THE GLOBAL MANUFACTURING REVOLUTION

Product-Process-Business Integration and Reconfigurable Systems

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Dedicated to my loving and supporting wife, Alina, who encouraged the writing of this book
In memory of
Professor Shien-Ming (Sam) Wu (1924–1992)
Pioneer in introducing advanced statistical techniques to manufacturing research
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Preface

I began teaching a class on global manufacturing in 1995. Since there were no books on this topic (and prior to this publication, there are still none) I started to write this book in 2002. The first edition of this book was submitted to an NSF review panel in May 2004. This current 2009 edition includes much new data, additional numerical examples, and professionally done drawings.

The book is intended for engineers who desire to pursue managerial careers in the manufacturing industry, to students in business schools who are motivated to lead manufacturing enterprises, as well as to leaders of global enterprises. It provides the tools and knowledge needed for making manufacturing enterprises thrive and ensure their growth in a global environment.

The theme of the book is: "globalization creates both opportunities and challenges for companies that manufacture durable goods." My main challenge in writing a book on globalization is that the pace of events involving the manufacturing industry in the last few years is changing faster than my writing speed. The book aims at helping manufacturing companies to succeed in this turbulent business environment of a newly interconnected world where all competitors have similar opportunities. The book proposes new technologies and new business strategies that can increase an enterprise’s responsiveness to volatile markets and enhance the integration of its own engineering and business. Both are crucial for global success.

For manufacturing enterprises to succeed in this current volatile economic environment, a revolution is needed in restructuring all three main components of a manufacturing enterprise: product design, manufacturing, and business model. A company can succeed in globalization if and only if it has (1) a sound strategy for developing new innovative products that fit cultural needs in several world’s regions, (2) business models that encompass a global strategy, and (3) factories with reconfigurable manufacturing systems (RMS) that can be rapidly changed to produce
new products and quickly respond to changes in market demand. These topics are covered and mathematically analyzed in this book.

I first became concerned about the future impact of globalization on the U.S. manufacturing industry and jobs in the early 1990s. In 1992, the European Union had been formed, and in 1994, the North American Free Trade Agreement (NAFTA) became public. People in the United States were becoming acutely concerned for the future of the domestic automotive industry. We looked for technical solutions and wrote a large proposal to the National Science Foundation (NSF).

On August 1, 1996, we opened the Engineering Research Center (ERC) for RMS with an 11-year grant of $35 million from the NSF to develop and implement reconfigurable systems. Establishing the RMS Center opened the era of reconfigurable manufacturing in which the speed of responsiveness is the prime business goal and reconfiguration is an important technology enabler for achieving our goal:

“Exactly the capacity and functionality needed, exactly when needed.”

To understand the current revolution in global manufacturing enterprises it is necessary to analyze the technical and business dimensions of previous manufacturing paradigms, such as mass production and mass customization. Original models are offered here to study these paradigms. This book introduces many innovations to the whole manufacturing culture: an original approach to the analysis of paradigms; suggested methods for developing creativity in product design; a quantitative analysis of manufacturing system configurations; discussions of the globalization impact on enterprises, and an original approach to the use of information technology for workforce empowerment. The book contains 200 original illustrations and pictures that clarify the topics.

Chapters 2 and 3 of this book deal with product design for globalization with emphasis on creativity and developing innovation skills. The topic of Chapters 6 through 10 is manufacturing systems, including thorough analysis of RMS. Chapters 11, 12, and 13 focus on business issues relevant to manufacturing enterprises: business models, company organization, and enterprise globalization strategies needed in the twenty-first century. The focus of Chapters 1, 4, 5, and 14 is the integration of product–manufacturing-system–business. This integration is the systems-view approach that is very essential for leading manufacturing enterprises in the future.

This book is unique in focusing on these globalization issues; as of this printing there have been no others. Thomas Friedman’s famous book, The World is Flat, deals with the impact of globalization on society and business. Although his work does not discuss manufacturing in detail, it explains how the newly leveled playing field of an integrated world has created a revolution in global business. We have been energized by Friedman’s work but we have focused on the manufacturing industry and offered many concrete enterprise and engineering solutions.

This serves as a textbook for a graduate-level class entitled “Global Manufacturing,” which is offered at the University of Michigan to graduate engineering students and MBA students. Student’s assignments include solving problems,
submitting chapter reviews, and a team project that is described in Appendix D. The publisher’s website includes material that may help instructors in teaching a similar course. Throughout each chapter we have included the comments of students of previous classes about the material presented. Since the book introduces new ideas, original models, and novel technologies, I asked students (most of whom have had at least some industrial background) to compare their experience with the theories and claims made in the book. I am grateful for their contributions and find them to be very thoughtful and enlightening.

Finally, I would like to thank my wife Alina, who suggested that I write this book and encouraged me through its writing; to Rod Hill for the many professionally prepared illustrations and cartoons and for his editorial support; to my colleagues for their interest and assistance; and to the readers who sent comments, only a small sample of which could be published here.

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Globalization is the integration and interdependency of world markets and resources in producing consumer goods and services

Globalization has created a new, unprecedented landscape for the manufacturing industry, one of fierce competition, short windows of market opportunity, frequent product introductions, and rapid changes in product demand. Indeed, globalization is challenging, but it presents both threats and opportunities. To capitalize on the opportunities, industry needs to offer products that are innovative and also can be made to appeal to buyers from many cultures so they can be sold all over the globe. The challenge, however, is to succeed in a turbulent business environment where all competitors have similar opportunities.

Success in such a turbulent environment requires a global enterprise structure that can rapidly respond to changing markets and customer’s needs. This enterprise should be equipped with a manufacturing system that can be rapidly changed and reconfigured to respond to volatile demand. This new generation of manufacturing systems will need to be reconfigured within two categories: product quantities (changed capacity) and product mix (changed functionality). Capacity reconfiguration is needed to produce exactly the product quantities required by the market at any given time. Manufacturing system and supply-chain functionality must also be reconfigured to support an accelerated pace of product innovation, and to produce the right mix of products required by various regions around the globe.
In short, a new global manufacturing revolution is needed to succeed in the new global economy; it must be a revolution based on responsive manufacturing systems and responsive business models. Responsive business models should aim at expanding into global markets by developing products that fit the culture of those markets and can be sold there. The business model must encompass not only selling, but also the international buying of components, and establishing global supply chains. The global enterprise should more closely integrate product design with its manufacturing systems and its global business model.

Charles R. Darwin’s statement in his book *On the Origin of Species*: “It is not the strongest species that survive, nor the most intelligent, but the ones most responsive to change,” is now valid for global manufacturing enterprises.

### 1.1 THE IMPORTANCE OF MANUFACTURING TO SOCIETY

Why are we worried about manufacturing in the twenty-first century? Isn’t manufacturing an “old-economy” profession that should be relegated to only poor countries? Is manufacturing really so important for a fully developed nation in the global economy?

Manufacturing is today, as it always has been, a cornerstone of the U.S. economy as it is for other developed nations. Having a strong base of manufacturing is important to any advanced country because it impels and stimulates all the other sectors of the economy. It provides a wide variety of jobs, both blue- and white-collar jobs, which bring higher standards of living to many sectors in society, and builds a strong middle class. Simply put, its most important benefit to society is that manufacturing creates wealth.

Think about this:

*Only art, agriculture, construction, and manufacturing, and more recently the software industry, create something of value from nothing.*

However, there is a big difference in the types of jobs that each industry creates.

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An important advantage of manufacturing is that it creates a whole range of diverse jobs. Whereas agriculture and construction generate lots of low-skilled jobs, and art and software create a few jobs for higher-skilled elites, manufacturing calls on the skills of everyone from entry-level factory workers to scientists, engineers, and business professionals.

*Charles R. Darwin (1809–1882) developed in England the theory of evolution. His most known book is *On the Origin of Species*, in which he describes the evolution of life on earth and includes this famous quote: “It is not the strongest species that survive, nor the most intelligent, but the ones most responsive to change.”*
To meet its far-ranging needs, manufacturing stimulates employment in other sectors of the economy. It has been calculated in 2001 by the Association of Manufacturing Technology (AMT) that each $1 million in sales of manufacturing goods produced in the United States supports eight jobs in the manufacturing sector and an additional six jobs in other sectors, such as information technology (IT), transportation, and construction. That means an average of 14 jobs are created by the U.S. manufacturing industry for each $1 million in sales. No other sector comes even close.

American manufacturing has been a strong contributor to the U.S. national economy for generations. In addition, gains in manufacturing productivity pass down to other sectors, building wealth and generating employment through the whole economy. The finished goods amount to only a portion of manufacturing’s value. Production of intermediate-level goods (parts included in other products like engines, compressors, pumps, etc.) contributes significantly to the economy. Further, the design and production of manufacturing infrastructure, tooling, and equipment are industries of their own. And this says nothing of the high levels of transportation, information, and communications infrastructure that are all required to support world-class manufacturing. Because of its scale and volume, no other industry can replace manufacturing industry in any nation’s economy. While the products America builds may and must change over time, domestic manufacturing continues to play a critical role in U.S. prosperity.

Manufacturing was, is, and shall remain the foundation of a strong economy. No other sector can replace it. Without a solid manufacturing base, the service and finance sectors will collapse.

As shown in Figure 1.1, the percentage of GDP of the U.S. private manufacturing sector has been gradually declining from 32% in 1950 to 13.4% in 2007.* From 1950, the manufacturing sector was constantly the highest in GDP percentage until 2005. In 2006, the real-estate sector moved ahead (14.9%) with manufacturing second (13.8%), and, as depicted in Figure 1.2, these sectors were 14.3% (real-estate) and 13.4% (manufacturing). However, even 13% is still a huge portion of the economy. In fact, manufacturing still remains the largest productive sector in the overall U.S. economy.

The GDP percentages of several sectors of the economy are shown in Table 1.1. In the late 1980s, “information” emerged as a new sector, which gradually increased to 5% in 2000. It is worth noting that, since 1990, investments in IT on behalf of manufacturing enterprises have contributed significantly to development of the information sector.

*Source for Figures 1.1 and 1.2 as well as Table 1.3 is U.S. Department of Commerce, Bureau of Economic Analysis, (http://www.bea.gov).
Table 1.1 shows that the productive sectors of the economy halved in 35 years. Simultaneously with the 50% decline in manufacturing in the last 35 years, agriculture also declined at the same percentage. During the same period, the service sectors (including education, health, finance, and insurance) doubled. These data show that the U.S. economy is becoming more of a service economy than an economy that creates tangible wealth. But, is this a healthy trend?

Some renowned economists argue that the future of the United States is in the service industry. However, many portions of the service industry depend on the domestic manufacturing industry—truck ing, financing, education, and infrastructure. Furthermore, an export of the service industry is very limited. A balance of export and trade is vital to a nation’s economy, and therefore for the economy to thrive, manufacturing must remain healthy.

Figure 1.1  Manufacturing share of the U.S. Gross Domestic Product, 1950–2007 (as a percentage of the private industry). Source: U.S. Department of Commerce, Bureau of Economic Analysis.

Figure 1.2  Decomposition of private industries in 2007.
Advanced industrial countries, including the United States, heavily subsidize agriculture, rendering that sector’s benefit to the nation’s economy as questionable. And yet, by contrast, manufacturing is not subsidized in the United States, even though its growth directly contributes to the wealth of the country.

Enhancing manufacturing growth depends on increasing productivity and inventing manufacturing technologies. Many major innovations in manufacturing methods originated in the United States—the invention of mass production by Henry Ford at the beginning of the twentieth century, the invention of numerical control (NC) machines of the 1950s, and the invention of reconfigurable manufacturing systems (RMSs) in the late 1990s. Coincidently, these three inventions that contribute to productivity improvements were started in the state of Michigan—the first in Dearborn, the second in Traverse City, and latest in Ann Arbor.

1.2 THE BASICS OF MANUFACTURING IN LARGE QUANTITIES

Manufacturing revolves around the production of quantities of new products. First, the product is developed, then it is manufactured, and finally it is sold to customers. Important factors for product developers to consider include how products look, how they work, and how the user interacts with them. To verify the product design, a product prototype is often constructed and tested to validate the design and product functionality. A prototype is built as a one-of-a-kind, essentially a work of art, and that can take a lot of time and labor. Even so, the prototyping method can be cost-effective when only a handful of copies are ever going to be sold.

When the manufacturer intends to produce large quantities of the product, as in the production of automobiles, refrigerators, or microprocessors, a more economical method is required. If large quantities were produced in the same way as the prototype, each product could be 10–20 times more expensive than the ones produced by a well-designed manufacturing system. For large quantities of products, a manufacturing system capable of mass production has to be developed.

The goal of a manufacturing system is to produce high-quality products at a fraction of what it took to build the prototype, so they can be sold at a marketable price. The manufacturing system achieves “economies of scale” that the prototype shop cannot, neither in output nor in consistency. In a globally competitive environment, designing a cost-effective manufacturing system and operating it efficiently is a key factor in maintaining competitiveness.
competitive challenge especially when competitors have an advantage in countries where labor costs are substantially smaller.

Manufacturing systems typically consist of multiple stages, where each stage contains a machine or an assembly station to perform a given set of operations, as is illustrated in Figure 1.3. The machines are connected with a material transport system.

When the operations in one stage are completed, the raw product is transferred to the next stage, and so forth until all needed operations are completed and the product is finished. When especially large quantities are needed, multiple machines (or assembly stations) can be installed in parallel to perform the same operations at the same time on each machine (Figure 1.3, bottom), which increases the system throughput but makes the system design and operation more complex.

Most manufacturing is applied in multi-stage systems including assembly, such as those used to build automobiles, office chairs, or personal computers from given parts; or they may be systems with chemical processes, such as those on which semiconductor wafers are produced; or they may be machining systems for products that have to be machined, such as engine blocks, motors, pumps, and compressors. In machining systems, the products start out as rough castings that have to be drilled, milled, shaped, and polished using computerized numerically controlled (CNC) machine tools.

1.2.1 Dedicated and Flexible Systems

At the dawn of the twenty-first century, industries around the world used two basic types of manufacturing systems: dedicated manufacturing lines (DMLs) and flexible manufacturing systems (FMSs). Dedicated lines (often referred to as “transfer lines”) are designed to produce very large quantities of just one product, and they operate at very high productivity because the machines are simple and robustly designed. For example, engine blocks for cars can be machined on dedicated machining lines at a
cycle time of 30 seconds (two engines are produced every minute). Therefore, once the line is properly tuned and calibrated, and as long as the dedicated line operates at its planned high-volume capacity, it produces products very quickly at very attractive prices (but it is only able to produce that one single product per line).

So what happens when there is no longer a need for that many engines, and demand is reduced to say one engine every 3 minutes (1/6 of the line designed capacity)? When that happens the dedicated line is underutilized, and therefore, the cost per product becomes higher. A report published in Italy in 1998 indicated that the average utilization of the surveyed DMLs in the European auto-industry was only 53%. That means that barely half of the potential capacity was being utilized and the lines stood idle for long periods.

Furthermore, DMLs cannot be easily converted to produce new products even if they are similar and of the same product family. In the new global manufacturing paradigm, this is the main drawback of DMLs. With globalization, the marketable life of products is becoming shorter and shorter, and new products are being introduced faster and faster. These realities make DMLs uneconomical, and in fact they are vanishing in many manufacturing industries.

On the other end of the product volume versus variety spectrum (Figure 1.4) are FMSs. Unlike DMLs where each machine does a few simple operations, FMSs include machines that are capable of performing a variety of operations, and by extension can produce a large range of different products. FMSs, however, fit the factory portfolio only when relatively small product volumes are needed because they are slow and expensive (compared to DMLs).

FMS systems are expensive most particularly because the equipment possesses features enabling general flexibility that are expensive to build and maintain. Obtaining general flexibility requires added degrees of freedom, motors, mechanical components, and complex control. They are also expensive in the sense that companies typically purchase machines with more functionality than they really need, because they think they may use them in the future. However, the extra flexibility and functionality that the general-purpose FMS can offer is in many cases
a waste of resources, since the extra cost paid for this general functionality equals unrealized capital investment until the extra functionality is actually used. Experience shows these extra resources are rarely utilized.*

The spectrum of products that are produced with FMS is quite large, and includes optical parts, missiles, aircrafts, automotive engines, integrated circuit boards, and even shoes. There are even applications in which the FMS is not built for multi-stage operations. In these cases, the FMS consists of a group of identical CNC machines that are arranged in parallel and each machine does the whole set of operations.

### 1.2.2 Business Models

Products are developed, then manufactured, and finally sold. The business unit of the manufacturing enterprise is in charge of marketing and selling, and the business model actually drives the whole enterprise. Our definition of a business model is:

A business model is a strategic approach for creating economic value for the company by utilizing the competitive advantage of the company, for enhancing the product value to its customers

A business model considers three essential elements: (1) economic value (e.g., profit from selling products); (2) competitive advantage (over competitors); and (3) value to the customer. The business model should define who the customer is and how to create economic value for the company by providing customers with a product or service from which they can derive benefit.

For some products it is not so easy to define who is the customer, and a thorough understanding of the market may be required. Suppose a manufacturer tries to market a mechanical mini-robot that aids in orthopedic surgery. The customers of this technology are, in the order of importance: (1) orthopedic surgeons, (2) hospitals, (3) insurance companies, and (4) the patients. Yes, the patients come last. If the surgeons don’t like the device, it will not be bought; if they do like it, they will recommend it to the hospitals. But only when the hospitals are convinced of the usefulness of the robot for improving surgery results, will they ask for an approval from their insurance companies. Finally, the patients must be convinced that a robotic-aided surgery enhances the success of their surgery. Each one of these four customer groups represents a necessary, but in themselves insufficient condition for the product success. Note that insurance coverage procedures are country-dependent, which makes the global marketing of this device more challenging.

In the business model of the surgery-aid robot, the product (i.e., the robot) may not necessarily generate the full economic value for the manufacturer. It’s the consumables! In particular the disposable clamps that connect the mini-robot to the patient’s

*See industry survey in Section 6.5.
spine generate the main economic value. Because of contamination this clamp must be thrown away after every use. Since a sole supplier (a monopoly) provides this clamp at non-competitive prices, it is the primary economic value for the robot manufacturer. Computer printer manufacturers utilize a similar business model: they sell inexpensive printers that consume very expensive ink cartridges.

In many cases, inventing a new business model rather than a new product can generate success. Tom Monaghan, for example, became a billionaire by starting a new firm in Ann Arbor, Michigan—Domino’s Pizza. This firm created an economic value not by inventing a new product (the pizza was invented in Italy hundreds of years ago) and not by inventing the process of making the pizza, but rather by inventing a business model of home delivery of his pizza. Home delivery added benefits for the customer, and none of the competition had pizza home delivery when Domino Pizza started. Dominos’ competitive advantage was its delivery system and transportation fleet.

Michael Dell also became a billionaire by creating a new business model. By integrating online communication with simple assembly factories for Dell Computers, he created a combination that generates huge economic value. His business model—exactly the computer that you need—benefits the customer, although it required a substantially complex IT infrastructure that Dell built into a competitive advantage.

1.2.3 The Traditional Sequence—Product, Process, Business

Traditionally, the marketing, product design, and manufacturing units work successively on the development of new products. First, the marketing unit conducts research and furnishes the design team with requirements and specifications for a new product, together with its target price and forecasted sales. The product design team must develop a product that includes all the features given by marketing, no matter how much it costs to produce each feature. The real production cost of each feature is not a parameter when marketing makes decisions. The product design team then optimizes for performance versus cost tradeoffs, where material cost is given. Only then is a manufacturing system built to produce the product. This routine substantially increases the product time-to-market, often by many months. By the time the product is manufactured, and the business unit tries to sell it, the customer’s requirements and interest may have moved on or been fulfilled by a competitor. In the globalization era, this routine must be changed to speed up the product time-to-market.

1.3 THE 1990s: A DECADE OF INTENSIFIED GLOBALIZATION

Modern globalization means the integration and interdependency of world markets in producing consumer goods and services. But when did the era of globalization begin? Goods have been traded globally for thousands of years; for example, the Silk Road between China and Europe spanned the whole Eurasian supercontinent. And before
that, some 4000 years ago, King Solomon in Jerusalem traded with Queen Sheba of Ethiopia in Africa. Nevertheless, globalization, as we know it today, emerged in just the last decade of the twentieth century.

The globalization revolution was shaped mainly by the events that occurred during the 10 years from 1991 to 2001. This decade started with the economic liberalization of India in 1991 that was initiated by Dr. M. Singh, then Indian finance minister, and allowed automatic approval of foreign investment in India. The last landmark in this decade was the inclusion of China as a member of the World Trade Organization (WTO) on December 11, 2001. To do so, China agreed to undertake a series of commitments to open and liberalize its market to foreign products. The WTO, which developed to its current structure in 1995, is a multi-governmental entity (as of July 2008 it had 153 countries as members) that facilitates doing business internationally by (1) formulating rules to govern global trade and capital flows through member consensus and (2) supervising member countries to ensure that the trade rules are implemented.

During that same decade the European Union (EU) and the North America Free Trade Agreement (NAFTA) were also created. The EU was established on November 1, 1993 along with the European Economic Community. The EU is not only a free trade zone, but also an economic and political union of 27 countries, with 500 million people (in 2007), that has its own parliament. NAFTA is a trilateral trade bloc created by the governments of the United States, Canada, and Mexico, which came into effect on January 1, 1994. It is one of the most powerful, wide-reaching treaties in the world.

In addition to these four government initiatives, Russian president Yeltsin initiated changes in 1993 that started to privatize industries in that country that were government controlled prior to that time. These five governmental initiatives are marked 1–5 in Table 1.2.

In parallel to these governmental initiatives, U.S. and European manufacturing industries started to take advantage of the new global conditions. The manufacturing world was shocked when in 1994 GM announced its plan to open factories in China “to penetrate Asia’s growing market and to save money by using low-cost Chinese labor.”2 Before then, no one had imagined the fierce competition that was to come across the ocean from China. At the same time, U.S. manufacturing industry, and especially the automotive industry, started to migrate abroad, first to Mexico and later to other parts of Asia as well.

All through that decade, high-capacity fiber-optic cables were laid across the oceans. These cables serve as the information highways of the world and enable Western companies to utilize brainpower in countries where talented professionals can work while we sleep; for example, because of the time difference, GM R&D in Warren, Michigan can send a problem in the late afternoon, to GM R&D in Bangalore, India, and get an answer the next morning; and there are no language barriers. These fiber-optics cables are the blood vessels of globalization, enabling integration of the world’s knowledge and markets.

On January 1, 2002, the Euro currency was adopted in 12 countries of the EU and stands as a symbolic milestone at the end of this decade of intensified globalization.