Sharon, with kind regards. Bob & Ram

NORTH-HOLLAND

The Role of Standards in Innovation

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ABSTRACT

We review and explore the role of standards in innovation, with particular emphasis on design and manufacturing processes. We begin by defining and classifying standards and by exploring their role and infrastructure in society. This is followed by a similar discussion for innovation. By examining the relationships between innovation and standards, we extract the negative impact and the positive impact each has on the other. A study of four case histories in different domains—manufacturing, computer hardware, mechanical component design, and product data exchange—reveals that, as expected, standards are often derived from innovative technology. Surprisingly, however, innovation is often spurred—directly and indirectly—from standards as well. We conclude that, in general, the benefits of standards on innovation in design and manufacturing outweigh the possible limitations on creativity imposed by such standards. © 2000 Elsevier Science Inc.

Introduction

Innovation has always been a major ingredient to developing technology or advancing technology (or both) [1]. As technologies develop or advance, standards are required to ensure performance, conformity, and safety of new products and processes [2]. One example of the need for standards can be envisioned easily with fiascoes like the $125 million Mars Climate Orbiter, which was lost because of inconsistent measurement units between two control teams. One technology reaping the benefit of a standard is Europe's cellular industry. Their dependence on a unified Global System for Mobile Communications, or GSM, is the reason they have a continent wide digital network. This standard, along with extensive agreements among carriers, allows one cell phone to work from southern Italy to eastern Poland. In contrast, the United States has four different standards, including an odd version of GSM, so that a phone manufactured for one system will not work on another.

As a result of this dependence, there exists a relationship between standards and innovation that is complex and dynamic [3]. Our purpose in writing this paper is to begin to evaluate that relationship, and explore under what circumstances innovation and standards affect each other. We begin by defining and categorizing standards and innovation, and examine case histories to evaluate how standards have depended on,

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Technological Forecasting and Social Change 64, 171–181 (2000)
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655 Avenue of the Americas, New York, NY 10010

0040-1625/00/$–see front matter
PII S0040-1625(99)00104-3

helped, and hindered progress of innovations, and how innovations have had these same effects on standards.

Standards: Definition and Types

One dictionary definition of the word "standard" is a means of determining what an entity should be; another definition is a fixed, customary, or official measure (as of quantity, quality, or price). Typical synonyms for "standard" include benchmark, criterion, gauge, measure, touchstone, and yardstick. One example of this is the unit of measure of mass in the International System of Units—the kilogram. Being a fixed and agreed-upon artifact under stringent controls, the standard kilogram [4] is an example of a fixed measure against which all can compare.

For the purpose of this paper, we adopt the definition that standards are documented agreements containing technical guidelines to ensure that materials, products, processes, representations, and services are fit for their purpose. Under this definition, there are four broad types of standards. One type is the measure or metric standard. This is one used against which to measure; all comparable quantities are measured in terms of such a standard. Classic examples of these primary or fundamental standards are the kilogram for mass measurements, the meter for length measurements, and the liter for volume measurements. This type of standard is particularly useful for the consumer, as it makes it easier, and in some cases possible, to comparison shop—for price, function, or features.

Another type of standard is process oriented or prescriptive, where descriptions of activities and processes are standardized. These standards provide the methodology to perform tests and perform processes in a consistent and repeatable way. One example of this type of standard is American Society for Testing and Material (ASTM) C1028, "Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method" [5]. Without making judgments about how results of the friction tests should be interpreted, this standard prescribes the method and materials for performing friction tests on floor surfaces under four different conditions.

The third type of standard is performance based. In these standards, process is not specified, but ultimate performance is. These standards are often based on product experience. For example, in 1992, Hurricane Andrew damaged or destroyed more than 15,000 mobile homes in the Southeast US. As a result of that event, The American Society of Civil Engineers (ASCE) developed a series of standards to ensure that mobile homes are able to resist 160-kph (100 mph) winds. These standards were adopted by the U.S. Department of Housing and Urban Development, which sets mobile home standards [6]. As a result, mobile homes sold after 1994 in hurricane-prone counties are designed to be wind resistant up to 160 kph.

The last standard type is based on interoperability among systems. In these type of standards, process and performance are not explicitly determined, but a fixed format is specified. The goal of this type of standard is to ensure smooth operation between systems that use the same physical entity or data. Examples of this type of standard abound in computer-aided design (CAD). In this activity, engineers and designers use software as a tool to help create and represent geometric models. Because CAD applications generally do not use the same format for data input and output, exchanging data among systems requires multiple translations. By creating generic formats, standards, such as the International Organization for Standardization (ISO) data representation for exchange, more commonly known as STEP [7]—the STandard for the Exchange of Product model data—facilitate the exchange of data representation.

Although the four types of standards described above—fundamental, prescriptive, performance-based and interoperative—are separately categorized, specific standards can certainly be of more than one type. For example, one architectural prescriptive standard in the United Statesis a standard door width of 36 inches. Although prescriptive, it is also performance based, because this width can readily accommodate most wheelchairs, and it is also interoperative, because the "standard" door fits the standard frame.

Standards: Categories

Beyond these types, there are three categories of standards that distinguish themselves by the processes by which the standards came about. The de facto standard is one that is widely accepted and used, but lacks formal approval by a recognized standards organization or organizations. The de facto standard generally results from widespread consensus on a particular product or protocol that has a large market share. Examples of de facto standards in the computer marketplace today are the QWERTY[1] keyboard, the personal computer (PC) architecture, and the UNIX™ operating system.

Another standards category is regulatory. As the name implies, regulatory standards are created by regulatory agencies to ensure uniformity in processes that are not driven by market forces. Typical applications are safety standards and environmental standards such as those published by the Occupational Safety and Health Administration (OSHA) or the Environmental Protection Agency (EPA). For example, OSHA Regulation 1915.1, "Air Contaminants," dictates how much time a worker can be exposed to certain types of pollutants.

Consensus standards make up the third category. Consensus standards are voluntary standards developed or used by voluntary consensus standards bodies, both domestic and international. Voluntary consensus standards bodies are domestic or international organizations that plan, develop, establish, or coordinate voluntary standards using agreed-upon procedures. Examples of such national organizations include the American Society of Mechanical Engineers (ASME) and ASCE in the US, Deutches Institut fur Normung (DIN) in Germany and the British Standards Institution (BSI) in England. The ISO is one example of an international consensus standards organization. One common example of a universal voluntary standard is the format of credit cards, phone cards, and "smart" cards. Adhering to an ISO standard, which defines such features as standard thickness (0.76 mm), allows cards to be used worldwide. Universally accepted standards thus contribute to increasing the reliability and effectiveness of the goods and services we use.

Standards: Infrastructure

As suggested by the different types of standards, and the different processes by which they come about, the standards infrastructure is a complex interdependent system of primarily technical activities that often results in codified or accepted practices. Having an infrastructure in place allows for the basis in confidence when exchanging technical information between scientists and engineers, between providers of goods and services and customers, and between government and the private sector. The value of having standards in place is clear: they are critical for economic advancement and national security. Global standards also facilitate exports and international trade; although, regional standards can pose trade barriers.

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[1] The traditional keyboard is often defined by the first six characters—QWERTY—in the upper row of letters.

The standards infrastructure varies across the globe. In general, developed nations produce quality standards [8]. In Europe and the Pacific Rim, standards development organizations (SDOs) have a unified plan, are centralized, and are government funded. In the United States, SDOs have no unified plan, are decentralized, and are funded by their respective memberships and sales of standards. As a result of increasing international commerce, the European and Pacific Rim models can have greater effectiveness than the U.S. model [9]. For example, a 1991 Vienna Agreement allows ISO to use the European Union developing standards as international standards in much less time than usual, leaving other nations' contributions out of consideration [10]. The U.S. standards industry and U.S. government agencies are taking steps to create a more equitable environment. These include government funding of standards bodies, presenting positions to the ISO, and garnering worldwide support for change.

In the United States, there are over 400 private sector standards developers with close to 100,000 standards in place. Standards development organizations make up the majority of the voluntary standards efforts in the Unites States. The American National Standards Institute (ANSI) is a private, nonprofit organization that brings together private and public sectors to develop standards for a wide array of U.S. industries. ANSI does not itself develop American National Standards (ANSs); rather, it facilitates development by establishing consensus among qualified groups [11]. ANSI also accredits SDOs that operate via consensus, openness, and due process; it is also the sole voting member from the United States to ISO and the International Electromechanical Commission (IEC). Standards emanate from scientific and professional societies such as ASME, trade associations such as the National Electrical Manufacturers Association (NEMA), and standards-developing membership organizations such as ASTM, which has developed and published about 8500 standards. The Federal government also produces standards primarily through its regulatory, defense, and procurement agencies. Stemming from WWII, about 40% of all U.S. standards relate to defense. Since the 1980s, competitiveness in the global economy has become a United States priority, resulting in an increased number of performance-based standards.

Within the federal government, the National Institute of Standards and Technology (NIST) coordinates the technological basis for standards and promotes economic growth by working with industry to apply technology, measurements, and standards. Established by Congress in 1901 as the National Bureau of Standards (NBS), the Institute's goal has been to support industry, commerce, scientific institutions, and all branches of government. For nearly 100 years the NIST/NBS laboratories have worked with industry and government to advance measurement science and develop standards.

NBS was created at a time of industrial development in the United States to help support the steel manufacturing, railroad, telephone, and electric power industries, all industries that were technically sophisticated for their time but lacked adequate standards. In creating NBS, Congress sought to redress a long-standing need to provide standards of measurement for commerce and industry and support the "technology infrastructure" of the 20th century.

Innovation

One dictionary definition of innovation is the introduction of something new, such as an idea, method, or device. An innovative enterprise or product is one that is distinguished from previous ones by its uniqueness in form, function, or behavior. Innovations generally fall into two categories: fundamental and adaptive. A fundamental innovation results in a new product or process, and is one that is not thought to be required prior to its introduction. An adaptive innovation is one that is need generated [12].

However, this definition of innovation is limiting in that it does not distinguish between enterprises or products that are merely new and those that are innovative. The firms that launch a new product usually do so in a bid to obtain more of an existing market share. In a sense, such products are more business ventures rather than innovations. From a business perspective, innovations generally yield far better returns (56%) than the average return on investment in American business (17%) [13]. A *necessary* condition for innovative enterprises or products—such as McDonald's,[2] the videorecorder, and the personal computer—is that they create new enterprises or products. However, this is not sufficient. They also must diffuse [14], or create new markets. In this sense, Thomas Edison, arguably the most successful inventor on record, was not a good business innovator because he was not successful at exploiting his own inventions.

In the case of McDonald's, innovators took an existing product—the hamburger—and developed a whole infrastructure to deliver a standardized version in just-in-time preparations, at a low price in a clean environment. In short, they created a new market category. In the case of videorecorders, Japanese innovators took an existing American technology—videorecording with 2-inch, reel-to-reel tapes and a niche market in broadcasting—and transformed it into a portable device for the home market. This fundamental innovation created a demand that resulted in $15 billion in sales in the 1980s [13]. Curiously, a standards issue prevented Betamax, an earlier videocassette format than VHS, from becoming the dominant mode. In the case of the personal computer, Apple Computer proved to the established computing community in the early 1980s that a desktop computer was not only possible, but desirable. Curiously, Apple lost the dominant market share it had in 1983 because it failed to adapt Open Architecture, the market *standard* for personal computers [14].

Timing also has much to do with success in innovation. When IBM introduced its 360 series mainframe computer in 1965, it was based on a hybrid circuit technology, even though the integrated circuit was already in a demonstration computer in 1961 [15]. As a result, the series, despite being new, was not innovative.

In his book on innovation dynamics, Utterback [2] defines product life cycle in terms of innovation. In the *product innovation phase*, there is a variety of technically changing products that are supported by a multitude of suppliers. These suppliers make a relatively small number of widely varying parts. New suppliers enter the market based on technical innovations that create parts with unique and distinguishing advantages. In the *process innovation phase*, innovation is limited to product improvements that enhance standards, to manufacturing improvements and to marketing and distribution improvements. New products that attack the market standard are destined to fail.

Innovative engineers and thinkers manipulate their ideas and experiences in ways that are initially unfamiliar [1]. This leads to fundamental innovations. For example, Johannes Gutenberg, a goldsmith by training, is believed to have invented the printing press over 500 years ago by connecting two previously unconnected technologies: the coin punch and the wine press. The coin punch is a device used to make a permanent mark on a coin. The winepress is used to apply a force over a large area. Gutenburg combined these two ideas to form the notion of a printed page [16].

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[2] Commercial products and names, many of which are either registered or trademarked, are identified in this paper for illustrative purposes only. In no case, does the National Institute of Standards and Technology imply recommendation, endorsement, or discommendation.

Beyond the individual, there are a number of environmental factors—both global and local—that encourage or discourage innovation [14]. Specifically, on the global scale, there are cultural tendencies and technological limitations that affect the ability to innovate. For example, the 15th-century helicopter, while demonstrating da Vinci's genius, could not work for more than 400 years because of numerous technological limitations. Similarly, Charles Babbage's analytical engine (computer) of the 1840s could not work primarily because technology of the era did not include electronics or Boolean algebra. Nearly a century passed before the critical technology could be integrated into a working prototype [17]. Innovation and diffusion is also affected largely by culture. One society may invent a technology but not advance it. American inventors developed videorecording, but Japanese innovators advanced the technology to be suitable for the home market. China was the source of many early inventions including 1) paper in the second century before the common era; 2) the seismograph in the second century; and 3) cast iron, the helicopter rotor, and the decimal system in the fourth century [18]. However, the culture of China was such that these inventions did not become technologies until *centuries* later in other civilizations. Paper reached India in the seventh century and West Asia in the eighth. These cultures diffused the technology by selling paper to Europeans until manufacture was achieved in the West in the 12th century, more than a millenium after the invention of paper.

On a local level, factors affecting innovation include company and industry size and structure, management attitudes, and mechanisms, such as *standards*, for widespread diffusion. Visionary companies, for example, set up internal mechanisms that instill a culture for innovation [19]. Art Frye was able to develop the Post-It™ note based on a glue that did not dry, because 3M, although a large company, empowers its employees to be independent and somewhat autonomous. Although his idea was initially shot down at a meeting specifically designed to convey novel ideas, he persisted by giving out sample pads to his manager's *secretaries.* Within a short period, management was sold, and so was a new technology.

Natural Relationships Between Innovation and Standards

Having established definitions and categories for standards and innovation, we now examine selected case histories for the purpose of identifying the affect of one on the other. Each case history selected represents how standards and innovation interacted in different and sometimes surprising ways. We have also selected these case histories to capture a variety of industries and processes.

The Ridging of Coins

Pure silver and pure gold are too soft to be practical for coins, as the metals wear down substantially and rapidly. To make these metals more durable, they historically have been (and still are) alloyed with other metals [20]. In the 17th and 18th centuries, each country (or sometimes each mint or city) used its own ratio of precious metal to alloy in minting coinage. As a result, the coin weight alone would not yield its true value, for one needed to know the percent of alloy (sometimes called impurity) in the silver or gold. The purity is known as its fineness. For example, Britain then used a mix of 925 parts pure silver to 75 parts copper, resulting in 92.5% silver content expressed as 0.925 fine silver. This was the standard for the British Pound Sterling [21].

Due to Great Britain's international trade, silver and gold coins from different countries were regularly exchanged for British coins, both at home and abroad. To make an accurate determination of the relative value of the foreign coins, an assay had to be performed. This entailed melting down unclipped full weight samples of each coin, then extracting or adding alloy until the silver or gold was at a predetermined fineness. Once a uniform fineness had been achieved, each sample would be weighed.

There was another detriment to keeping coin values true. The innovative, albeit unsavory, practice of clipping off around the coin circumference without detection was prevalent during the late 17th and early 18th centuries. To prevent this practice, the Mint introduced the practice of marking the edges of coins in 1662. Into this century, 3 mm-thick English one-pound coins still bear the words, "Decus et tutamen," meaning "An ornament and a safeguard," around their circumference.

Although the Mint had been producing coins with milled edges for 30 years when Isaac Newton took over as Master in 1700, a large number of clipped and badly worn unmilled coins were still in circulation as legal tender. This was causing inflation, and was a serious problem due to the expensive war with France in progress at the time. The government decided to recall all unmilled coins and recoin them with the new machines.

Newton demonstrated his innovative and lateral thinking [22] when he ordered the most influential assay be performed in 1702. While undertaking a general assay of 44 foreign silver and 12 foreign gold coins in relation to the British standard, Newton also used new machines to ridge newly minted coins. He developed a weight measurement scheme sufficiently accurate to be with about 0.01% (a mite) of a troy ounce, the typical coin measure of the time. Newton undertook this project to assist British trade; however, it became quite important for colonial America as well, because several of these coins were used in the colonies. Two years after the assay, Queen Anne issued a proclamation establishing standard rates for coins in the colonies. Curiously, when Queen Anne knighted Newton in 1705, the reason given was not for contributions to science and mathematics, but rather for his work as Mint Warden.

This review of numismatic history reveals how material properties and innovative cheats led to the need to standardize coinage. The standardization in turn, led to innovations in technology (ridging and assay methodology), and eventually to innovations in paper money that continues today to ensure robustness and to thwart counterfeiting. This demonstrates a symbiotic relationship between standards and innovation.

The QWERTY Keyboard

An example of innovative thinking leading to a de facto standard that no longer applies is found in the current QWERTY keyboard configuration, shown in Figure 1. In the 1870s, the Remington Arms Company, a leading manufacturer of manual typewriters, received complaints that their typewriters often became jammed when typists operated too quickly [23]. To solve this problem, one theory is that a Remington engineer (Densmore) conceived the idea of separating commonly connected letters, such as q and u. The logic being quite simple—the slower the typing rate, the less frequent the jams. Hence, the notion that QWERTY configuration was designed in part to deliberately slow the typist down [23].

1	2	3	4	5	6	7	8	9	_	=
Q	W	E	R	T	Y	U	I	O	P	½
A	S	D	F	G	H	J	K	L	;	‘
Z	X	C	V	B	N	M	,	.	/	

Fig. 1. The standard (ANSI X4.7—1966) QWERTY keyboard configuration.

?	,	.	P	Y	F	G	C	R	L	/
A	O	E	U	I	D	H	T	N	S	-
'	Q	J	K	X	B	M	W	V	Z	

Fig. 2. The Dvorak simplified keyboard (1936).

When better linkages—a true engineering solution—resulted in less frequent jams, other typewriter manufacturers still promoted different keyboard arrangements, each claiming technical advantages. However, the reason for these claims was more Machiavellian than truthful. Each manufacturer knew that once a typist learned to use its keyboard, she was unlikely to use a different arrangement (hence, brand) in the future. In 1911, however, the QWERTY keyboard was the first one that allowed a typist to see a character immediately after typing it. This innovative improvement over the state of the art resulted in the vast majority of non-QWERTY typists switching loyalty to learn the QWERTY configuration. As a result, competing typewriter manufacturers were forced to adopt the QWERTY configuration to sell to the majority of trained typists.

As a result, the keyboards were configured, and still are configured, to be a fairly inefficient typing configuration. For example, the letters o, a and i are among the top six letters most commonly used in letters in English, yet their position on the keyboard is such that they must be depressed with relatively weaker fingers (ring and pinky). The left hand performs most typing (57%); many common words (was, were, extra) only involve the left hand. Most typing (52%) occurs on the back row, as opposed to the home row (32%). The pinky is overloaded with shift, backspace and tab [23].

Since 1911, however, the state of the art in keyboard technology has advanced such that any typing speed would be acceptable. In fact, August Dvorak developed a more efficient keyboard, shown in Figure 2, in the 1930s [24]. His configuration is more efficient in a number of ways. For example, the right hand does more typing than the left (56 to 44%). Seventy percent of typing is carried out on the home row; the keyboard is designed so that the middle row of keys includes the most common letters. Common letter combinations (qu, in, un) are positioned in such a way that they can be typed more quickly than on QWERTY [23]. Cassingham [24] estimates that professional typists can type up to 20% faster using a Dvorak keyboard. Beyond that, during an 8-h day, a typist's hand travels 16 times further on a QWERTY keyboard than a Dvorak one. The American National Standards Institute endorsed the Dvorak keyboard configuration by publishing a standard (ANSI) X4.22.

Yet, despite these advantages, 99.99% of keyboards today are QWERTY based, demonstrating, in this case, that standards hindered innovation and progress. This is an example of a product entering the market during the *process innovation phase* [2]. Because QWERTY was a de facto standard for more than 20 years before Dvorak's keyboard appeared, society was (and will probably remain) too entrenched in that standard to accept a product that changed it, even if doing so improved performance.

Industrial Hydraulic Fittings

Hydraulic fluid systems provide power to mechanical systems in a variety of ways, including lifting, clutching, and gear shifting. A hydraulic system transmits and controls power through a fluid under pressure within an enclosed circuit. In general, the circuit remains closed via components that have threaded ports and connect to hydraulic fittings with stud ends to a hydraulic hose. Among its performance characteristics, current industrial hydraulic fittings must resist pressures up to 40 MPa (6,000 psi) without leakage. In addition, these connections need to operate in temperatures ranging from below freezing to boiling, and need to absorb vibration over a life expected to exceed one million cycles. Typically produced in large volumes, fittings are built to industry standards.

Before 1980, when line pressures were lower, connections typically were metal-to-metal, and varied in style from industry to industry and from region to region. Details between components lacked significant standards. As line pressures increased, no single port/stud interface had emerged to meet the robust and leak-free needs of industry. The International Standards Organization completed several relevant, and competing, draft international standards (DISs) for ports only: ISO/DIS 1179 (Whitworth threads), ISO/DIS 9974 (metric threads), and ISO/DIS 11926 (inch threads). One standard, ISO 6149, entitled "Fluid Power Systems and Components—Metric Ports—Dimensions and Design," was published in 1980 to indicate the international shift to the metric system. This standard, however, defined only the port connection; no metric end fittings had been tested or defined to engage in the port. As a result, multiple fittings emerged in the global marketplace. These included tractor-manufacturer John Deere' metal-to-metal seals such as cone-metric fittings and flare inch-based fittings, and the Society of Automotive Engineering' (SAE') O-ring Face Seal fitting. Two principal standards governed these fittings: the German (metric) standard, DIN 3852, "Scewed plugs; tapped holes; with fine pitch thread, general outlay of types," and the American (inch-based) standard, SAE J1453, "Fitting—O-Ring Face Seal."

It was clear to John Deere in the 1980s that O-ring–based fittings were needed to best ensure leak-free systems [25]. At the same time, they were proposing two new lines of agricultural tractors for introduction in 1992. Their plant in Mannheim, Germany, was to manufacture the lighter tractor series, 66–85 HP, and their facility in Waterloo, IA, was to produce the heavier series, 110–145 HP. Because each plant was to produce tractors for international markets, principal design goals for these new programs included using common parts for both series and using international standards to the greatest extent possible.

One innovative result of these goals was to decide that hydraulic fittings and ports for each tractor series would be the same. This would allow production and service for these connections to be uniform throughout the world, thus saving manpower and money. This decision, taken in the late 1980s, forced John Deere to take a lead in adopting and enhancing ISO 6149 and in promoting an elastomeric fitting design that could mate with ports designed in accordance with ISO 6149. Technical difficulties associated with this undertaking focused primarily on interchanging and distinguishing inch and metric designs, sizing the O-ring, and testing of the new design.

To overcome these problems, John Deere was an active participant in the voluntary standards-making process among DIN, SAE, and ISO. The end result of that process was the acceptance in the international community of a standardized hydraulic port and fitting.

Product Data Exchange

The current design and manufacturing process employs a series of computer applications tailored for specific tasks. For instance, Computer Aided Design (CAD) systems are used to design parts, while process planning systems are used to establish manufacturing processes. Design and manufacturing corporations depend on these applications to produce their products and to bring them to market. With their own data formats, CAD systems cannot exchange data without translation for *each* exchange. Data interchange issues cost corporations time and money. Even with STEP in place, imperfect interoperability imposes at least a $1 billion cost *annually* on members of the US automotive supply chain [26].

How does this cost issue result in innovative processes? One example of that can be seen in the design of the Boeing 777 [27]. In this project, Boeing literally risked its future by agreeing in the early 1990s to design and build a high-quality jet in less time and for less money than it had *ever* done previously. While many innovative techniques were employed to do this, a principal one was designing the plane *without* paper drawings. All technical information about the plane was to be represented, stored, and shared electronically.

Here is a typical scenario. Boeing's customers require that it use engines from different manufacturers, such as General Electric, Pratt and Whitney, and Rolls Royce. Boeing's designers use Dassualt's CATIA as their CAD tool, while the suppliers use different CAD systems, such as Computer Vision's CADDS and Parametrics' ProEngineer. Each of these systems has its own unique data format, and interoperability is a major concern. For a pair of CAD systems, two translators are needed; for three systems, six translators; for n CAD systems, $n(n-1)$ translators. Because there were hundreds of systems for which Boeing needed to exchange data in the 777 design, the number of translators became astronomical. By creating generic and *standard* data formats for exchanging information with other systems, the number of translators was reduced to $2n$.

The principal standard that facilitated the exchange of CAD data was and is ISO 10303, or STEP. STEP enabled the exchange of product model data between different modules of their product, or it enabled the sharing of that data by different modules through the use of a common database. The risk that Boeing took was that the first parts of STEP that achieved International Standard status were not published until 1994, well after most of the design of the aircraft. (Many other parts have since been published or are under development, and will eventually be added to the standard [28].) By involving themselves in the standards development process, Boeing assured that their data interchange—and revolutionary product—would be a success. It is likely that neutral data interchange formats will continue to spur innovation by playing a major role in making electronic business *a standard.*

Summary and Conclusions

Our exploration of standards and innovation, and our study of four case histories confirm the complex and unique relationship between standardization and innovation [8, 14]. In the case of manufacturing currency, the relationship was, and still is, symbiotic and mutually beneficial. With the keyboard, a de facto standard limited innovation. With the hydraulic fittings, the need for a standard spurred innovation. In the case of the Boeing 777, a data exchange standard spurred innovation and also created a mechanism that could help achieve a previously unattainable solution or completion to a task.

Although standards can inhibit innovation by codifying inefficient or obsolete technology, and thus increase the resistance to change, standards generally spur innovation directly by codifying accumulated technological experience and forming a baseline from which new technologies emerge. Standards also spur innovation indirectly because they increase global competitiveness, which in turn spurs innovation.

The authors gratefully acknowledge the support provided by the System Integration for Manufacturing Applications (SIMA) program and the National Advanced Manufac-

turing Testbed (NAMT) program at NIST. We also thank Neil Christopher for initial input into the paper, Sam Schneider for his input on standards organizations, and Sharon Kemmerer for her thoughtful and thought provoking comments.

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Accepted 15 November 1999