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Computer Aided Design and Manufacturing

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Series Preface

The Wiley-ASME Press Series in Mechanical Engineering brings together two established leaders in mechanical engineering publishing to deliver high-quality, peer-reviewed books covering topics of current interest to engineers and researchers worldwide.

The series publishes across the breadth of mechanical engineering, comprising research, design and development, and manufacturing. It includes monographs, references and course texts.

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Preface

Manufacturing Engineering is to apply mathematics and science in practice to design, manufacture, and operate products or systems. *Manufacturing engineers* are responsible for designing, developing, and running manufacturing systems to produce competitive goods. In most universities' engineering curricula, the courses in a manufacturing program cover the fundamentals such as *mathematics*, *physics*, *computing engineering*, *management*, as well as disciplinary subjects such as *materials science*, *machine designs*, *solid mechanics*, *thermodynamics*, *fluid mechanics*, *manufacturing processes*, and *design optimization*. Currently, most engineering curricula cover as many sub-disciplines of mechanical and manufacturing engineering as possible and students take their options to be specialized in one or more sub-disciplines. Therefore, existing curricula are mostly discipline-oriented.

Designs of modern products and processes are very complex, and complex designs rely heavily on computer aided technologies. However, computing and information technologies have been developed in a way that is very different from the manufacturing engineering education. Numerous computer aided tools become commercially available; moreover, the number and capabilities of computer tools keep increasing continuously. These tools are usually application-oriented and they have been developed by integrating design theories in multiple disciplines, rather than the theories and methods in an individual discipline. Due to the strongly decoupling of multiple disciplines, the classification of sub-disciplines in traditional engineering curricula is not aligned with the varieties of computer aided tools.

The misalignment of the discipline-oriented curricula and a variety of functional computeraided tools cause the dilemma in manufacturing engineering education. *On the one hand*, the sub-disciplines in manufacturing engineering are highly diversified. Keeping an increasing number of elective courses in an engineering programme becomes a great challenge since the number of required credit hours for an engineering degree has been continuously reduced in public university systems. *On the other hand*, engineering universities are facing an increasing pressure to train students for the appropriate set of knowledge and skills of using advanced computeraided tools to solve complex design problems. There is an emerging need to re-design engineering curricula so that the CAD/CAM-related courses can be aligned with discipline-oriented curricula.

We deal with this misalignment by proposing a new course framework to integrate *Computer Aided Design* (CAD), *Computer Aided Manufacturing* (CAM), and other Information Technologies (ITs) in one course setting. In the framework, the inclusion of engineering disciplines and computer aided technologies are driven by the needs in designing products and manufacturing processes. While the theories in engineering disciplines are used to clarify design and analysis problems, computer aided tools are presented as the corresponding solutions. In addition, the framework is modularized and the course contents can be customized for some specialties.

The current version is customized to meet education needs of students in *Mechanical Engineering*, *Manufacturing Engineering*, and *Industrial Engineering* at junior or senior levels. It consists of three parts: Part I – *Computer Aided Design* (CAD), Part II – *Computer Aided Manufacturing* (CAM), and Part III – *System Integration*. Part I includes Chapter 2 – *Computer Aided Geometric Modelling*, Chapter 3 – *Knowledge-Based Engineering*, Chapter 4 – *Platform Technologies*, Chapter 5 – *Computer Aided Reverse Engineering*, and Chapter 6 – *Computer Aided Machine Design*. Part II includes Chapter 7 – *Group Technology and Cellular Manufacturing*, Chapter 8 – *Computer Aided Fixture Design*, Chapter 9 – *Computer Aided Manufacturing (CAM)*, Chapter 10 – *Simulation of Manufacturing Processes*, and Chapter 11 – *Computer Aided Design of Tools, Dies, and Moulds (TDMs)*. Part III includes Chapter 12 – *Digital Manufacturing (DM)*, Chapter 13 – *Direct and Additive Manufacturing*, and Chapter 14 – *Design for Sustainability (D4S)*.

The concepts of CAD, CAM, and system integration are not new; a number of textbooks on these subjects have been on the market for a long time. However, CAD, CAM, and system integration technologies have been greatly advanced recently due to the rapid development of IT and computer hardware and software systems. Most of the available textbooks in relevant subjects become obsolete in terms of design theories, methods, and technical coverages. Modern manufacturing systems in the digital era become ever more complicated, and product and system designs demand more advanced computer tools to deal with the complexity, varieties, and uncertainties. In contrast to other textbooks in similar areas, this book is featured (i) to update computeraided design theories and methods in modern manufacturing systems and (ii) to cover mostly advanced computeraided tools used in digital manufacturing. It will be an ideal textbook for undergraduate and graduate students in *Mechanical Engineering*, *Manufacturing Engineering*, and *Industrial Engineering* and can be used as a technical reference for researchers and engineers in mechanical and manufacturing engineering or computer aided technologies.

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About the Companion Website

The companion website for this book is at

www.wiley.com/go/bi/computer-aided-design

The website includes:

- PDFs
- PPTs

Scan this QR code to visit the companion website.

1

Computers in Manufacturing

1.1 Introduction

1.1.1 Importance of Manufacturing

The life quality of human being relies on the availability of products and services from primary industry, secondary industry, and tertiary industry. According to the *three-sector theory* (Fisher 1939), *the primary industry* relates to the economic activities to extract and produce raw materials such as coal, wood, and iron. *The secondary industry* relates to the economic activities to transfer raw or intermediate materials into goods such as cars, computers, and textiles. *The tertiary industry* relates to the economic activities to provide services to customers and businesses. The secondary industry supports both the primary and tertiary industries, since the businesses in the secondary industry take the outputs of the primary industry and manufacture finished goods to meet customers' needs in the tertiary industry. In contrast to the wealth distribution or consumption in the tertiary industry, the secondary industry creates new wealth to human society (Kniivila 2018).

A manufacturing system can be very simple or extremely complex. Figure 1.1a shows an example of blacksmithing where some simple farming tools are made from iron (Source Weekly 2012). Figure 1.1b shows an example of a complex car assembly line, which is capable of making Ford Escape cars (Automobile Newsletter 2012). Despite the difference in complexity, both of them are good examples of a manufacturing system since *manufacturing* refers to the production of merchandise for use or sale using labour and machines, tools, chemical and biological processing, or formulation (Wikipedia 2019a). Manufacturing is one of fundamental constitutions of a nation's economy. Manufacturing businesses dominate the secondary industry. Powerful countries in the world are those who take control of the bulk of the global production of manufacturing technologies. Over the past hundreds of years, advancing manufacturing has been the strategic achievement of the developed counties to sustain their national wealth and global power. The importance of manufacturing to a nation has been discussed by numerous of researchers and organizations. For example, a summary of the importance to the USA economy is given by Flows (2016) and Gold (2016) as follows:

1. Manufacturers contributed \$2.2 trillion with ~12% of gross domestic product (GDP) to the USA economy in 2015.

Computer Aided Design and Manufacturing, First Edition. Zhuming Bi and Xiaoqin Wang.

Companion website: www.wiley.com/go/bi/computer-aided-design

(a) (b)

Figure 1.1 A manufacturing system can be very simple or complex (a). Blacksmithing (Source weekly 2012), (b). Ford assembly line at Kansas City (Automobile Newsletter 2012).

2. The manufacturing multiplier effect is stronger than in other sectors. For $1.00 spent in manufacturing, $1.81 is added to other sectors of the economy. Manufacturing has the *highest multiplier effect*. Gold (2016) argued that the impact of manufacturing has been greatly underestimated; it is supported by the findings of the Manufacturers Alliance for Productivity and Innovation (MAPI) Foundation that the total impact of manufacturing on the economy should be 32% of GDP and that the full value stream of manufactured goods for final demand was equal to $6.7 trillion in 2016.
3. Manufacturing employs sizeable workforces. The manufacturing sector provides ~17.4 million jobs, or over 12.3 million.
4. Manufacturing pays premium compensation. Manufacturing workers earnt a high average of $81 289 annually in 2015.
5. Manufacturing dominates US exports; the United States is the No. 3 manufacturing exporter.
6. The US attracts more investment than other countries and foreign investment in US manufacturing grows; the foreign direct investment in manufacturing exceeded $1.2 trillion in 2015. New technologies allow manufacturers to alter radically the way they innovate, produce, and sell their products moving forward, improving efficiency and competitiveness.

1.1.2 Scale and Complexity of Manufacturing

From a system perspective, a manufacturing system can be described by the *inputs*, *outputs*, *system components*, and *their relations*, as shown in Figure 1.2. The system is modelled in terms of its *information flow* and *materials flow*, respectively. System inputs and outputs are involved at the boundaries of a manufacturing system in its surrounding business environment. For example, the materials from suppliers are system inputs and the final products delivered to customers are system outputs. System components include all of the manufacturing resources for designing, manufacturing, and assembling of products as well as

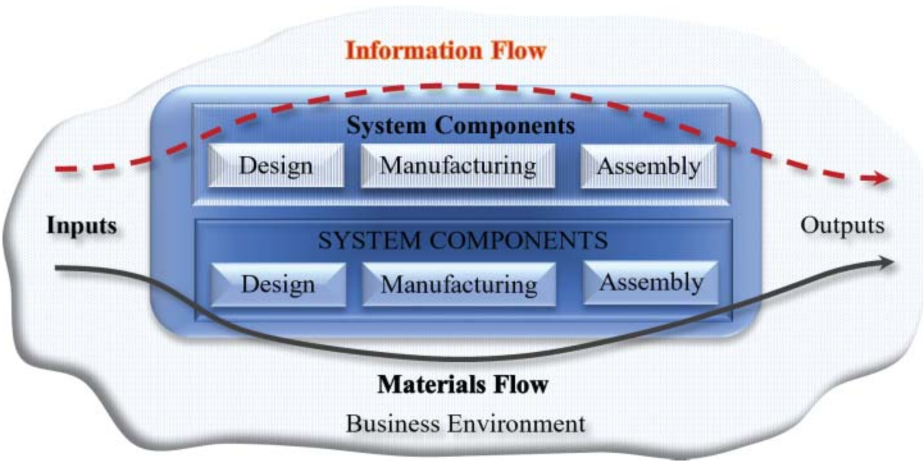

Figure 1.2 Description of a manufacturing system.

other relevant activities such as transportations in the system. In addition, a virtual twin in the information flow is associated with a physical component in the materials flow for decision-making supports of manufacturing businesses.

In the evolution of manufacturing technologies, the scale and complexity of manufacturing systems have been growing constantly. Note that both the scale and complexity of a system relates to the number and types of inputs, outputs, and system components that transform inputs to outputs. Figure 1.3 shows the impact of the evolution of system paradigms on the complexity of manufacturing systems (Bi et al. 2008). The evolution of system paradigms is divided into the phases of craft systems, English systems, American systems, lean production, flexible manufacturing systems (FMSs), computer integrated manufacturing (CIM), and sustainable manufacturing.

Historically, the manufacturing business began with *craft systems* where some crude tools were made from objects found in nature. The system inputs were simple objects and the requirements of the products were basic functions. In the 1770s, James Watt improved Thomas Newcomen's steam engines with separate condensers, which triggered the formation of *English systems*. In an English manufacturing system, machines partially replaced human operators for heavy and repetitive operations, the power supply became an essential part of the manufacturing source, and the production was scaled to make functional products for profit. In the 1800s, Eli Whitney introduced interchangeable parts in manufacturing that allowed all individual pieces of a machine to be produced identically. Thus, mass production became possible, the manufacturing processes began to be distributed, and system inputs in general assembly companies included parts and components. The criteria of system performance were prioritized with productivity and product quality. Mass production in the *American system* paradigm brought the rapid growth of manufacturing capacities that led to the saturation of manufacturing capacities in comparison with global needs. The global market became so competitive that the profit margin was such that without consideration of cost savings in the manufacturing processes profits would be insufficient to sustain manufacturing business. The *lean production* paradigm was conceived in Japan to optimize

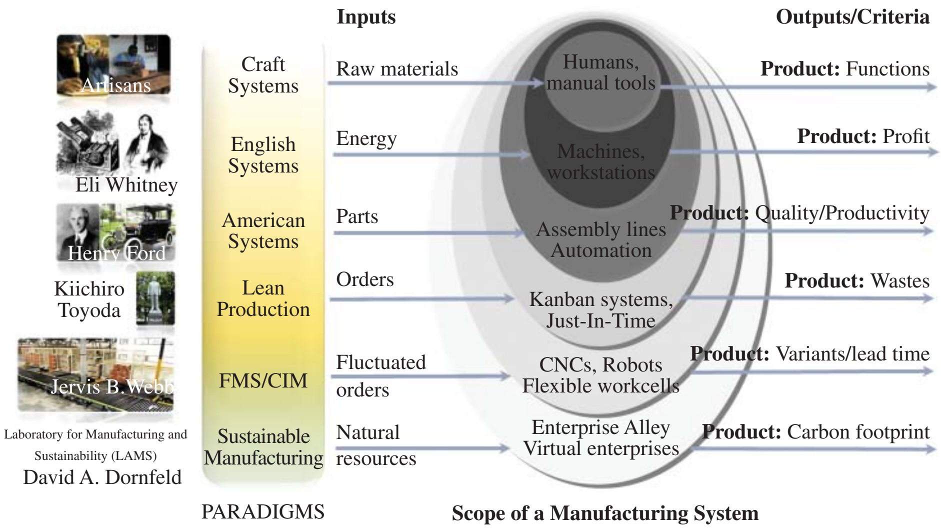

Figure 1.3 The growth of scale and complexity of manufacturing systems (Bi et al. 2014). (*See color plate section for color representation of this figure*).

system operation by identifying and eliminating waste in production, thus reducing product cost to compensate for the squeezed profit margin. Most recently, *sustainable manufacturing* paradigms were developed to optimize manufacturing systems from the perspective of the product life cycle. This was driven by a number of factors, such as global warming, environmental degradation, and scarcity of natural resources. Manufacturing system paradigms are continuously evolving. The trend of the evolution in Figure 1.3 has shown that manufacturing systems are becoming more and more complicated in terms of the *number of system parameters*, the *dependence on system parameters*, and *their dynamic characteristics* with respect to time. The engineering education for human resources must evolve to meet the growth needs of the manufacturing industry.

1.1.3 Human Roles in Manufacturing

Computer aided technologies (CATs) in manufacturing are of the most interest in this book and are widely adopted to replace humans in various manufacturing activities and decision-making supports. To appreciate the applications of CATs, the roles of the human being in manufacturing systems are firstly discussed to explore the possibilities of automated solutions.

As shown in Figure 1.4, the importance of human being in a manufacturing system has been widely discussed. In developing the Purdue system architecture, Li and Williams (1994) classified manufacturing activities into the activities in information/control flow and material flow, respectively. Human resources are needed to accomplish the tasks in both information and material flows. For example, human labourers are commonly seen in an assembly plant to accomplish manual assemblies in the material flow; technicians are needed by small and medium sized companies (SMEs) to generate codes and run computer

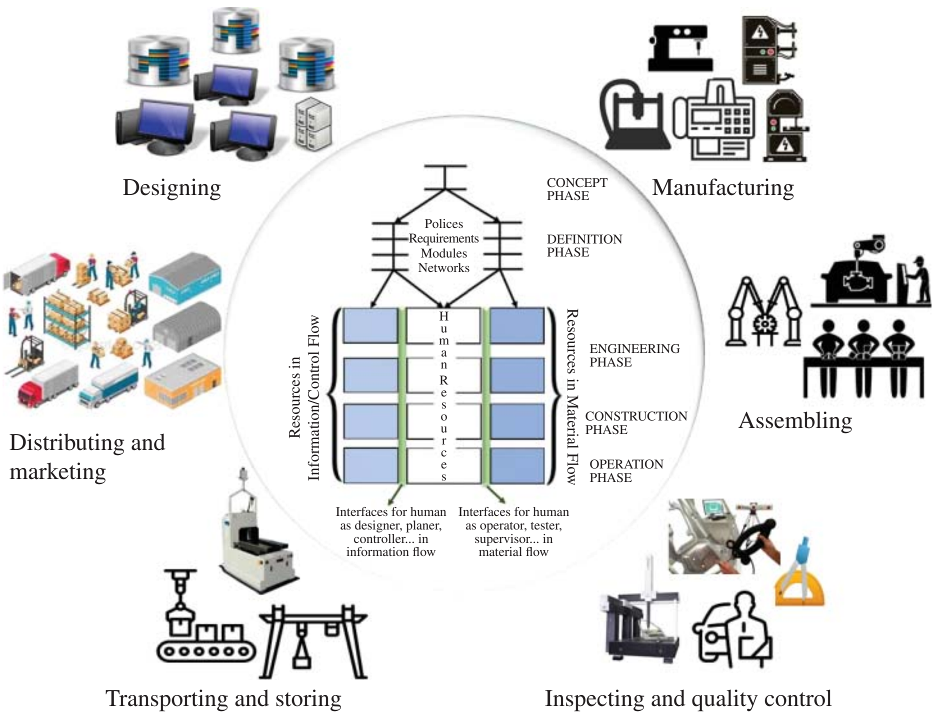

Figure 1.4 Human's role in manufacturing (Ortiz et al. 1999). (*See color plate section for color representation of this figure*).

numerical controls (CNCs) in the information/control flow. From the perspective of a product lifecycle (Ortiz et al. 1999), human resources are needed at every stage from designing to manufacturing, assembling, inspecting, transporting, marketing, and so on.

Human resources will certainly play an essential role in the future of manufacturing where manufacturing technologies and human beings are being integrated more closely and more harmoniously than ever before. While the focus should be shifted to the effective human–machine interactions to synergize both strengths of human beings and machines, manufacturing technologies should be advanced to balance the strengths and limitations of human resources optimally.

With the rapid development of information technologies (IT), CATs are replacing human beings for more and more decision-making support. The design and operation of a manufacturing system involves numerous decision-making undertakings at all levels and domains of manufacturing activities. In any engineering decision-making problem, one can follow the generic procedure with a series of design activities: (i) defining the scope and boundary of a design problem and its objective, (ii) establishing relational models among inputs, outputs, and system parameters, (iii) acquiring and managing data on current system states, and (iv) making decisions according to given design criteria. In the information flow of a manufacturing system, each entity normally has its capabilities to acquire the input data, process data, and make the decision as an output data.

1.1.4 Computers in Advanced Manufacturing

The performance of a manufacturing system can be measured by many criteria. Some commonly used evaluation criteria are *lead-time*, *variants*, and *volume*s of products, as well as *cost* (Bi et al. 2008). Manufacturing technologies have advanced greatly to optimize system performances. Figure 1.5 gives a taxonomy of available enabling technologies in terms of the *strategies*, *domains*, and *product paradigms* of businesses to optimize systems against the aforementioned evaluation criteria. In the implementation of production, the majority of advanced technologies, such as CIM, FMS, Concurrent Engineering (CE), Additive Manufacturing (AM), and Total Quality Management (TQM), are enabled by CATs.

The advancement of CATs can be measured by their capabilities in dealing with the growing scales and complexities of systems and the autonomy of system responsiveness. Figure 1.6 shows the evolution of CATs from the perspective of these three measures (Bi et al. 2014), together with computer applications in manufacturing using numerical control (NC)/CNC workstations, FMSs, CIM, distributed manufacturing (DM), and predictive

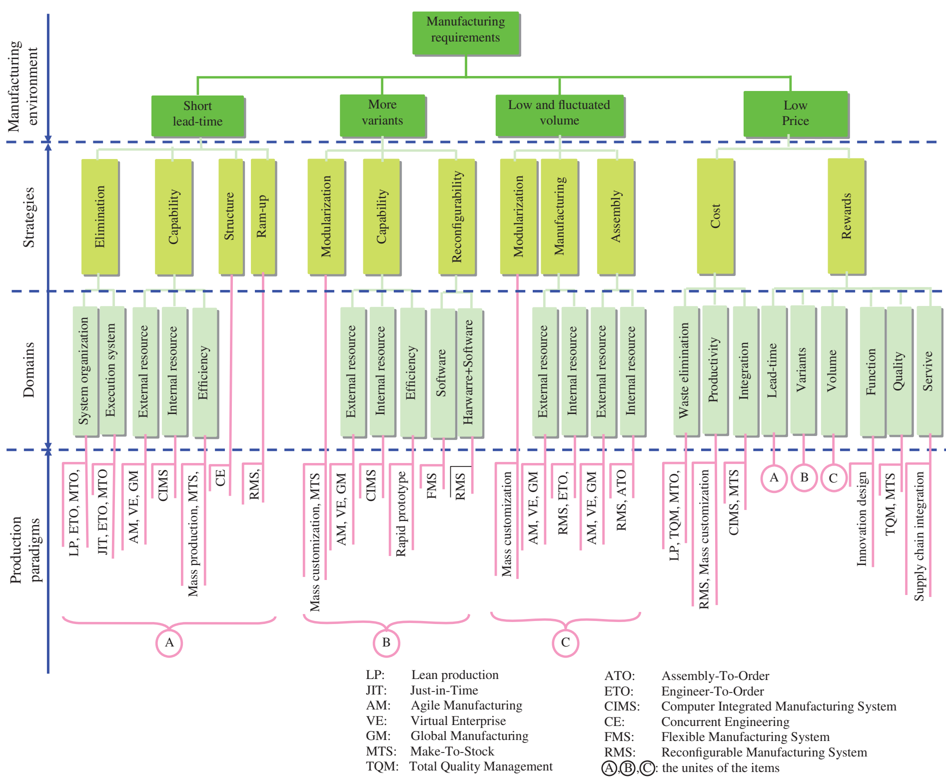

Figure 1.5 The strategies, domains, and production paradigms of advanced manufacturing technologies (Bi et al. 2008). (*See color plate section for color representation of this figure*).