1

Computers in Manufacturing

1.1 Introduction

1.1.1 Importance of Manufacturing

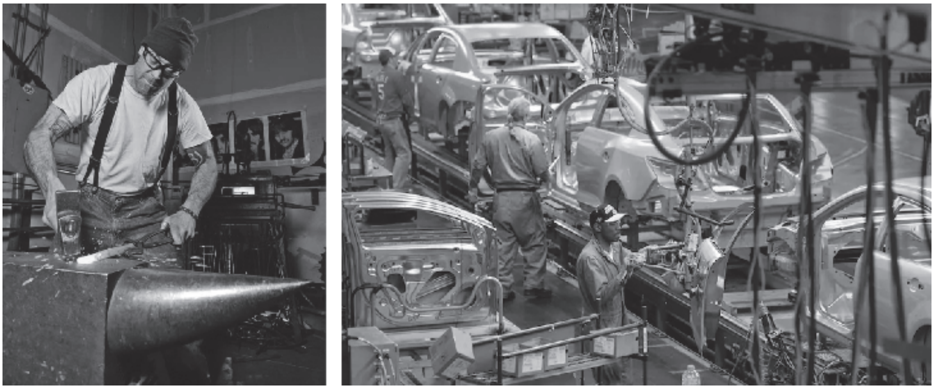
The life quality of human being relies on the availability of products and services from primary industry, secondary industry, and tertiary industry. According to the *three-sector theory* (Fisher 1939), *the primary industry* relates to the economic activities to extract and produce raw materials such 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

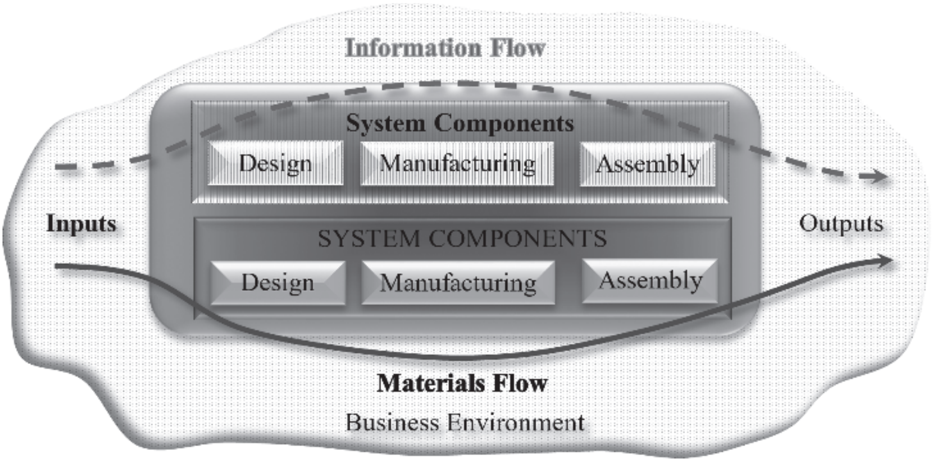


Figure 1.2 Description of a manufacturing system.

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

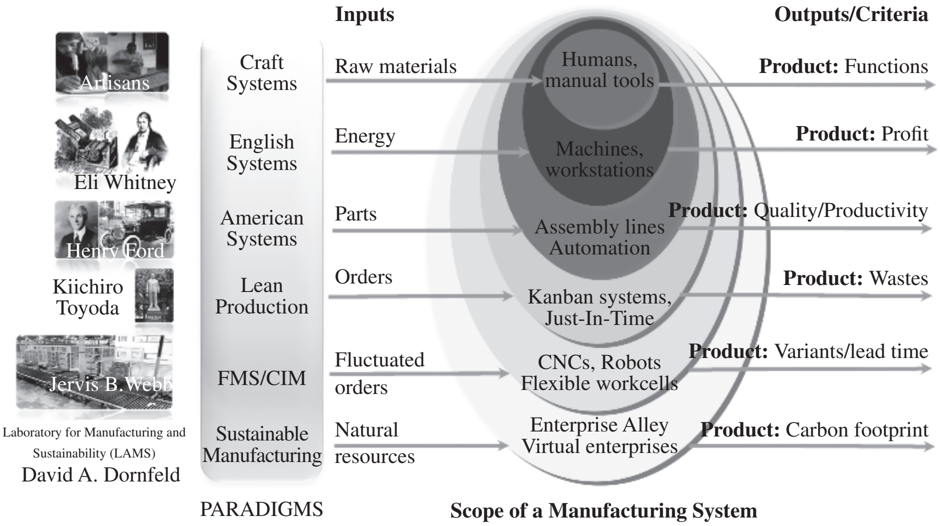


Figure 1.3 The growth of scale and complexity of manufacturing systems (Bi et al. 2014). (*See color plate section for color representation of this figure*).

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

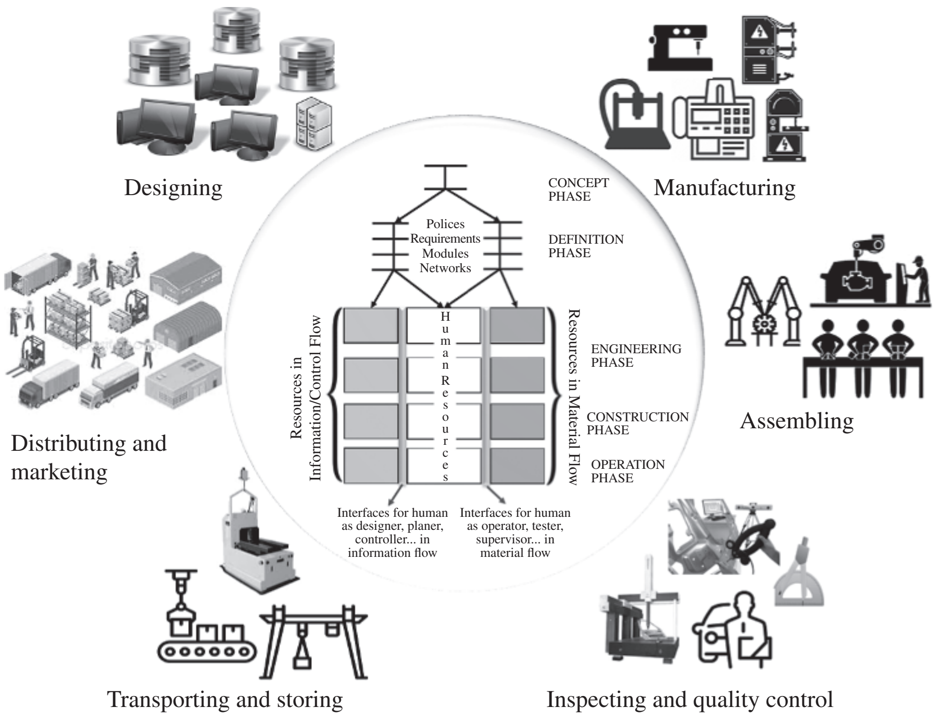


Figure 1.4 Human's role in manufacturing (Ortiz et al. 1999). (*See color plate section for color representation of this figure*).

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

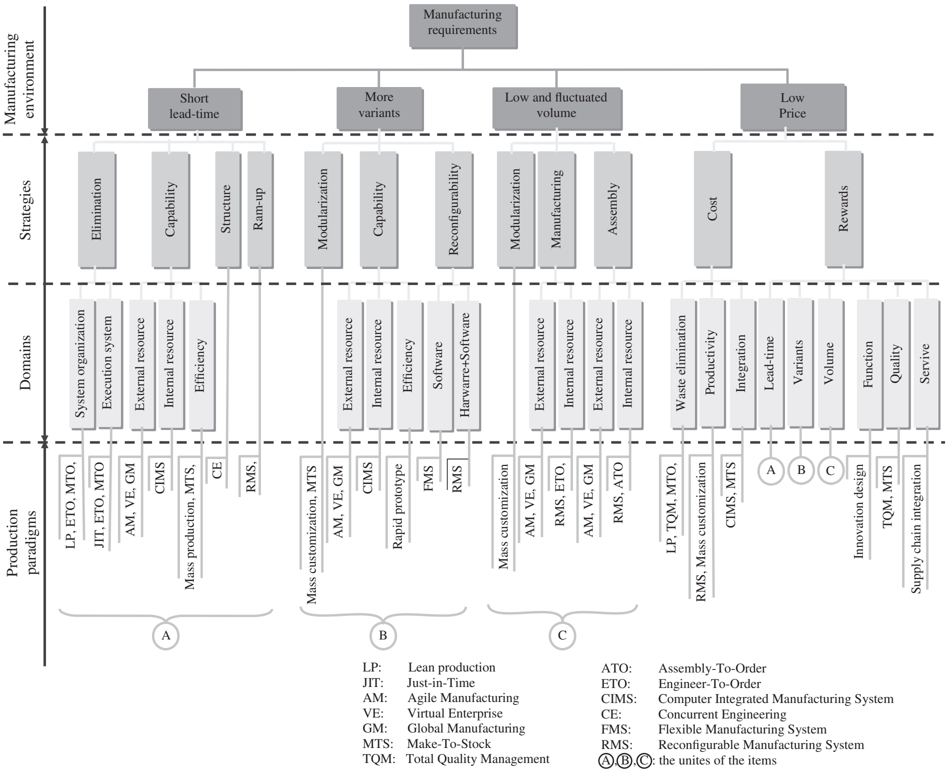


Figure 1.5 The strategies, domains, and production paradigms of advanced manufacturing technologies (Bi et al. 2008). (*See color plate section for color representation of this figure*).

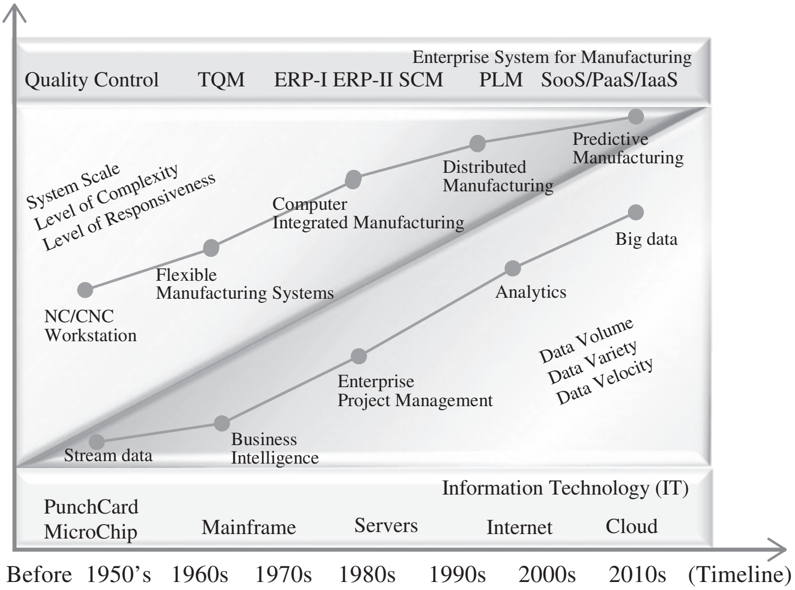


Figure 1.6 Evolution of computer aided technologies in manufacturing (Bi and Cochran 2014). (*See color plate section for color representation of this figure*).

manufacturing (PM). Typical computer aided tools to support these enabling technologies are *Quality Control* (QC), TQM, *Enterprise Requirements Planning* (ERP-I), *Enterprise Resources Planning* (ERP-II), *Product Lifecycle Management* (PLM), *Software as a Service* (SaaS), *Platform as a Service* (PaaS), and *Infrastructure as a Service* (IaaS), respectively. Correspondingly, the capacities of software systems to deal with volume, variety, and velocity of the data have been increased gradually from stream data early in the digital era to big data now. IT hardware systems must be capable of processing data in a timely manner. The computing environments have evolved from Microchip, mainframe, servers, the Internet, to today's Cloud.

1.2 Computer Aided Technologies (CATs)

Computer aided technologies provide the aids for design, analysis, manufacture, and assembly of products and for design, planning, scheduling, controlling, and operations of production systems. Various CATs have been gradually known and adopted by engineers since CATs and tools were developed in the late 1950s. Wikiversity (2019) divides the historical development of computer aided design (CAD) into the stages of two-dimensional, three-dimensional, and parametric designs. Many other researchers discussed the development of CAD technologies by marking some significant theoretical contribution and products as milestones.

Table 1.1 Milestones in the 60 year history of CAD development (Computer History 2019a).

Year	Products, developers, and features
1957	PRONTO was developed by Patrick Hanratty as the first commercial numerical control programming system. It sparked everything that is CAD, known as the building block of everything CAD.
1960	Sketchpad was developed by Ivan Sutherland as the first tool with a graphic user interface. Users wrote with a light pen on an *x–y* pointer display, let users constrain properties in a drawing, and created the use of objects and instances.
1966	Computer Aided Design and Drawing (CADD) was developed by McDonell-Douglas. It was used to create layouts and geometry of designs and could be customized and improved for specific uses.
1967	The Product Design Graphics System (PDGS) was developed by Ford and used internally at Ford and its partners as CAD/CAM systems. Digigraphics was developed by Itek as the first commercial CAD system with a unit price of $500 000; only six copies were sold.
1970	SynthaVision was developed as the first available commercial solid modelling program.
1971	Automated Drafting and Machining (ADAM) was developed by Patrick Hanratty as an interactive graphics design, drafting, and manufacturing system. It was written in Fortran and designed to work on virtually every machine. Today, nearly 80% of CAD programs can be traced back to the roots of ADAM.
1975	ComputerVision by Kenneth Versprille was where the rational B-spline geometry was added to CAD systems.
1977	CADAM was used by Lockheed to pioneer the applications of CAD in aerospace engineering.
1978	Unigraphics was developed by Siemens as a high-end and easy to use software; it was used by many corporations and set a new gold standard for CAD software at that time.
1980	MiniCAD was introduced as the bestselling CAD software on Mac computers.
1981	Geometric Models (GEOMODs) were developed and featured geometric precision and accuracy due to the modelling capability using a non-uniform rational B-spline (NURBS).
1982	AutoCAD was developed by Autodesk as the first CAD software made for Personal Computers (PCs) instead of mainframe computer workstations.
1987	Pro/Engineer was developed as the first mainstream CAD tool incorporating the ideas of Sketchpad. It was based on solid models, history-based features, and the uses of design constraints. It marked a high point in CAD history.
1994	AutoCAD version 13 was released with 3D modelling capabilities. The Standard for the Exchange of Product Model Data (STEP) was initially released as a new format and international standard of 3D models for data exchanges.
1995	eCATALOG was developed by Cadenas as the solution of digital product catalogs with multiple native CAD formats. SolidWorks 95 was developed by Dassault Systems as another software that succeeded in ease of use, and allowed more engineers than ever to take advantage of 3D CAD technology. Solid Edge was developed by Siemens as a Product Lifecycle Management (PLM) software. It was Window-based and provided solid modelling, assembly modelling, and a 2D orthographic view.

(*continued*)

Table 1.1 (Continued)

Year	Products, developers, and features
1996	Computer-Aided Three-Dimensional Interactive Application (CATIA) Conference Groupware was developed by Dassault Systems as the first CAD tool allowing users to review and annotate CATIA models with others over the Internet.
1999	Inventor was developed by Autodesk; it aimed to be more intuitive, simple, but allowed complex assemblies to be created in a shortened time.
2012	Autodesk 360 was developed whose computing was moved to the cloud.
2013	The first application (APP) for 3D CAD manufacturers was developed.
2015	Onshape was developed as a completely cloud-based CAD program.
2017	PARTSolutions was provided by Cadenas to help manufacturers with future proof of their catalog by keeping up to date with future native formats, versions, and revisions.

The first system of CATs in manufacturing was developed by Patrick Hanratty in 1957 as a programming system for numerical control. The major innovation in CATs occurred in 1963 when Ivan Sutherland, for his PhD thesis at MIT, created Sketchpad, which was based on a GUI (Graphical User Interface) to generate x–y plots. The innovation in Sketchpad pioneered the use of object-oriented programming in modern CAD and CAE (Computer Aided Engineering) systems. In the 1960s, the extensive works were developed in the aircraft, automotive, machine control, and electronics industries for three-dimensional modelling and the programming for numerical control. A few significant works were published as the fundamentals of the CAD theory, such as the mathematical representations of polynomial curves and surfaces by Bezier and Casteljau (Citroen Automotive Company) and Coons at MIT (Ford Motor Company).

Due to the rapid growth of computing power and reduction of hardware sources, three-dimensional (3D) modelling techniques are now widely used in video games, robotics, simulation of discrete systems, medical imaging and diagnosis, and in computer-controlled surgeries. As a milestone, the Manufacturing and Consulting Services Inc. (MCS) had developed CAD technologies in their commercially available Automated Drawing and Machining (ADAM) (Cadhistory 2019). The software was used and updated by McDonnell Douglas as *Unigraphics* and by Computer Vision as CADDs. Later, 3D printing technologies were developed and 3D printing technology evolved from 3D polygonal modelling to some objects with highly curvy surfaces, machine objects, and many other objects. 3D printing gave a boost to the development of computer aided manufacturing (CAM) technologies. As a few examples of successful companies in the CAM fields, (i) 3D Systems Corporation specializes in converting 3D solid or scanned models into physical objects; (ii) Stratasys Ltd. adopts additive manufacturing (AM) for direct manufacture of end parts; (iii) Intuitive Surgical Inc. designs, manufactures, and markets da Vinci surgical systems, as well as related instruments and accessories; and (iv) iRobot Corporation designs, develops, and markets robots for consumer, defence, security, telemedicine, and video collaboration. Caudill and Barnhorn (2018) provided a comprehensive summary of the milestones in the 60-year development of CATs, which is given in Table 1.1.

1.3 CATs for Engineering Designs

1.3.1 Engineering Design in a Manufacturing System

Design science uses scientific methods to analyse the structure of technical systems and their relationships with the environment. The aim is to derive rules for the development of these systems from system elements and their relationships. *Design methodology* is a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology, and from practical experience in different domains.

Designs of products and processes are essential to manufacturing systems. For example, some typical activities to design a product are (i) a *functional design* to determine functional modules and features and their relations, (ii) a *parametric design* to determine geometrics and dimensions of parts, (iii) a *tolerance analysis* of geometric dimensioning and tolerances (GD&Ts) to determine the quality, position, and shape of all parts, and (iv) an *assembly design* to determine the assembly relations of parts and components.

1.3.2 Importance of Engineering Design

A manufacturing system is understood from the technological and economic perspectives. Technologically, a manufacturing system is to transform raw materials into final products via a set of operations. Economically, a manufacturing system is a process to add values to final products via a set of economic transactions associated with manufacturing processes. Making a profit is always a primary goal to entrepreneurs. The profit can be maximized in two ways: (i) to reduce costs on no value-added activities and (ii) to increase the sale price by providing a corresponding value to the customer.

Engineering design plays a significant role in implementing these two strategies. Figure 1.7 shows the impact of the activities of design, manufacturing processes, raw materials, management, and marketing on the overall product costs. The impacts are measured by the percentages of overall product cost affected by the activities in a certain

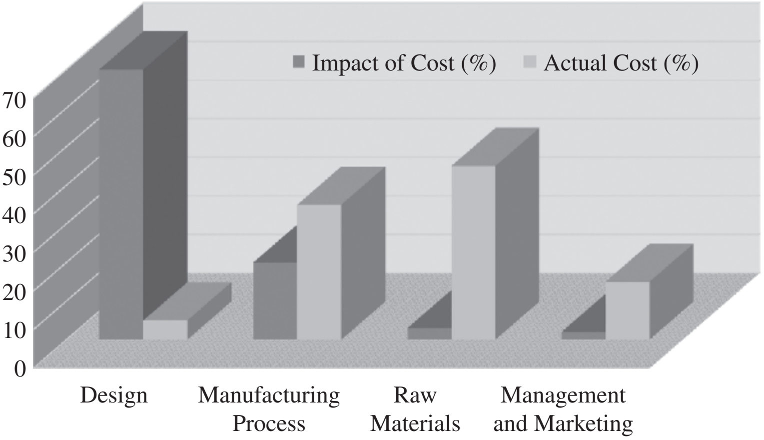


Figure 1.7 Significant impact of design activities on overall product cost.

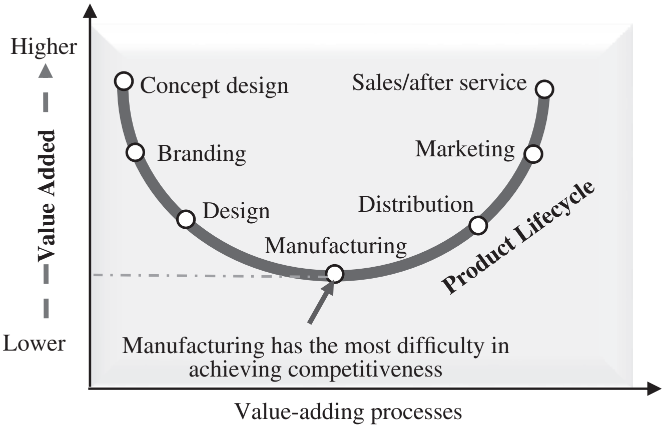


Figure 1.8 Value-added chain smile curve (IEC 2019; ITC 2019).

category. Even though the minimal percentage of the actual cost is related to the design activities, they mainly affect the overall product cost.

In Figure 1.8, the value-added chain smile curve by ITC (2019) shows the importance of design effectiveness on the possibility of added values of products in contrast to competitors. Business activities in a manufacturing system can be classified based on its involvement with hardware systems. The more dependence on hardware systems, the less chances a company gains in competitiveness on adding more values to products. Along with the product lifecycle, the more design activities are involved, the better the chances to gain competitiveness by adding more values of products than competitors.

The importance of engineering design can also be reflected by the additional costs a company may spend to fix some defects and errors occurring to different phases of a product lifecycle. *The first-time correct* is an idea goal to make highly diversified products and can only be achieved when CAD tools are capable of eliminating all of the design defects at the design stage. Figure 1.9 shows that, conventionally, the errors with a 75% fixing cost are

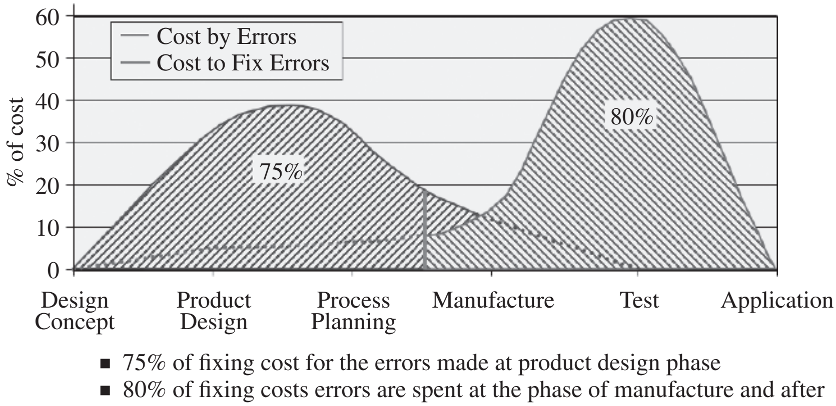


Figure 1.9 Relative costs to fix errors at different phases of product lifecycle.

made at the design stage of products, but the errors fixed at the manufacturing stage or later take around 80% of the fixed cost. It is clear that the earlier an error or defect is identified, the less cost is needed to fix it.

1.3.3 Types of Design Activities

In this section, the role of CATs in the design aspect is analysed, the nature of engineering designs is discussed, and the potential for using CAT technologies for design problems with different creativity levels is explored. Based on the level of creativity, Designwork (2016) classifies the engineering design problems into types: *routine design*, *redesign*, *selection design*, *parametric design*, *integrated design,* and *new design* (Table 1.2).

Corresponding to the needs to involve computers, human–machine interaction, and human designers, a rougher classification based on the level of creativity and innovation may facilitate further discussion. To this end, the designs can be regrouped as:

1. *New design* for a design from scratch to conceptual design, detailed design, and assembly design to the final product to meet specified design requirements.
2. *Incremental design* for a design subjected to given product structures, change individual parts, and functions to meet additional requirements of products.
3. *Routine design* for a design subjected to given functionalities, topological relations, layouts, and parametrize dimensions for the design of product families.

The level of creativity and innovation can be characterized based on the types of *solution space* and *design variables*. Goel (1997) corresponded routine design, innovative design, and new creative design to different combinations of solution space and design variables (Table 1.3).

Table 1.2 Types of design activities.

Type	Description	Example
Routine design	To perform a design by following existing standards and codes that outline the steps and computations for certain products or systems.	Follow the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Codes to design a pressure vessel.
Redesign	To revise an existing design when FRs have been changed in a dynamic environment.	Reprogram a robot when the tag points on the motion trajectory are changed.
Selection design	To find a solution by selecting appropriate components from an existing design inventory.	Select standardized fasteners to join two metal plates.
Parametric design	To determine design variables in a given conceptual structure for an optimized performance.	Minimize the materials usage of a cylindrical container subject to the given volume.
Integrated design	To design and assemble components as an integrated product or system to meet strongly coupled FRs.	Design a robotic configuration for a given task in a modular robot system.
New design	To design a product or system from scratch to meet emerging FRs.	Design a patentable product or system.

Table 1.3 Characteristics of solution spaces and design variables.

Level of creativity		Routine design	Incremental design	New design
Solution space	Structure	Known	Known	Unknown
	Search procedure	Known	Unknown	Unknown
Design variables	Types	Fixed	Fixed	Changed
	Ranges	Fixed	Changed	Changed

The characteristics of the solution space and design variables determines whether or not an engineering design belongs to a 'routine', 'incremental', or 'new' design. Both humans and computers can compete to accomplish some design activities; however, computers and human designers are good at different things, and it is desirable to synergize the strengths of designers and computers to achieve the effectiveness of engineering designs. Many researchers have discussed the differences between humans and computers. Table 1.4 summarizes the role differences of human beings and computers in engineering design processes.

1.3.4 Human Versus Computers

A manufacturing system has been set up to transfer raw materials into final products by performing a series of manufacturing and assistive activities in a system. Section 1.1.3 showed that a conventional manufacturing system relies heavily on human resources in both materials flow and information flow. With the continuous growth of scale and the complexity of systems, human designers and operators approach their limits to make

Table 1.4 Comparison of human designers and computers.

	Human designers	Computers
Strengths	• Identifying design needs • Brainstorming to think solutions 'out of the box' • Engineering intuition and a big knowledge base • Selecting design variations • The flexibility to deal with changes • Qualitative reasoning • Psychologically, human decision is more trusted than artificial intelligence • Predict trends, patterns, or anomalies, and • Learn from experience	• Fast speed, reliable, endurance, and consistent • Capable of exploring a large number of options • Carry out long, complex, and laborious calculations • Store and efficiently search large databases and • Provide information on design methodologies, heuristic data, and stored expertise
Weaknesses	• Easily tired and bored • Cannot do micro manage • Biased and inconsistent • Prone to make errors • Not good at quantified reasoning • Incapable of utilizing the data presented in an awkward manner	• Difficult to synthesize new rules • Limited knowledge base • No common sense

decisions or operate machines in cost-effective ways. To sustain vital manufacturing systems, CATs are expected to fully or partially substitute for a human being in a material or information flow. Table 1.4 gives a brief comparison of human designers and computers in terms of their strengths and weaknesses.

1.3.5 Human and Machine Interactions

It is critical to take advantage of modern computing technologies to improve the effectiveness of engineering designs. The limitations of human designers can be addressed by computer programs. As shown in Figure 1.10, human designers and computer aided tools are good at providing a *new design* and a *routine design*, respectively. Statistics shows that the percentages for providing a new design, increment design, and parametric design are 24%, 56%, and 20%, respectively. The total new design only took 24%. If the requirements of standardization are high, the parametric design is higher, where 50% of design activities are of a routine parametric design.

While the majority of engineering design activities are incremental designs, the computer assisted interactive design can maximize the synergized strengths of both human designers and computer aided tools. This implies that engineers might spend a lot of time to repeat existing work by others. Therefore, it becomes mandatory to utilize CAD/CAM to improve productivity. CAD/CAM is designed to synergize the methodologies, tools, and expertise to solve design problems of CAD/CAM applications.

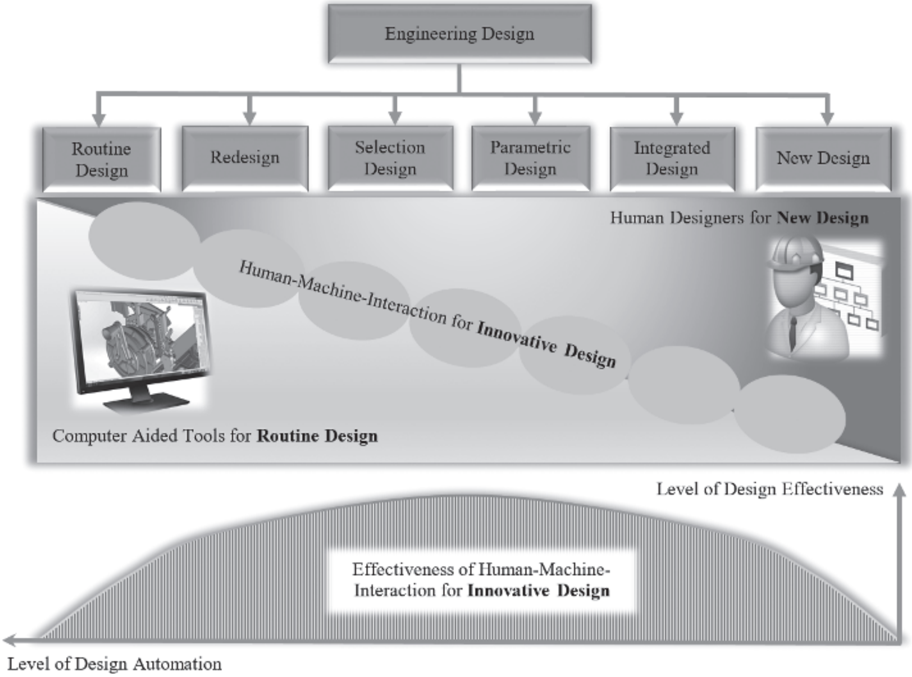


Figure 1.10 Human designers and computers in engineering design.

1.4 Architecture of Computer Aided Systems

System architecture is used to represent system components and their relations. Like any computer application system, the components in a computer aided system can be classified as hardware components or software components, as shown in Figure 1.11. The hardware components are further classified into *computers*, *peripheral equipment*, and *servers and networks* for Manufacturing Resources. The software components are classified into *system software*, *support software*, and *application software*.

1.4.1 Hardware Components

Hardware components of computers are organized based on their functions: computing units focus on data processing and other peripheral devices are for inputs, outputs, storage, and communications (Savage and Vogel 2013).

Computing units differ in *size* for mass and *power* for computing speed, and common categories are *supercomputers*, *mainframes*, and *microcomputers*. Mainframes are usually larger than microcomputers, but modern microelectronics allows very large power systems such as computer workstations to be packed into small spaces. Supercomputers are very advanced and expensive, and are characterized as having the fastest computing speeds for the most complex problems. The most critical measure of computer power is Million Instructions per second (MIPS). Moravec (1998) discussed the evolution of computer power/cost as shown in Figure 1.12, which shows that computers doubled in capacity every two years since 1945. This predicted speed was used as an indicator by computer manufacturers. They had to make new products whose computing speeds exceed the predicted speed, and those who failed to catch up with the increase in computing speed would lose business. In the 1980s, the doubling time contracted to 18 months and the computer performance in the late 1990s doubled every 12 months. Accordingly, the cost for computer power has been greatly reduced. The level of MIPS was predicted to be millions per $1000 in 2020. The core of the computing unit is the processor. Evolution of

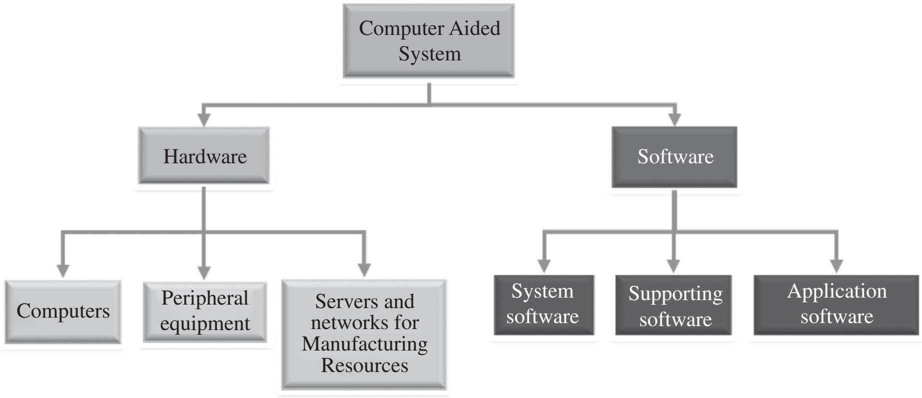


Figure 1.11 Architecture of computer aided systems.

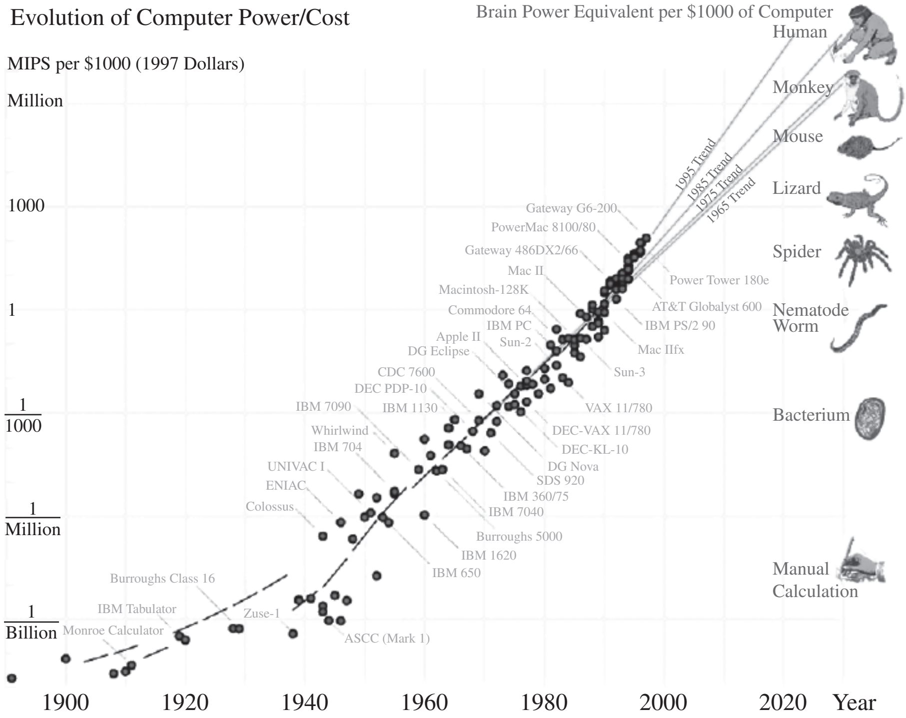


Figure 1.12 Evolution of computer hardware (Moravec 1998).

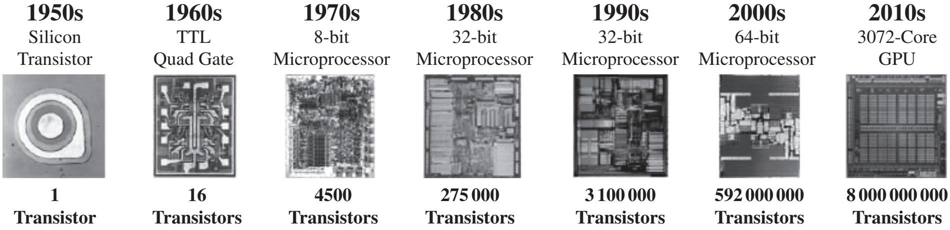


Figure 1.13 Evolution of semiconductors for processors (Computer History 2019a).

the computer processors is shown in Figure 1.13. The growth of processing capabilities matches Moore's Law – *transistor density on integrated circuits doubles about every two years.*

Another important specification of a computing unit is memory, which is a type of integrated circuit used to store data. The memory for the storage of the data for immediate use in a computer is called *primary storage*. Primary storage such as random-access memory (RAM) operates at a high speed. *Secondary storage* such as external drives provides slow-to-access data but offers higher capacities (Wikipedia 2019b). The idea of computer memory came with the usage of punch cards as memory by Charles Babbage in 1837; it was not until 1932 that Gustav Tauschek invented drum memory. Later in 1946, magnetic core memory became popular, which was attributed to the application of Williams-Kilburn

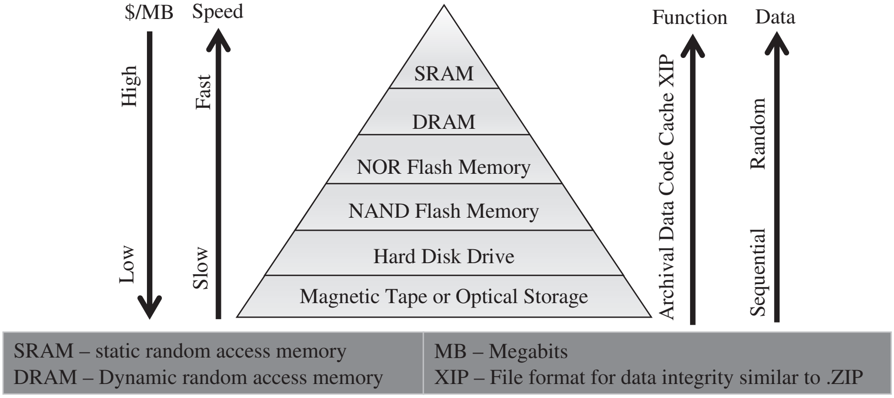


Figure 1.14 Main types of computer memories (Computer History 2019b).

tubes. Magnetic core RAM was introduced by MIT and the patent on pulse transfer controlling device by An Wang in 1955. Thereafter, dynamic random-access memory (DRAM), phase-change random-access memory (PRAM), static random-access memory (SRAM), due drive rate (DDR) RAM, and solid state RAM were gradually developed (Computer Hope 2019). Bhatt and Die (2015) give a summary of existing solutions of computer memories as well as a comparison of the main specifications on cost, speed, function, and data type in Figure 1.14. The more powerful a computer aid system is, the higher the requirements to the computer and memories are.

Computers to an information system are machines to a manufacturing system. Computers serve as the transformers to transfer input data to output data. Peripheral devices serve as the interfaces for computers to input raw data and output processed data in applications. Computers at an early time have limited choices of input and output devices such as punch-cards and printers. Today, many types of devices can be used as inputs and output devices of computer systems. Figure 1.15 shows a classification of computer devices for human machine interfaces. A peripheral device can be a *unidirectional input*, *unidirectional output*, or *bidirectional input and output* device (Wole 2018). It is worth noting that with an increase in the capabilities of computer aided systems, more and more smart devices, such as indoor Global Positioning Systems (GPSs), haptic systems, and 3D printers, can be connected to computer systems directly as input and output devices.

1.4.2 Computer Software Systems

A computer aided system runs on computers and consists of a set of functional components at different layers of information, from the layer for hardware interfaces to the layers of operating systems, networking, database, sophisticated computer aided tools, and finally to the system layer of applications. Figure 1.16 shows the architecture of a computer aided software system. The functional components in the system are generally encapsulated and used independently. These functional components are classified into four groups: (i) *software for hardware* operation interacting with computers, printers, plotters, and so on, (ii) *system software* associated with operating systems and networking, (iii) *support*

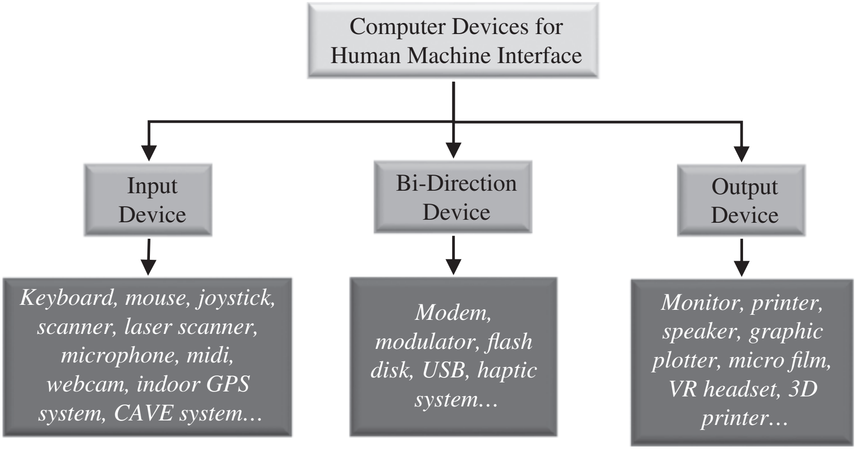


Figure 1.15 Types of peripheral devices for inputs and outputs.

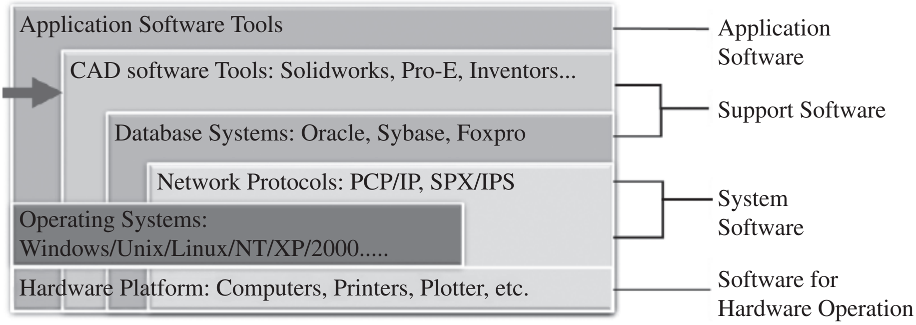


Figure 1.16 Computer aided software system architecture.

software consisting of database systems and CAD software, and (iv) *application software* as comprehensive computer aided systems.

The architecture of a computer aided software system is modularized; it allows the developers to customize the selections of functional components and integration of the selected components to meet the design needs at different domains and levels of manufacturing systems. It seems obvious that the capabilities of computer aided systems will be continuously expended due to the rapid development of information systems in computing systems, networking systems, and databases. In the next section, the impact of networking and cloud technologies on computer aided systems is briefly discussed.

1.4.3 Servers, Networking, and Cloud Technologies

As an information system, a computer aided software system needs the capabilities to deal with the variety, complexity, and changes of design needs. Three basic strategies to deal with the variety, complexity, and changes are to (i) modularize system architecture, (ii) make functional components flexible, and (iii) support system integration (Bi and Zhang 2001a,b; Bi et al. 2008). To implement these strategies, functional modules must be interoperated, collaborated, and integrated. Therefore, servers and networking technology play a significant role to advance CATs. A *server* acts as an agent to accept and perform tasks and to generate the results of a task to requesters. *Networking* allows a number of the servers working collaboratively to solve a holistic problem, whose solution consists of a set of sub-solutions that are used to divide subproblems with the given constraints. For example, networking makes the following technologies possible in computer aided application systems.

Parallel computing is a type of computation in which many calculations or the execution of processes are carried out at the same time. Large-scale design problems should be decomposed into smaller ones, so that the sub-solutions can be obtained by using a number of computing resources concurrently. Parallel computing may refer to parallel processing by a set of central computing units (CPUs) or graphic processing units (GPUs) in one computer or parallel supercomputers containing hundreds or thousands of processors, networks of workstations, multiple-processor workstations, and embedded systems (Foster 1995). Computer aided systems, especially CAE systems, need parallel processing capabilities to achieve scalability in solving complex design problems, which may involve multiple physics, transient dynamics, or large-scale coupled models.

Hardware in the loop (HIL) simulation is a type of real-time simulation for the design of real-time control systems. In HIL, the machine or physical part of the system is networked with the control model through actuators and sensors. The rest of the system is represented by the mathematic model in the simulation. HIL assists in developing and testing complex real-time embedded systems while considering the complexity of the real-world system. HIL simulation shows how a control model responds to realistic virtual stimuli in a real-time manner and can be used to determine whether the mathematic model for a physical system is valid (MathWorks 2018).

Distributed database is a storage solution where a common processor accesses the data in a distributed system. Data may be stored in multiple networked computers in the same location or can be dispersed over a network of interconnected computers. A system server distributes collections of data across network servers or independent computers over intranets, extranets, or the Internet. Computer aided systems benefit from the distributed databases in increasing the scalability, modularity, reliability, and flexibility of systems (Wikipedia 2019c).

Cloud computing is the delivery of computing services such as data collections, computing, data mining, analytics, storage, servers, and more over the Internet for faster innovation, flexible resources, and economies of scale (Microsoft 2019). Computer aided systems greatly benefit from cloud computing over a number of aspects. *Firstly*, cloud computing allows single users, freelance designers, and SMEs to participate in the entire design processes of complex products; large and multinational companies can work with several hundred SMEs and individual designers to seek design solutions. *Secondly*, this helps to reduce an overall cost of the design and development processes. Cloud computing helps to reduce the investment on computer aided systems. Traditionally, commercial software tools are associated with the licensing and training costs as well as the additional cost on maintenance, software and hardware upgrades, IT personnel, power requirements, and rental costs for additional space. Cloud solutions offer an alternative where licensing costs are substituted with a subscription fee and the expenditure is substantially reduced since

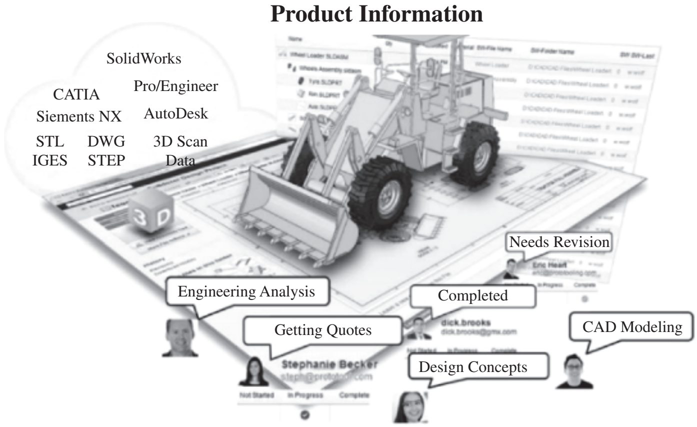


Figure 1.17 Computer aided collaboration in virtual environment (Wu et al. 2015; Wu 2014).

the resources are shared by users in the cloud. *Thirdly*, most of the cloud services offer pay-as-you-go options, where one pays only for the used computational resources. Such services reduce the overall cost for both the provider and the client since the service loads are customized to the needs (Harish 2018).

Manufacturing systems became highly distributed for enhanced flexibility and adaptability to meet the needs of regional markets promptly. The high-speed 3G, 4G, and 5G wireless networks helped to mobilize product information so that the PLM could be accessed by mobile apps. From the perspective of information technology, we have entered the fourth industrial revolution, where nearly every device will be networked, which allows continuous data streams to populate in memory databases. The Internet of Things (IoT) will transform the manufacturing sector in the coming years. More and more cloud-based solutions will be available to manufacturing enterprises to support their operations (Bi et al. 2014; Wang et al. 2014; Morley 2014).

Virtual enterprise (VE) is a temporary alliance of businesses for partners to share core competencies, resources, and skills in order to take advantage of emerging business opportunities. VE is facilitated by computer networks (Wikipedia 2019d). The core competencies, resources, and skills in VE are mainly for CATs. Figure 1.17 shows that using the virtual environment over the Internet, designers across different regions, domains, enterprises, and disciplines can collaborate on all of the CAD activities involved in the lifecycle of product development (Wu et al. 2015; Wu 2014).

1.5 Computer Aided Technologies in Manufacturing

A manufacturing system is involved in numerous decision-making activities and computers outperform human beings at many tasks in both materials and information flows, such as *machine operation, planning and scheduling, engineering, analysis, data acquisition and sharing*, *computing*, *data storage*, *data retrieval*, and *inspection* (Cummings 2014; Sotala 2012). The importance of computer aided technologies can be clearly evidenced

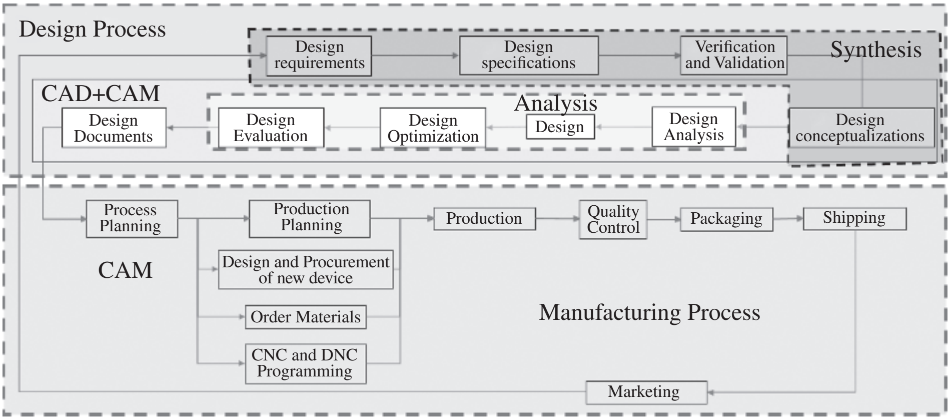


Figure 1.18 CATs in designing, manufacturing, and assembling and system integration.

by the growing number of computer aided tools exemplified in Figure 1.5. The rapidly developing information technologies (IT) make all of these advanced manufacturing technologies practical.

Figure 1.18 shows some typical manufacturing activities in a product lifecycle from the identification of design requirements of products to the delivery of final products to end-users. The fulfilment of these manufacturing activities is mostly assisted by computer programs. For example, CAD tools are used to create, modify, and optimize the design of parts, products, processes, and systems by using computer systems. CAM tools use computer software to control machine tools and related machinery in the manufacture of workpieces. CAD/CAM tools provide an integrated solution to bridge CAD and CAM systems. Figure 1.19 gives some typical computer aided tools under the categories of

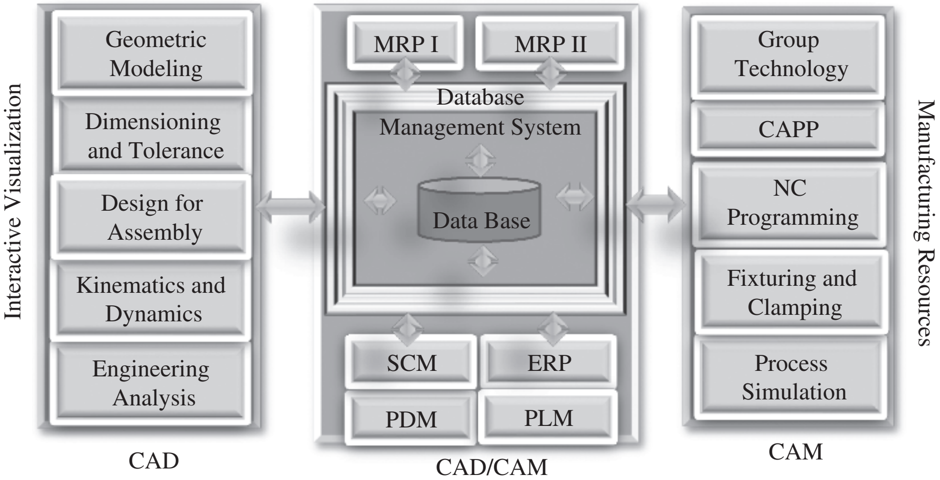


Figure 1.19 Typical computer aided tools in CAD, CAM, and CAD/CAM. (*See color plate section for color representation of this figure*).

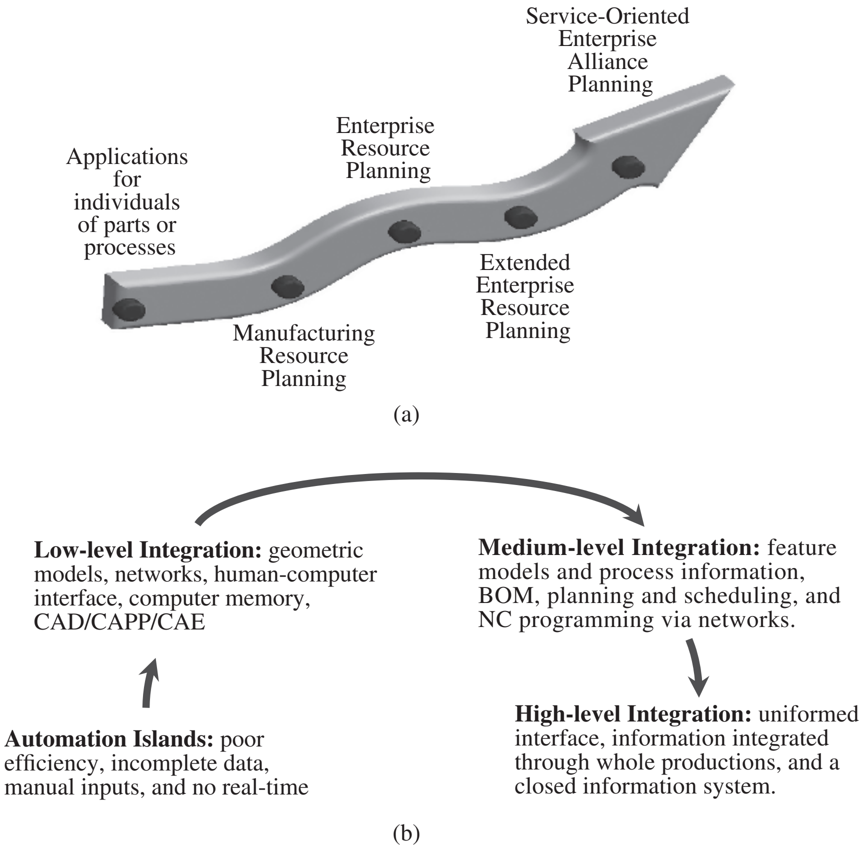


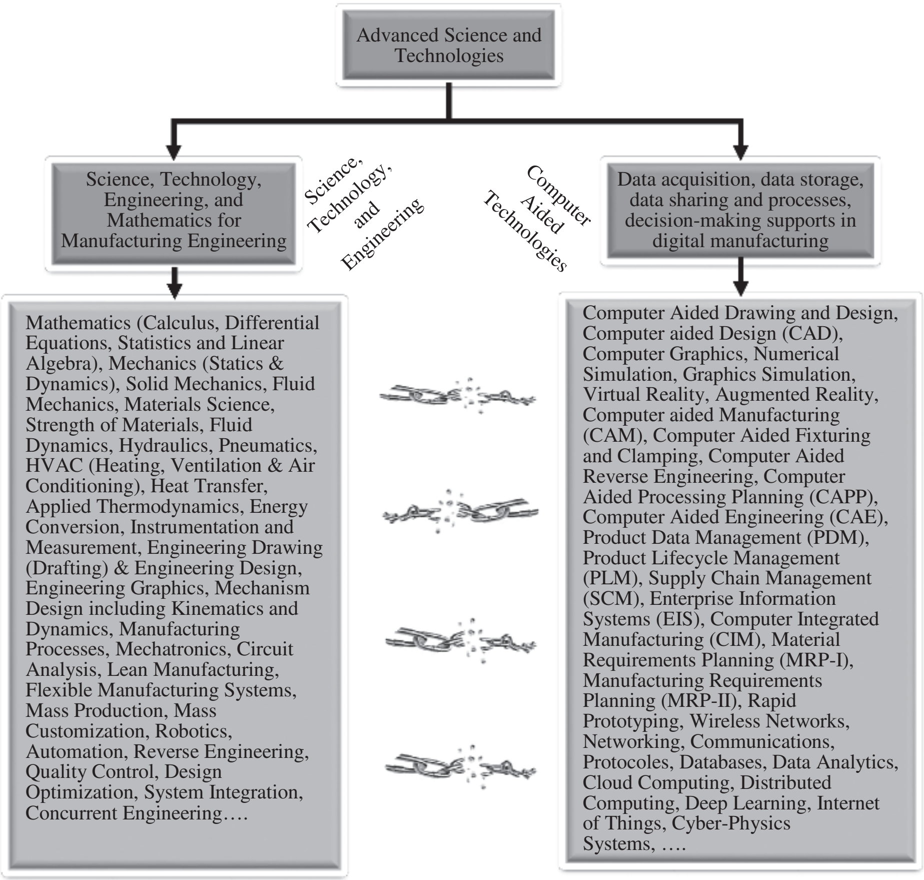
Figure 1.20 The evolution of computer aided technologies in manufacturing, (a) The increasing varieties of system functionalities and (b) the increasing level of system integrations.

CAD, CAM, and CAD/CAM tools. For example, the CAD tools for *geometric modelling*, *dimensioning and tolerance*, *design for assembly*, *kinematic and dynamic simulation*, and *engineering analysis* will be covered in this book.

Figure 1.20 shows that the capabilities of CATs have been continuously expanded in two aspects: (i) the variety of functionalities from isolated applications for individuals of parts or processes at a lower level to the planning for service-oriented enterprise alliances at a higher level and (ii) the level of system integration from isolated system components to holistic integration across enterprises.

1.6 Limitation of the Existing Manufacturing Engineering Curriculum

Manufacturing engineering is to apply mathematics and science in practice to design, manufacture, and operate products. Engineers in the manufacturing sector focus on design, development, and operation of manufacturing systems to make competitive products. The



(a) (b)

Figure 1.21 Mismatch of subdisciplines and computer aided tools in manufacturing engineering. (a) Subdisciplines in manufacturing engineering and (b) computer aided tools in digital manufacturing. (*See color plate section for color representation of this figure*).

existing engineering curricula usually include some core courses in *mathematics*, *physics*, *computing engineering*, and *management*, as well as some sophisticated courses in mechanical and manufacturing engineering such as *materials science*, *statics and dynamics*, *thermodynamics*, and *fluid mechanics*. Engineering curricula are generally designed to cover as many sub-disciplines of mechanical and manufacturing engineering as possible. Students have options to specialize in one or more sub-disciplines. Some typical courses for the bachelor's degree in design in manufacturing engineering are listed in Figure 1.21a (Wikipedia 2017). From this perspective, existing curricula are mostly discipline-oriented.

From the perspective of computer aided technologies, numerous computer aided tools become commercially available. However, these software tools are application-oriented, and most of the tools are developed based on the theories in multiple disciplines. Figure 1.20b shows a list of commonly used computer aided tools in the manufacturing sector. Due to the strong decoupling of multidisciplinary knowledge in these software tools, the classification of disciplines in manufacturing engineering is not well aligned with the classification of available computer aided tools. Figure 1.20 shows that there is no one-to-one correspondence between sub-disciplines and available computer aided tools.

The misaligned engineering curricula and a broad scope of computer aided tools in manufacturing pose a great challenge in the teaching of manufacturing engineering. *On the one hand*, the sub-disciplines in manufacturing engineering are so diversified that an ever-increasing number of elective technical courses are needed in engineering programmes. Meanwhile, public education systems are facing the pressure to reduce the number of credit hours for college degrees. Taking as an example the mechanical engineering program at Purdue University, Fort Wayne, the number of required credit hours for a bachelor degree has been reduced from 126 in the spring of 2012 to 120 in the spring of 2017 (Bi and Mueller 2016). *On the other hand*, engineering programmes are responsible for preparing students for an appropriate set of knowledge and skills using advanced computer aided tools; however, more and more computer aided tools are becoming commercially available and so their functionalities need to be upgraded and expanded continuously. This proves to be a great challenge to integrate disciplinary theories and computer aided tools in the limited selection of engineering courses.

1.7 Course Framework for Digital Manufacturing

The concern on the discipline-oriented curricula has attracted a great deal of attention in recent years. A number of educational programmes were proposed and implemented to address this issue. For example, the Engage Program sponsored by the National Science Foundation (NSF) aimed to increase the capacity of engineering institutions to retain undergraduate students by facilitating the implementation of three research-based strategies, i.e. (i) improve faculty–student interaction, (ii) improve spatial visualization skill, and (iii) use everyday examples in engineering teaching, to improve educational experiences (Nilsson 2014; Bi and Mueller 2016).

To adapt the rapid advancement of CATs, this books proposes to improve existing discipline-oriented engineering programmes, at least for some upper-level engineering courses. The objective is to develop a new course framework where constitutive elements are not varied with an increase of computer aided tools or the diversification of sub-disciplines.

The design of an engineering course curriculum is similar to the design of any engineering system in the sense that the complexity and dynamic characteristics become two critical factors to deal with when the system is continuously evolving. The modularity concept has proved to be an effective way to deal with system complexity and dynamic characteristics (Bi et al. 2008). In the similar way, the modularity concept is proposed to deal with the misalignment of discipline-oriented curricula and a large variety of computer aided software tools in manufacturing engineering.

Figure 1.22 shows an alternative to the discipline-oriented curriculum. It can be referred to as a 4-P engineering curriculum since the manufacturing fundamental is differentiated for *Product*, *Process*, *Production*, and *Platform*, respectively, for the required system functionalities in a product lifecycle. The objective of the proposed curriculum is to minimize

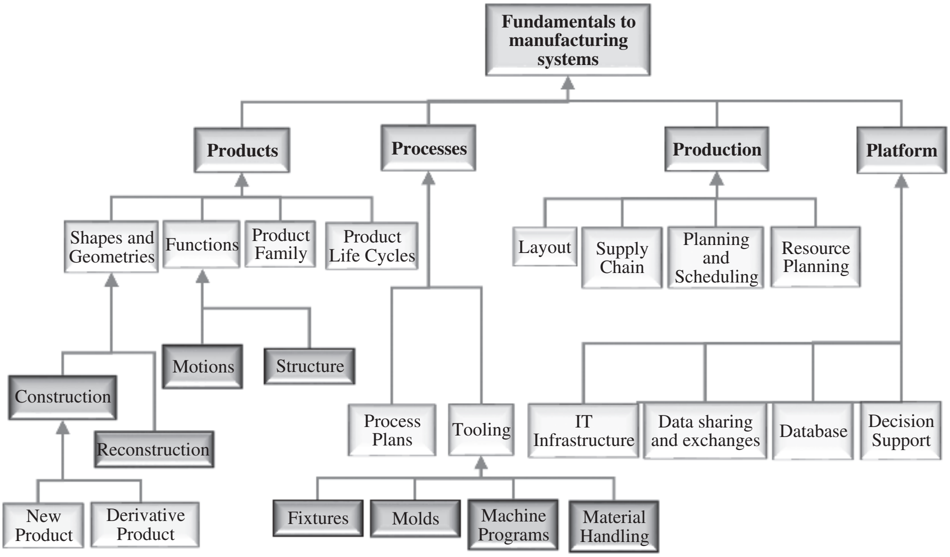


Figure 1.22 Proposed course framework for digital manufacturing.

the impact of the ever-increasing complexity of the system as well as computer aided tools. Since any manufactured product has its own lifecycle, a taxonomy of engineering courses based on the product lifecycle can sustain its consistence, even though the scope of a manufacturing system or computer aided tools may vary with respect to time.

Following the axiomatic theory (Cochran et al. 2016a, 2016b, 2017a, 2017b), the high-level functionalities for the product, process, production, and platform can be further decomposed as a modularized structure. Take an example the functional requirements (FRs) for a product design, FRs have been decomposed further into the designs of geometries, motions, product families, and a sustainable design related to the product life cycle. The granularity of the functionalities can be appropriate to match the functionalities for well-established engineering sub-disciplines as well as available computer aided tools. Due to the modularized structure, the proposed framework has the flexibility to customize the selection of sub-disciplines and corresponding computer aided tools in a specific engineering curriculum.

1.8 Design of the CAD/CAM Course

The modular framework of digital manufacturing provides the flexibility to select course elements to customize the educational needs in a specific engineering programme. This book is written as a CAD/CAM text to achieve two main goals: (i) introduce manufacturing fundamentals, which are not usually covered in depth in traditional mechanical engineering programmes and (ii) expose students to as many computer-aided software tools as possible, so that they can utilize advanced computing tools to deal with the designs related to manufacturing processes.

Table 1.5 Examples of existing CAD/CAM textbooks (Wang and Bi 2018).

Author(s)	Title	Year	Publishers
M. Groover and E. Zimmers	CAD/CAM: Computer-Aided Design and Manufacturing	1984	Pearson
P. Martin, N.E. Larsen, and David D. Hansen	Computer Aided Design in Control and Engineering Systems	1986	Pergamon
M. Bedworth, R. Henderson, and P.M. Wolfe	Computer-Integrated Design and Manufacturing	1991	McGraw-Hill International
M. Groover and E. Zimmers	CAD/CAM: Computer-Aided Design and Manufacturing	1993	CRC Press
Jami J. Shah and Martti Mäntylä	Parametric and Feature-Based CAD/CAM: Concepts, Techniques, and Applications	1995	Wiley
Nanua Singh	Systems Approach to Computer-Integrated Design and Manufacturing	1996	Wiley
Kunwoo Lee	Principles of CAD/CAM/CAE	1999	Pearson, Elsevier
Alberto Paoluzzi	Geometric Programming for Computer Aided Design	2003	Wiley
T.C. Chang, R.S. Wysk, and H.P. Wang	Computer-Aided Manufacturing	2003	Prentice Hall
Ibrahim Zeid	Mastering CAD/CAM (Engineering Series)	2004	McGraw-Hill
André Chaszar	Blurring the Lines: Computer-Aided Design and Manufacturing in Contemporary Architecture	2006	Wiley
Khoi Hoang	Computer-Aided Design and Manufacture	2011	McGraw-Hill Custom Publishing
Kuang-Hua Chang	Product Manufacturing and Cost Estimating using CAD/CAE	2013	Academic Press
Kuang-Hua Chang	Product Design Modeling using CAD/CAE	2014	Academic Press

1.8.1 Existing Design of the CAD/CAM Course

The importance of computer aided technologies in manufacturing engineering has been well recognized. The majority of higher educational institutions offer one or several CAD/CAM courses in their engineering programmes. However, selecting an appropriate textbook proves to be a challenge since all of the textbooks are too sophisticated in certain subjects but lack in coverage on a broad scope of disciplines and CAD/CAM tools. In our primary survey, we found a few common CAD/CAM textbooks that were adopted by different institutions, as shown in Table 1.5.

Since the information technology (IT) has developed so rapidly in recent years, most of the textbooks in Table 1.5 are out of the date, and the last three recent ones cover only the integration of CAD and CAM. No appropriate textbook has been found that has a wide coverage of subdisciplines and computer aided tools.

1.8.2 Customization of the CAD/CAM Course

Undergraduates in mechanical engineering with a minor in manufacturing engineering must understand theoretical fundamentals related to the design of products and manufacturing processes. On the other hand, the theories and methods relevant to high-level planning, scheduling, or computer implementation might not be the first priority for them. To meet our specified teaching needs, the engineering curriculum in Figure 1.23 can be utilized to choose appropriate contents for our students. The selected course elements are highlighted in Figure 1.23. The covered CAD/CAM theory and methods are illustrated in Figure 1.24 and the corresponding computer aided technologies and tools are accordingly specified in Figure 1.25. The customized CAD/CAM course consists both of the theoretical part in Figure 1.24 and the practical training part in Figure 1.25. To sustain the independence for the selection of course elements in a modularized course framework, the axiomatic design theory has been applied to map the theoretical part in Figure 1.24 to the computer-aided tools in Figure 1.25 (Bi and Mueller 2016).

As an introduction to the CAD/CAM course, human designers and computers are compared to clarify the roles of computers for design activities at different design phases of products and systems. The computer applications in engineering are overviewed. The course structure is presented and the main design concepts related to products and manufacturing processes are discussed. Figure 1.26 illustrates the organization of the customized CAD/CAM book. Each of the selected concepts corresponds to a section/chapter in the course. Besides the introduction section, all of the other sections include the laboratories where one functional module of the CAD/CAM software tool is utilized to illustrate the

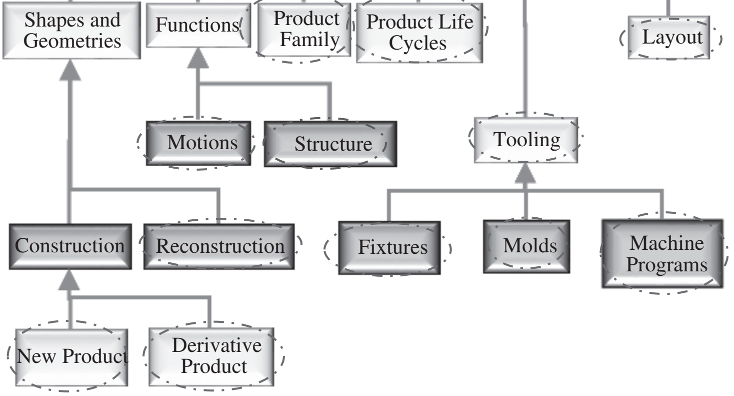


Figure 1.23 Selective subjects in a new CAD/CAM course.

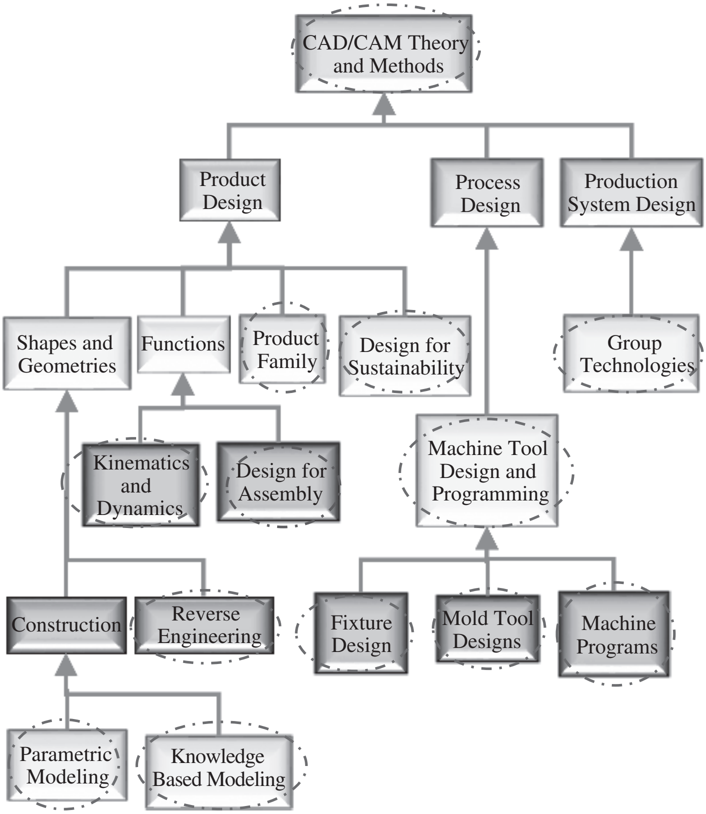


Figure 1.24 Selective concepts in the CAD/CAM theory.

application of computer aided technology to formulate and solve real-world engineering design problems. The unique features of this course framework include (i) coverage of a broad scope of sub-disciplines so that the students can understand better the design challenges over the product lifecycles in a minimal class setting, (ii) selection of course elements that is oriented where individual functional modules are available in commercial computer aided software tools to handle the formulated design problems in corresponding disciplines, and (iii) emphasis on the self-guiding exploration of a comprehensive CAD/CAM software tool, so that students in mechanical or manufacturing engineering are able to formulate multidisciplinary problems and use the correct computer aided tools to solve problems effectively.

1.9 Summary

Through the discussion in this chapter, we find that the majority of existing CAD/CAM course designs are out of date due to the rapid development of CATs. There is a misalignment between the classification of sub-disciplines and the types of emerging computer aided tools. To address these two concerns, a new course framework has been presented

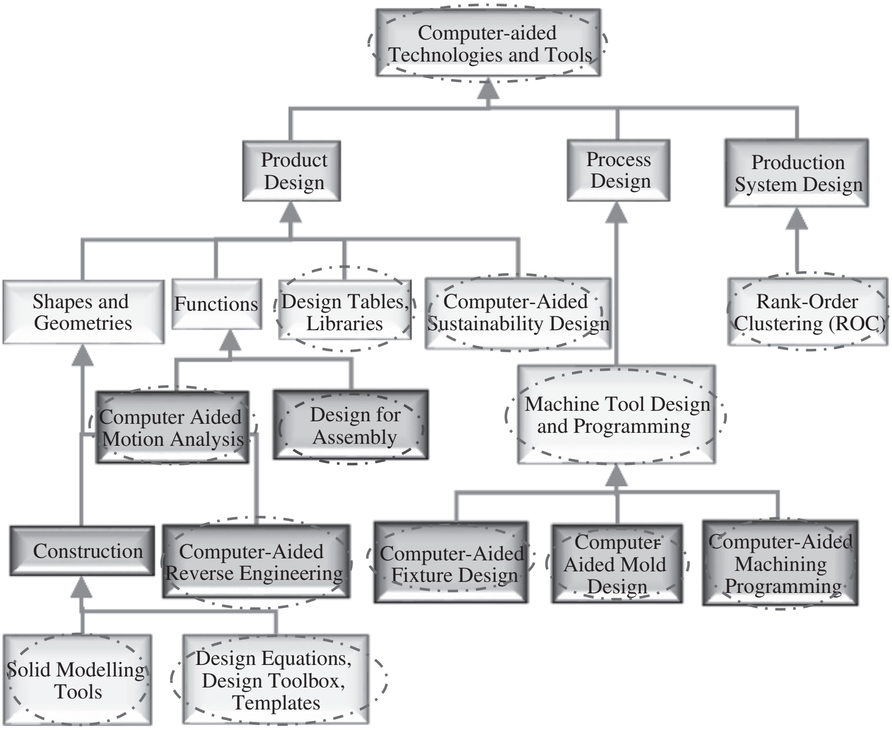


Figure 1.25 Selective CAD/CAM tools.

for Digital Manufacturing. It is unique in the sense that (i) the course topics are defined based on the design needs in product lifecycles, which are likely to be changed over time; (ii) the types of computer aided tools are application-oriented for manufacturing systems, so that the correspondence of course topics can be readily mapped to existing computer aided tools for training; (iii) the framework is modularized so that educators have flexibility in selecting course subjects to tailor the digital manufacturing teaching needs of their degree programmes; and (iv) emphasis is put on the balance of theoretical knowledge and the skills involved in using CAD/CAM tools, where each course topic corresponds to training in the use of computer aided tools to solve real-life design problems.

The proposed framework of a Digital Manufacturing course is modularized and expandable. The following chapters cover a limited number of computer aided tools, but the continuous effect of using multiple aspects is expected to broaden the coverage of contemporary computing aided systems.

1.10 Review Questions

1.1 Discuss how CAD/CAM helps in modern manufacturing? Elaborate on any one aspect.

1.2 What is CAD/CAM?

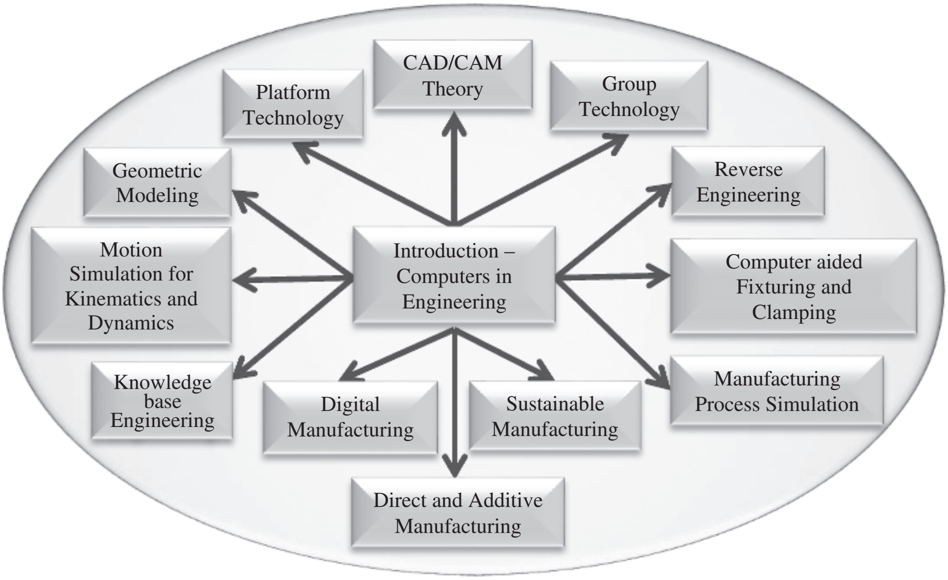


Figure 1.26 Customized outline of the CAD/CAM book.

1.3 What are basic elements of a CAD/CAM system?

1.4 What are the objectives of using CAD/CAM?

1.5 What advantages does the CAD/CAM approach offer in NC programming?

1.6 List a number of enabling technologies related to CAD/CAM and discuss their functions.

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