economics: a case study in alloying disparate elements. *International Journal of Continuing Engineering Education and Life-Long Learning, 19* (1): 82-96.

Sheldrake, J. (2003). *Management Theory.* London: Thomson.

Smith, M.R. (1973). John H. Hall, Simeoon North, and the Milling Machine: the nature of innovation among antebellum arms makers. *Technology and Culture, 14* (4): 573-591.

Taylor, F.W. (1914). *The Principles of Scientific Management.* New York, NY: Harper and Brothers Publishers.

Womack, J.P., Jones, D.T. & Roos, D. (1990). *The Machine that Changed the World: The story of lean production*. New York, NY: HarperPerennial.