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Fundamentals of Digital Manufacturing Science

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Preface

In this era of knowledge economy, digital manufacturing as a new manufacturing technology and manufacturing mode has become a strong manufacturing power, promoting the development of manufacturing in the 21st century. Its main features are that digital technology has gradually been integrated into the lifecycle of product manufacturing, traditional manufacturing will be transformed and the level of modern manufacturing will be upgraded through information and digital technology, and digitalization will be the indispensable driving factor for the whole product lifecycle in manufacturing. Digital equipment produced by digital manufacturing systems not only has a broad and flexible processing capacity, but also a powerful information processing capability.

Digital manufacturing science is a science, of which the main research object is the digital manufacturing system, the main research contents are basic concepts and pivotal technology, the main research method is the methodology of informatics and system engineering, and the research target is the optimal operation of the digital manufacturing system. It is also a new interdisciplinary research area and the inevitable result of digital manufacturing technology's rapid development.

Based on the never-ending fusion, development, and abroad application of digital technology, network information technology and manufacturing technology, digital manufacture is generated and has become the necessary result of manufacturing enterprises, the manufacturing system and manufacturing process as all continue to realize their digitalization. It makes use of digital quantity, expression, storage, disposal, and control to support global optimal operation in the product lifecycle and enterprise. Its basis is the knowledge fusion of the manufacturing process, and its features are digital modeling, simulation, and optimization. Supported by virtual reality, computer networks, rapid prototyping and databases, it will affect the whole manufacturing process, including product design, function simulation, rapid prototyping manufacture, digitalization of the technology process of products, and rapid production of product that satisfies users, and it will have high-performance through analyzing, programming, and recomposing information about products, technology and sources according to consumer demand.

Along with the development of digital manufacturing technology, digital manufacture has evolved into generalized digital manufacture involving the product lifecycle and its operation environment from its origin of single production manufacturing and digitalization. Generalized digital manufacture includes digital analysis, design, operation and management of certain links in the manufacturing process such as product demand, product design and simulation, management of production process, operation control of equipment, management of product quality, product sale and maintenance and so on, and the digital operation environment that supports the whole product lifecycle. Moreover, research on digital manufacture also becomes a systematic research including basic theory and technology rather than just a technical one, and digital manufacture becomes digital manufacturing science developed from advanced manufacturing technology.

As a new interdisciplinary subject, the integral subject system of digital manufacturing science should be studied alongside the digital manufacturing system and process, namely on the macroscopic and microscopic aspects. Therefore, this book firstly expatiates on modeling theory and the main modeling method of digital manufacturing science, constructs its basic modeling system and denotes its theoretical supporting system. Secondly, it analyzes and introduces the main basic subject theories that constitute the digital manufacturing scientific theoretical system. These theories involve computing manufacturing science, manufacturing informatics, manufacturing intelligence science, bionic manufacturing science, and technology management science. Lastly, the key technologies of digital manufacturing science are identified and analyzed, and the future development of digital manufacturing science is considered. Digital manufacturing science is a basic element of the modern manufacturing system, and the scientific problem facing modern manufacturing is how to construct its subject system integrally. The contents in this book contribute to the continued enriching and development of digital manufacturing theories and methods.

This book contains nine chapters; we introduce the foundation, concepts, and theory system of digital manufacturing science in chapters one and two; the main subject knowledge in its theoretical supporting system is introduced and analyzed in chapter three to chapter seven; chapter eight analyzes and discusses the key technologies of digital manufacturing science; chapter nine discusses the future development of digital manufacture. Chen Dejun, Zhang Jinhuan, Hu Peng, Ding Guoping, Wei Li, Xu Wenjun, and others compiled the various sections of the book and Chen Dejun is responsible for amending the relevant sections and for coordinating the whole book. Here, I express my heartfelt thanks!

I also appreciate the help and funds from the important international cooperation project “The New Theories and New Technology Research of Network-based Digital Manufacturing Environment” (item number: 50620130441) of the National Natural Science Foundation of China for the publication of this book.

This book about digital manufacturing science is only a preliminary exploration. Due to my limitations, it is inevitable there will be errors in the book, so if experts and readers have any comments or suggestions regarding this book, or detect any errors no matter how trivial, please send them to me; I would be grateful for this!

Contents

Chapter 1
Introduction

1.1 Development Course of Manufacturing and Manufacturing Science

Manufacturing is defined in the *Oxford English Dictionary* as the action or process of manufacturing something; production, fabrication, and also the sector of the economy engaged in industrial production. Original manufacturing was accomplished by hand, but most modern manufacturing operations are highly mechanized and automated. The history of manufacturing is as long as the history of human civilization, and it has become the basis of human existence and development. We cannot imagine how the world would be without manufacturing, thus manufacturing develops with the progress of human beings, and manufacturing technology progresses alongside the progress of human society.

1.1.1 Manufacturing as Craft and Technique

In the long historical process, manufacturing has always existed as a skill. In early times, people processed rough fur by hand for warmth, hunted by creating simple tools and made the original equipment used for cooking. These simple tools and skills led to human progress. Manufacturing as the evolution of a skill made human history develop from the Stone Age into the Bronze Age, while early handcrafts and skills formed European manufacturing processes; for example, the ancient paraffin casting process is widely used in modern rapid prototyping manufacturing.

Manufacturing technologies in ancient countries not only produced a great glory for feudal dynasties but also made tremendous contributions to ancient human civilization. In the seventeenth century, manufacturing gradually developed into a technology from a skill. With the invention of the steam engine, weaving machine and metal cutting machine, the social division of labor caused huge changes, and in time, manufacturing was no longer owned or completed by handworkers.

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1.1.2 Manufacturing Becoming a Science

Modern manufacturing originated in the West. It gradually progressed into mechanical manufacturing in the nineteenth century and progressed in the direction of mechanization and electrification. From the 1980s, many new manufacturing methods and manufacturing concepts emerged, which greatly propelled the development of manufacturing. These new concepts guide us to analyze and anticipate the future of manufacturing, and these concepts (e.g., Automated Manufacturing, Agile Manufacturing, Concurrent Engineering (CE), Computer Integrated Manufacturing (CIM) and Intelligent Manufacturing, etc.) mutually promote and develop, analysis and looking ahead to future manufacturing. From this period on, manufacturing is no longer a single skill or technology, but a science including engineering science, organization science, information science and so on.

1.1.2.1 Engineering Science in Manufacturing

Harrington, Merchant and Bjorke used computers in manufacturing early on, and they proposed to turn all operations of the whole manufacturing system into automation, optimization and integration with the concept of CIM. During the 1980s, CIM naturally expanded to the field of robotics and artificial intelligence (AI).

The conception of CIM has functioned as a connection between manufacturing, systematic science, and other related issues, and they are merging into the manufacturing industry. The CIM age, which takes Harrington, Merchant and Bjorke as representative, includes the physical process of each manufacturing technology (such as machining, welding or semiconductor manufacturing), control issues (such as servo-control on robots in various production machines), as well as the scheduling of Flexible Manufacturing Systems (FMS). Its structural scheduling connects the original CIM concept with related scientific issues, developing manufacturing from engineering to manufacturing science.

Firstly, for the physical process of manufacturing technology, the original scientific methods and principle can be used for the analysis of manufacturing technology. The physical process of materials processing and semiconductors can be explained by physical theory, for example, the interpretation of atomic dislocation theory on plastic deformation and the interpretation of lattice physics on the transistor. At the same time, when metals are deformed in a plastic deformation process (such as machining and forging), we use a general standard method (such as finite element analysis) to forecast the stress in various material processings and treatment processes.

Secondly, there is a whole set of scientific knowledge which is related to optics, materials science and solid mechanics. We possess a set of mature control theories to explain the stability, stable time and accuracy of machines in manufacturing. In addition, we established a theory related to mechanical control in another manufacturing industry, combining the dynamic analysis and tribology on cam, linkage and propelling machinery.

Thirdly, FMS planning uses analysis methods such as discrete event simulation, statistical modeling, optimization and queuing theory. These are just the main methods of the industrial and operational research department. In recent years, the field of AI has added the scientific method of reasoning based on constraint. In summary, the mathematical theory which supports dispatching operations is now mature and is very important in the process of production scheduling. Although there are many engineering scientific methods described above in manufacturing, they cannot really play their roles without combining with the organization methods which will be discussed below.

1.1.2.2 Organizational Science in Manufacturing

The combination of organizational sciences such as Total Quality Management (TQM), Just in Time (JIT) manufacturing, Concurrent Engineering (CE), and Lean Production (LP), with engineering science is represented by CIM. The "Toyota production system" advocated by the vice president Taishi Ono of the original Toyota Motor Corporation uses FMS to pull product production, in order to reduce work in process, rather than pushing unnecessary parts into a crowded production line like traditional manufacturing. JIT manufacturing is often used to describe this way of operating. Lean manufacturing (LM) is another relevant expression emphasizing reducing work in process and in inventory. At the same time, Toyota also advocates a new quality control (QC) method. In the traditional definition of QC, we test the parts after they are completed to ensure whether they accord with the designed size range. If these parts do not meet the specified dimensions, they will be rejected. By contrast, the new methods which are used by Toyota focus on measurement in production activities. Therefore the focus changes: rather than testing and scrapping unqualified parts after manufacturing, tests are conducted throughout the whole process. In addition, machines should be adjusted in advance to avoid the appearance of defective goods. We call this practice in-process QC or TQM. Moreover, it allocates responsibility to the individual worker and/or machine rather leaving undiscovered problems for the inspector. TQM is thus added to the CIM cycle, the intrant part of which includes: CE, enterprise integration (virtual company) and customer demand. In the new cycle, CE is called sometimes synchronous design, which is a topic closely related to TQM. Because most American companies became used to over-the-wall manufacturing in the past, in the late 1980s, organizational science represented by TQM, JIT, CE and LM combined with engineering science represented by CIM began to have an important influence on the advancement of American manufacturing, which laid a foundation for the economic growth of the 1990s. In a word, CIM joined organization science, forming the new theory and concept of manufacturing integration.

The new concept of open structural manufacturing and agile manufacturing runs through the 1990s. Rapid reconfigurable enterprises should make reactions to new consumers that have requirements on "due date, quality and product variety".

Total quality management is thus added as a new outer concept circle to the CIM circle, known as CIM++, which includes CE (totally quality management), enterprise integration (virtual corporations) and customer needs. In the newly added circles, CE is a topic that is closely related to TQM. CE also became important during the late 1980s because too many U.S. companies indulged in over-the-wall manufacturing. By the late 1980s the organizational sciences of TQM, JIT, CE and LM, combined with the engineering sciences of CIM, all began to create an important improvement in U.S. manufacturing. This set the stage for the economic growth of the 1990s. In sum, from the evolution process above, CIM will adopt the organizational science issues. In the middle of 1990s, manufacturing based on the Internet became an extension of the above new trends, emphasizing on shared design and manufacturing services. The emergence of Internet and audiovisual conference as well as convenient air travel created a way to increase global business. Large enterprises distributed over different continents of the world, for example, use the excellent design team of one country to transfer production to another country with a relatively cheaper labor force and higher manufacturing efficiency. In the twentieth century, because of the emergence of World Wide Web and audiovisual network conference, an item designed in an advanced design office can be produced quickly in another place with cheap labor.

1.1.2.3 Multi-crossed Disciplines in Manufacturing

With the rapid development of modern science and technology, especially the quick development of microelectronics, computer technology, network technology and information technology, the face and meaning of manufacturing theory, manufacturing technology, manufacturing industry and manufacturing science lead to a fundamental and revolutionary change.

Manufacturing also benefits from the development of the related theory of computer science and mathematics. Multimedia computer systems and communication networks realize parallelism, distribution, virtual cooperation, remote operation and monitoring. Electronic commerce and computer network can realize remote sales, production, maintenance and management.

In order to express, compute and deduce the physical parameters and scheduling and management in the manufacturing process, we must use intelligent methods from computer science and mathematics to establish a calculation model. Computational manufacturing science and manufacturing intelligence science will emerge as manufacturing science.

Information theory has also promoted the development of the manufacturing field. In a larger scope, all manufacturing activities involve human factors as well as information processing, expression, transmission and so on. The optimal configuration and effective operations of manufacturing resources are all related to information theory. These related researches will be resolved by manufacturing informatics based on information technology.

The analogy of the manufacturing process and biological process sheds light on new methods of solving problems in manufacturing including adaptability, autonomy, intelligibility, etc. In fact, Bionic Manufacturing is leading such an emerging research field.

Manufacturing must have high-quality management and operation. Human factors, cooperation and competition across enterprises, collaboration and the integration of manufacturing resources are not only a technical problem. Technology Management is the basic of those manufacturing issues.

Apparently, the trend of manufacturing becoming increasingly multidisciplinary is inevitable. With the development and progress of manufacturing science and technology, more and more subject knowledge will be used in future manufacturing fields, forming the new basic of manufacturing science.

Based on the characteristics above, manufacturing has developed as a multidisciplinary integrated system, and thus as a manufacturing science.

Open-architecture manufacturing, agile manufacturing, networked manufacturing and virtual corporation all sound exciting. New engineering science technologies, such as the Web, offer new ways of creating products and services. However, due to more and more digitized forms and knowledge representation of manufacturing activities, manufacturing information, the manufacturing process and manufacturing management calls for a fresher and larger outlook than the old ways. Digital Manufacturing (DM) has quietly entered our lives.

1.2 Concepts and Research and Development Status of Digital Manufacturing

Since the middle of the twentieth century, science and technologies, such as microelectronics, automation, computers, telecommunications, networks and informatics, have undergone rapid development, and a tidal wave that has information technology at its core has been raised. The twenty-first century, which is marked by “network” and “informatization”, will change the way of obtaining, processing, exchanging and using information and knowledge by human and will propel an unprecedented improvement of people’s lifestyle, production patterns and social structure. On this basis, new concepts, new theories, new technologies, new ideas and new methods are endless. The concepts of digital library, digital valley, digital home, digital enterprise, digital economy and even ‘digital earth’, which is the common framework used to describe the time sequence and spatial distribution of various information on the earth [1], are the same as the research works, which are constantly being introduced and have begun to enter our lives.

As the basis of the national economy, the manufacturing industry is shouldering the important responsibilities of providing technical equipment to national economic sectors and national defense construction and supplying living materials and wealth for people’s material life. For nearly half a century, as science and technology have undergone rapid development and a new technology revolution, and the manufacturing industry now faces the challenges of three major outstanding issues that are network, knowledgeable services, and the consequent complexity. Thus it is hard to control the nonlinearity, time variability, suddenness and imbalance of organizational structure and functions in manufacturing systems through traditional operation modes and control strategies. In addition, along with the rapid changes in market demand, global economic competition and the rapid development of high-tech, the profound revolution in the manufacturing industry is also further promoted, the depth and width of manufacturing activities are greatly expanded, and the manufacturing industry is developing in the direction of automation, intelligence, integration, network and globalization [2]. Consequently, profound changes in the token, storage, processing, transmission and machining of manufacturing information takes place, so that the manufacturing industry gradually shifts from the traditional energy-driven state to being information-driven. Digitalization has become the indispensable drive factor in the product lifecycle of the manufacturing industry, thus DM becomes a new manufacturing mode to adapt to the increasingly complex product structure, increasingly personalized, diversified consumptive demand and large manufacturing network, and naturally becomes an important feature in the future development of the manufacturing industry.

1.2.1 Definition of Digital Manufacturing

Digital Manufacturing is a manufacturing process which, with the support of technologies such as virtual reality, computer networks, rapid prototyping and database, is based on customer demand so as to analyze, organize and recombine the product information, process information and resource information, implement the product design and function simulation as well as rapid prototyping, and then to perform rapid production to meet customer demand and quality standards. As a new discipline of manufacturing science, it synthesizes various manufacturing disciplines and represents the mainstream development direction of Advanced Manufacturing Technology [3].

The conception of DM originated from the technology of Numerical Control (NC) or Computer Numerical Control (CNC) and the CNC machine tool. Digital design and digital management have fully developed along with the advancement of CAD and the development of material requirements planning (MRP). In the last 10 years, with the support of virtual reality, computer network, rapid prototyping, multi-media and so on, the simulation and prototype manufacturing of the design and the functions of product can be quickly realized by rapidly analyzing, planning and recombining, coordinating and sharing of all kinds of information (e.g., product information, process information, control information and resources information), to manufacture the product according to the user's requirements as soon as possible. All the processes involved with the above digital activities are related to DM. In the process, the control parameters and control flow to manufacturing equipment are digital signals; all kinds of signal to manufacturing

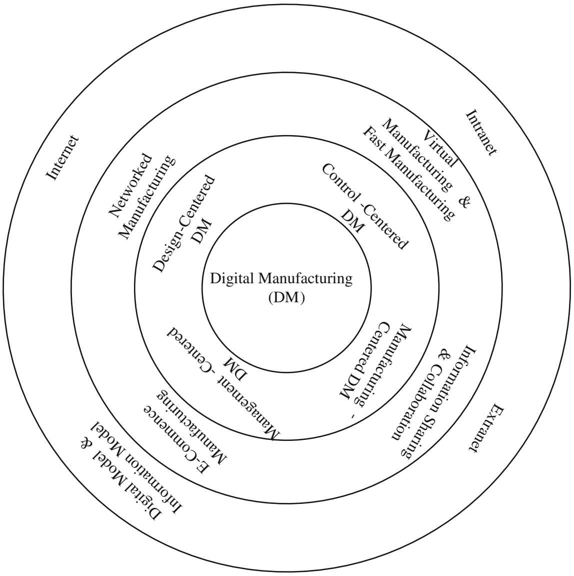

Fig. 1.1 Illustration of DM concept

enterprises, including design information, process information, manufacturing information, management information and manufacturing knowledge and skill, are transmitted in the form of digital signals among manufacturing enterprises through the digital network. Speaking of global manufacturing, all users issue their demands through a digital network and enterprises can design and manufacture the corresponding product according to their own predominance with the help of dynamic alliances. The product itself will become a digital code or a digital mark in the currency along with the appearance of digital logistics.

It is clear that the concept of DM is the result of the merging process of digital technology, network information technology, manufacturing technology and also the unavoidable result of the digitizing process in manufacturing enterprises, manufacturing systems and production systems [4]. In manufacturing devices, for example, the control variables are digital signals. In manufacturing enterprises, all sorts of information (graphic, data, knowledge, and technique) are in digital form, transmitting in internal enterprises through digital networks. In global manufacturing enterprises, users publish the information through digital networks; enterprises (large, medium, and small) cooperatively produce the products quickly and agilely. In the DM environment, individuals, enterprises, shop floors, devices, sales agents and markets form the nodes in the network over the Internet. On the other hand, DM contains the Control-Centered DM, Design-Centered DM, Management-Centered DM and Manufacturing-Centered DM. Currently, networked manufacturing is the implementation of the globalization of DM, virtual manufacturing is the entity of the digital factory, and digital products and e-commence are the dynamic federation of DM. The concept of DM is shown in Fig. 1.1.

In Fig. 1.1, different DM ideas with DM as the core reflect the effect of DM on different application layers.

1.2.1.1 Digital Manufacturing Idea Taking Control for Center

The concept of DM is first generated from numerical control technology (NC or CNC) and NC machine tools. NC technology gives directions expressed in numbers and characters and controls machines with those directions. Not only does it control position, angle, speed and mechanical parameters, but it also controls temperature, pressure, flow and other parameters. These parameters can not only be expressed in numbers but also are measurable and controllable. If one device uses numeric commands to achieve its automatic process, we call it NC equipment. Obviously, it is far from DM, but is a very important basis for DM.

With the development of numerical control technology, the multiple-machine has emerged, which is a manner to achieve integral controlling by one (or several) computer numerical control devices; this is the so-called Direct Digital Control. To achieve automation with many varieties and a small production batch, the collaborative operation between a number of CNC machine tools and one industrial robot develops in order to process a group or several groups of parts with similar shape and characteristics, thereby the so-called flexible manufacturing cell (FMC) is constituted. Supported by a logistic automation system, a large-scale machining automation will be realized by combining a number of FMC or workstations together, which constitutes a FMS. FMS achieves the token, storage and control of material flow, the machining flow and control flow in the machining process by digital quantity.

Digital control can make manufacturing processes automatic, detect and control parameters of the manufacturing process, notify faults and even propose decision-making and the suggestion of maintenance. With the development of network and computer technologies, a Local Area Network (LAN) constituted by networking more than one NC machine tool could make the production processes of a number of workshops automatic. Furthermore, the controller or control system in each piece of equipment will become a node in the Internet, which leads to the manufacturing process developing in the direction of automation with a larger scale and at a higher level. It is the so-called DM idea that takes control for center.

1.2.1.2 Digital Manufacturing Idea Taking Design for Center

Since the development of computers and the combination of computer graphics and mechanical design technologies, computer-aided design (CAD) has been developed, the core of which is the database, the means of which is an interactive graphics system and the mainstay of which is engineering analysis and calculation. The CAD system can describe an object accurately in two-dimensional and three-dimensional space, and improve the ability to describe products and productivity in the production process. The emergence and development of CAD lays the foundation for the automation and digitalization of the product design process in the manufacturing industry, which is the same as NC technology and NC machine tools.

First, the product design information in CAD will be transformed into information about a product's manufacturing and processing rules. The processing machines will be combined and ordered according to the scheduled procedure and work stages. Cutters, fixtures and measuring tools are then selected, cutting parameters are determined, and the maneuvering time and auxiliary time in each procedure are calculated. We call this computer-aided process planning (CAPP). We transform all plans including manufacturing, detecting, assembling, etc., and all information involving product-oriented design, manufacturing, processing, management, cost accounting, etc., into data that are understood by the computer and are shareable in all the phases of the manufacturing process, which makes the CAD/CAPP/CAM integrative, so that CAD rises to a new level. In recent years, computer networks have provided a platform to enable CAD technology to coordinate and cooperate to be able to design online. Network technologies and information technologies are developing fast, and multimedia visual environment technology, product data management system, distributed cooperative design and cross-platform, cross-regional, synchronous and asynchronous information exchange and sharing, as well as group collaboration and intelligence design between multi-businesses, multi-teams, many people, multi-applications, are all the subject of deep research and are entering into the practical stage, which forms a digital manufacture idea that centers on design.

1.2.1.3 Digital Manufacturing Idea Taking Management as its Center

Through the establishment and implementation of internal MRP, according to ever-changing market information, users orders and forecasts, aimed at the overall and long-term interests and through the decision-making model, we could evaluate the production and management of an enterprise, forecasts its future and operating conditions, devise an investment strategy and arrange the assignment of production, all of which form the highest level of the manufacturing production system—the management information system (MIS). In order to support the management and production process in manufacturing enterprises to reconstruct and integrate rapidly in accordance with market requirements, there is a products data management (PDM) system covering the entire enterprise that involves the market demand for products, research and development, product design, engineering manufacture, sale, service, maintenance and other information in the product lifecycle, and thus the process integration centering on "product" and "supply chain" is achieved. Presently, enterprise requirement planning (ERP) is the modern management platform based on information technology is extensively applied, because ERP has both information technology and advanced management thought, so that the logistic, information flow, capital flow, working flow in enterprise management activities are easily integrated and synthesized. Therefore, the DM idea that centers on management is formed, which makes ERP the center and integrates the various MRP/PDM/MIS/ERP technologies.

1.2.1.4 Digital Manufacturing Idea Taking Manufacturing as its Center

In recent years, supported by the theory and technology of virtual reality and virtual manufacturing, network manufacturing and E-manufacturing, rapid prototyping and rapid manufacturing, according to users' requirements, we are able to analyze, plan and reorganize, coordinate and share product information, processing information, control information and resource information quickly, realizing the simulation and prototyping of manufacturing to produce design and function, and to produce products that meet user requirements quickly. In the whole life cycle of product manufacturing, whether manufacturing equipment or manufacturing process, whether manufacturing shop or manufacturing enterprise, whether manufacturing information or manufacturing network, whether manufacturing culture or manufacturing personnel, various information (including design information, process information, manufacturing information, management information, even manufacturing knowledge and skills, manufacturing culture and manufacturing circumstance) in the manufacturing process, all transfers in the manufacturing process, and internal enterprise as well as collaborative enterprise, is in the form of digital information through the digital network. Users publish demand information through the network, and various global enterprises realize complementary advantages and make dynamic alliances to collaboratively design and manufacture corresponding products through the digital network, according to their superiority. Additionally, there are still a large number of manufacturing processes and production process data as well as manufacturing environment and manufacturing culture (including the offline data of uncertainty and the dynamic real-time information of uncertainty in the manufacturing process), so this information is obtained by using intelligence theory and intelligent sensing technology, and is stored in databases and data warehouses. Thus it is necessary to establish an intelligence model, in order to analyze, process, optimize and control the data and information in the whole manufacturing process and manufacturing system, and to realize the optimization of the manufacturing process, the high performance of manufacturing equipment, the high reliability of product quality and production link, as well as customer satisfaction, which form the view of taking manufacturing as the center of DM.

In short, in the DM environment, a net woven by figures and information is formed over a wide area, and individuals, enterprises, workshops, equipment, products, dealers and markets will all become a node, a mark or a digital code. In the process of design, manufacture, sale and maintenance, the DM information and technology assigned by the product will become the most active drive factors that dominate the manufacturing industry. DM science fused by DM theory and technology and the theories and technologies of other subjects will become the core of manufacturing science in the twenty-first century.

1.2.2 Features and Development of Digital Manufacturing

As a new manufacturing technology and a manufacturing mode, DM has become the prevailing way of promoting the development of the manufacturing industry in the twenty-first century. Its important features are: when it is described and expressed, its digital expression has exclusive meaning and is reusable; when it analyzes manufacturability and evaluates the performance of a product, it has the predictability of product development and product performance; and in the network environment, manufacturing activities have independence in distance, time and location. The DM innovates the science foundation of traditional manufacturing and converts product design manufacturing into comprehensive digital quantification from partial quantification, partial experience and qualitative mode. Thus, a series of basic theories and key technology issues are produced, such as the digital expression of product information, modeling and simulation of manufacturers process, digital prototyping technology, and open numeric control technology.

At present, the basic theoretical research of DM focuses on computational geometry, geometric reasoning, calculation of manufacturing, manufacturing informatics and so on. The geometric centers of the American Polytechnic University and the Southern Polytechnic State University in Georgia, the Navy Research Institute, NASA Research Center and other geometric internationally renowned research institutions have attached much importance to the engineering application research of the geometry [5], and have made great progress in the application of digital prototyping technology. Monostori et al. [6] study the issues of uncertainty and complexity that are at the forefront of DM in the network environment. Lee has the five-axis processed complex surface as studying object, and carries out effective research on surface design and processing methods [7]. The School of Mechanical Science & Technology at Huazhong University of Science and Technology has the support of major projects in the National Natural Science Fund and conducts in-depth research on geometric reasoning, reverse engineering, computer manufacturing and digitalization of the product model, with significant achievements [8]. A key theoretical issue in DM is to create constraint analysis and solve the constraint problem, which is how to realize the multi-objective global optimization of product developing indicators, such as time and cost, in the condition of being constrained by function, geometry, physics, technique and other factors. The constraint analysis includes mould typing, workpiece fixturing, interference checking, measurement planning, assembly planning, fixture designing and grasp planning. As the basic means to solve constraint analysis in the manufacturing process, the concept of C-space and spinor space, accessible and reachable analyzing methods has become one of the hot spots in the study [9]. Wuhan University of Technology has conducted in-depth study on embedded intelligence numeric control, grid-based DM resource sharing and information security and intelligence reconfigurable ERP system, and so on [10–13].

The premise of realizing digital manufacture is in establishing a digital model of products and presenting the digital definition of the entire process of the product lifecycle in a way that the computer can understand. The product models most studied are the geometric model, physical model, knowledge model and prototype model. The geometric model and knowledge model are mostly static describing models, mainly used for product design and manufacturing. The physical model and prototype model are dynamic simulating models, used for product-oriented performance analysis [14, 15]. The principal means of gaining digital product models includes positive design, reverse engineering and integration of positive design and reverse engineering, but these methods can only make the geometric information of product digital [16]. A key feature of DM is that it not only has to deal with a great deal of conventional engineering data and graphic information, but a large amount of empirical knowledge and other non-geometric information needs to be disposed of. In order to cast DM technology in the role of technological innovation, it is necessary to digitalize the dominant knowledge in the field. How to digitalize physical parameters (power, heat, sound, vibration, speed, errors, etc.) in the extreme manufacturing process, and to transform these parameters into a form that the computer can handle, means that there is a lot of work to be done [17].

In the network environment, the manufacturing equipment's capacity to handle the digital information is an important characteristic of DM systems. Digital manufacturing equipment (denoted as Digital Equipment), including numerical control machine tools, welding machines, industrial robots and the coordinate measuring machine (CMM) have developed from the simple executive entities of manufacturing into integrated information processing devices. In the network environment, these devices must have the functions of motion planning, performance modeling, state detection, autonomous control, self-preservation and self-reorganization to meet rapid product development and rapid response to the market requirement, and to adapt to the product innovation and market competition environment. The characteristics of digital equipment embody the digitalization of movement, including the digital modeling of the driving process, motion planning under the conditions of multiple restrictions, parameters identification based on sensor information and adaptive control for the change in working conditions, and other aspects [18, 19]. The representative study includes: the complex trajectory of cutters that generates automatically under high-speed conditions, high-accuracy machining, interference checking and error compensation [20]; dynamics modeling, parameter identification in drive systems and the influence of temperature, stress and other physical parameters on extreme working conditions [21]; high-speed tracking control in a numerical tracer under visual guidance [22]; the adaptive capacity and ability of autonomous control for changes in working conditions [23], and other issues. These researches are mostly confined to a particular equipment or certain functions, such as the cutter interpolation operation of the CNC machine, motion planning of an industrial robot, and path planning of the CMM probe, all have a specific programming system (heterogeneous equipment). These systems have many similarities, involving solution to relative motion between objects under the conditions of geometric restriction. Because of different application areas, a comprehensive programming system has not been established for this digital equipment, which is pending research and needs integration and collaboration. Because of the complexity of the manufacturing process (such as the friction, space, deformation, temperature of moving parts and the delay of light, electrical signal, and other non-linear and uncertainty factors), it is hard to ensure that control theories and methods are based on the prior model. The resolution of these issues has been seriously constrained by the theories and methods of digital modeling in dynamics, system identification based on sensor information, intelligence planning and autonomous control [24].

The computer network has provided an important condition for the transmission of DM information, sharing of manufacturing resources and optimizing the operation of manufacturing systems (http://www.siggraph2002.org/). In the network environment, DM puts more emphasis on coordination and cooperation between the constituent units and the independent adaptability to the manufacturing environment [25]. Nowadays, the research on manufacturing process planning, coordination and collaboration [26, 27] mainly concentrates on the system level, but the issues about how to solve the heterogeneity of equipment, the complex interaction and collaboration between types of equipment, and the search for collaborative ability in reachable heterogeneous resources lack in-depth study. When we study how DM equipments adapt to the network environment, most of us confine ourselves to resolving network communications, remote operation and data exchange [25, 28, 29, 30], but pay little attention to issues such as the automatic perception and independent adaptation of basic DM equipment to the complex dynamic manufacturing environment. These have become the core factors that constrain the integral performance of the system, which it is necessary to resolve.

From the research status and its analysis above, DM is clearly still an emerging research field, but also a fast-developing research area. The basic theoretical research on DM is not very systematic, and is far from being a scientific theoretical system. As the basis of kinds of advanced manufacturing technologies, it is important for DM to be subjected to systematic study and to establish its specialized scientific theoretical system in order to promote its healthy development. A new disciplinary system—DM Science-comes into being for the sake of meeting the needs of development of the times.

1.3 Connotation and Research Method of Digital Manufacturing Science

1.3.1 Basic Concept and Connotation of Digital Manufacturing Science

From the digital concept and its development and evolution, DM has gradually evolved into generalized DM to include the whole lifecycle of a product and its operating environment from simple production manufacturing and digitalization of product. Digital Manufacturing consists of mathematical basic theories including product demand, product design and simulation, management of the product manufacturing process, operational control of production equipment, management of product quality, product sales and maintenance and other aspects, and the all-digital analysis, design, operation and management of basic scientific questions, as well as the digital operating environment sustaining the entire product lifecycle, and the theoretical system. Therefore the research on DM has also evolved into a systematic research that includes basic theories and technologies from a technical study, and it becomes DM science from an advanced manufacturing technology as well.

As an interdisciplinary subject, DM science will devote itself to structuring the discipline theory system about DM, including the modeling theory and modeling methods of the DM system, architecture model of the DM system and the basic disciplinary theory of DM. Therefore, the definition of DM science is as follows:

Definition 1.1 Digital manufacturing science is a science, the main research contents of which are basic concepts and pivotal technology, the main research method of which is the methodology of informatics and system engineering and the research target of which is the optimal operation of the DM system.

The basic connotation of the definition firstly relates to the methodology of its research. Digital Manufacturing has its own special characteristics. Seino et al. [29] describe the basic attributes of DM from the perspective of both development and production, and think DM is a manufacturing methodology that applies both mathematics and information technology. It is used for product design and manufacturing process, and forms digital product, DM equipment, DM technology and other research areas. Their study highlights the intrinsic characteristics of DM, which change the meaning of the manufacturing mode. The concepts closely related to DM are virtual manufacturing, network manufacturing, intelligent manufacturing, and others. The core idea of virtual manufacturing to use the virtual prototype instead of the physical prototype to achieve the manufacturability design for manufacturing; network manufacturing mainly researches information exchange and sharing within the manufacturing industry and external network application services; intelligent manufacturing resolves the formalization of the description of manufacturing knowledge and experience, and researches uncertainty and problem-solving the manufacturing constraints under conditions of incomplete information. However, DM synthesizes some attributes of the technologies mentioned above from different angles, and represents the main direction of their development. In addition, compared to other advanced manufacturing technologies, DM reflects its effects of core and base such as parallel manufacturing, agile manufacturing, timely manufacturing, and CIM. They reflect the efficacy of changing manufacturing methods, enhancing manufacturing efficiency and reducing manufacturing cost from different perspectives, and represent different manufacturing concepts, but DM should be the foundation of those kinds of advanced manufacturing theories and technologies mentioned above. As DM is an opening concept, its theory and technology are able to be applied to various advanced manufacturing systems in manufacturing engineering, thus different application systems are generated. If the manufacturing theories and technologies used in all types of advanced manufacturing systems are abstracted, we can determine their common theoretical and technical base. Therefore, the system constructed by the common theory and technology can be a foundation system supporting the implementation of various advanced manufacturing technologies. Such a system is the DM system: it is the mathematic abstract and information integration of the modern manufacturing system and is a brand-new research methodology of the manufacturing system.

The research content of DM science is the basic theory and key technology of the DM system, and it is the core of all DM science. Summarizing the research results we have, its research contents are integrated system theory, element theory of DM and key technology of DM. Integrated system theory is the macroscopic integration theory in the manufacturing environment, such as the system organization model, function model, information model, operation and control model, and so on. It provides general models to advanced manufacturing systems which rely on the theory and technology of DM, and it is the basis for the actual systems to operate stably. Element theory is the digital modeling theory of all aspects in the product lifecycle, such as the modeling theory of product description, product collaborative design theory, product digital production manufacturing process and its management theory, digitalization of production equipment and its operation control theory, and the digital management theory of product sales and maintenance. The content of element theory mentioned above is distributed in different study monographs and the new research direction, for instance, the calculation of manufacturing, manufacturing informatics, manufacturing intelligence, bionic mechanics, technology management, network environment of DM, and so on. Together, they structure the discipline theory system of DM science, and construct the essential basis for the realization of digitalization; the key technology refers to various sustaining technologies that achieve the digitalization of the systems, including a variety of digital technologies and digital-manufacturing-oriented resources and the environment technologies in the whole lifecycle of the digital product, for example, the CAX technology, digital machining technology, digital diagnosis and maintenance technology, networks and grid technology, resources organization and management technology, resources dynamic management and scheduling, resource services and security technology, and they are important means of a perfect system. Thus, the research contents of DM science have rich connotations.

1.3.2 Research Method of Digital Manufacturing Science

The research object of DM science is the DM system, which determines that its research method is the methodology of informatics and system engineering.

Firstly, DM science must use the methodology of informatics. DM is based on quantitative description and achieves optimal operation and development of the manufacturing process and manufacturing system through using information and knowledge. Digitalization is the basis and the core of the informatization of the system. The specific targets of informatics are the things dominated by the information phenomenon, and the general characteristic of this type of thing has many common points with manufacturing process and manufacturing system; they generally belong to advanced motion form and complex systems, such as human intelligent manufacturing activities, manufacturing circumstance and manufacturing culture, as well as the advanced machine manufacturing system. Therefore, on one hand, these things often have a very complex structure of materials, and it is difficult to use conventional methods to describe and analyze them; on the other hand, it is not enough to solve all the problems which also existed in the past manufacturing process by knowledge of the energy conversion contained in the manufacturing process and manufacturing environment. Since the objects are the things dominated by the information phenomenon, it should be solved by viewpoints and methods of information, namely, the analysis methods of the information system, the integrated approach of information systems, the evolutionary approach of information systems, the function criteria and the integral criteria. These three methods are the soul of the whole methodology, and the two criteria are the laws of implementing the entire methodology correctly, which together constitute the methodology of informatics and are applied to the research on DM science.

Secondly, DM science must use the methodology of system engineering. Systems engineering theories point out that the "system" is an organic whole having specific functions and is combined by several components that are interactional and interdependent. Thus, the DM system can integrate all the basic theories of DM with all its technologies organically, and make itself show the entire functions of comprehensibility. Through the research on the mechanism, planning, design, construction, test, operation and management of the whole system, we can identify the mechanism and function owned by its basic theories and technologies themselves; we could provide thus services to all types of advanced manufacturing processes and manufacturing systems. The features of this method can be expressed as:

1. *Comprehensibility of Thought*. Looks at the manufacturing process in DM systems and all the hardware and software as a whole, and always analyzes and deals with problems in the manufacturing process from the perspectives of global area and the entire process. When we consider and dispose of the relevant problems in the manufacturing process, it stresses that it is necessary to synthesize the manufacturing system, various factors in the application environment and the dynamic process to study what is involved in those problems, to prevent attending to one and losing another.
2. *Integration of Knowledge*. This emphasizes the multi-disciplinary knowledge involved in the manufacturing process to study and deal with the major issues concerning the design, manufacture, management, operation, update, development and other elements within manufacturing systems. Individual parts of many new manufacturing systems may not show any change, but the new type of manufacturing system is an organic integration of the various parts and becomes an integer having novel features.
3. *Optimality of Target*. Refers to every aspect of planning, design, construction, management and operation, etc., of the DM system and is always in pursuit of

optimizing state and effect, with special emphasis on the optimization of the global area and the entire process.

As the research object of DM science is the DM system, the research goal of DM science is the optimal operation of DM systems. This system is the basic supporting system that supports the implementation of all kinds of modern advanced manufacturing technologies. Therefore, it must be ensured that the use of theories and technologies in DM allows the optimization of the various local functions, such as collaborative optimal design, optimal control of digital equipment, optimal sharing of manufacturing resources and so on, and the basic requirement must be satisfied: namely, is multi-target optimal operation.

In order to clarify the connotations of DM science clearly, the chapters of this book are arranged as follows:

Chapter 2 analyzes the basic mode of operation required by DM systems and the architecture of DM, then presents parts of the integral construction model in the DM system and the theoretical system of DM science;

The main disciplinary knowledge in the theoretical supporting system of DM science is analyzed and introduced in the Chaps. 3–7;

Chapter 8 analyzes and discusses the key technologies in DM science;

Chapter 9 discusses and forecasts the development of DM.

1.4 Summary

This chapter reviews the development of manufacturing science, clarifies the definition of DM, analyzes the current status of DM and finally achieves the inevitability of DM science. Consequently, the basic definitions of DM science have been proposed, and the connotation of its research and research methods have been elaborated, which lays the foundation for the following chapters and sections.

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Chapter 2
Theory System of Digital Manufacturing Science

Digital manufacturing science, as a new interdisciplinary area, has its own theoretic system, and its theory system is constructed based on its research object and content. According to the connotation of digital manufacturing science in Chap. 1, the research object of digital manufacturing science is the digital manufacturing system, and its research contents are the basic theory and key technology of the digital manufacturing system. Therefore, this chapter, which is based on the integrity of discipline theory and combines the connotation of generalized digital manufacturing and the actual demand of the digital manufacturing system, proposes the operation reference mode and architecture of the digital manufacturing system and discusses the critical modeling theory and method of digital manufacturing science. Finally, it puts forward the theory system of digital manufacturing science, and lays the foundation for subsequent chapters.

In this chapter, the first section analyzes the actual demand of operation in the digital manufacturing system, and proposes the operation reference mode and architecture of the digital manufacturing system; the second section analyzes the modeling theory and method of the digital manufacturing science; based on the two previous sections, the third section puts forward the theory system of digital manufacturing science, which includes the macro integrity theory of the digital manufacturing system and the meta theory constructing digital manufacturing science.

2.1 Operation Mode and Architecture of Digital Manufacturing System

The digital manufacturing system is the foundation on which various modern advanced manufacturing systems become a reality, and the realization of any modern manufacturing system must be constructed on the basis of a digital manufacturing system. Thus, it is necessary to clarify the operation mode of the

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digital manufacturing system and the demands of its architecture before studying the digital manufacturing system and constructing its integral model system. Accordingly, the basic realization process of digital manufacturing system is introduced in this section and its operation reference mode is then proposed based on this process. In addition, the architecture of digital manufacturing science is presented according to the discipline basis and application fields of digital manufacturing.

2.1.1 Operation Reference Mode of Digital Manufacturing System

The basic process of the digital manufacturing means that the design, simulation and production of a product are completed in a digital environment. That is to say, after receiving orders, a conceptual design and general design are first carried out, followed by a computer simulation or rapid prototyping process, and process planning engineering, the process of CAM and CAQ, until finally the product is formed. It is essential for production resources to be planned generally and coordinated in the entire manufacturing process. If resources are insufficient or the core competence of the manufacturing individual is limited, it is necessary to look for partners and create manufacturing alliances, and on that basis, production resources are planned and manufacturing processes are monitored to ensure that products will be realized on demand. In order to assure the effectiveness of the manufacturing process, we must also first acquire the product demands of potential markets. Therefore, we need to collect market information, analyze customer needs and capture opportunities in the market. In order to ensure that the manufacturing purpose of the product is met, the product must be quickly launched to the market after it is finished, to be able to possess market share and profit from product. It is thus necessary to engage in marketing and collect feedback information from users, and also to support perfect product maintenance and service work.

It can be seen from processes above that the digital manufacturing system is not just a simple manufacturing process; it also includes many links such as the relevant market demand, manufacturing organization, marketing and product maintenance. Therefore, it is a complex system related to many links. Obviously, the stable operation mode that supports digital manufacturing systems should include a great deal of subsystems, such as the management and decision-making of manufacturing individuals or alliances, market demand analysis, product collaborative design and simulation, collaborative manufacturing management of product, operation control of product manufacturing equipment, product quality management, product marketing and customer service.

From all aspects of the analysis above, in light of the operation mode in an actual enterprise, we derive the operation reference mode of the digital manufacturing system, as shown in Fig. 2.1. The meaning of every subsystem in Fig. 2.1 is as follows:

The management and decision-making systems of manufacturing individual or alliance. This is the core management and decision-making system of the entire

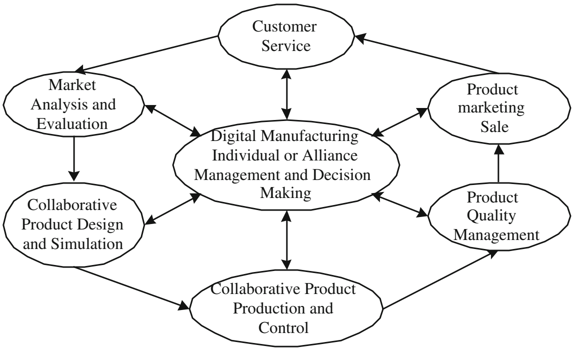


Fig. 2.1 The operation reference mode of digital manufacturing system

manufacturing organization, responsible for handling plans, operations, detection, control and maintenance in the enterprise, and is the backbone of the entire system. The individual is the smallest independent manufacturing unit, and may be a manufacturing department, workshop, digital intelligent manufacturing equipment or an independent enterprise; the alliance is a organization that is composed of a number of digital manufacturing individuals and can realize the integral function of product.

Market analysis and evaluation system. This is mainly responsible for collecting market information, tracking existing market products analyzing new market demand and evaluating the value and feasibility analysis.

Product collaborative design and simulation system. Aiming at demand for the new product, this system coordinates the design members in the manufacturing alliance and uses their respective core competences and advantages to achieve collaborative product design, realize the simulation and rapid prototyping manufacturing of the designed product, and evaluate the design results, to achieve a low-cost, high-quality and high-speed product design result that is also harmless environmentally [1].

Product collaborative manufacture and control system of manufacturing process. This system takes charge of coordinating members in the manufacturing organization by using their core manufacturing capabilities to implement rapid product production. It also ensures that all equipment and devices in the manufacturing environment are carefully planned and built, controlled collaboratively and run reliably. Optimization of the manufacturing process and product performance are achieved by using the technology optimization method, digital scheduling method and operating algorithm of system optimization [2].

Product quality management system. This is responsible for the quality detection and management of products, which ensures that quality products reach the market.

Product marketing system. This system is responsible for the formulation and implementation of the product marketing strategy and the commercialization of products in order to gain the biggest sales return and achieve the goal of product manufacturing.

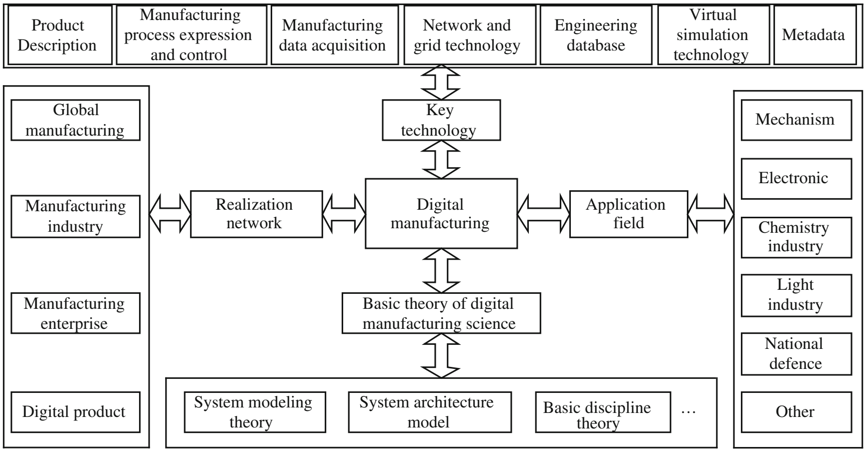


Fig. 2.2 Architecture of digital manufacturing system

Customer Service System. This is responsible for the maintenance and service of products to ensure the correct use of products, to gain market reputation, and promote the social benefits of products. Customer demand can be used as the basis for market analysis of new products.

In Fig. 2.1, the specific design and implementation function included in the product collaborative design and simulation system, and the product collaborative manufacture and control system of the manufacturing process could be purposely set according to the demand for a specific product.

In this figure, the functions of subsystems in the digital manufacturing system are independent, but the subsystems have interrelated and complicated relationships. The operational structure of the digital manufacturing system must have stability, open type and robustness to meet the constantly updating technology and development. Therefore, we must construct an architecture model of the whole system, including a reasonable organization model, organization model, operation and control model. On this basis, scientific management techniques could be implemented, and the optimal operation of complex systems could be ensured.

2.1.2 Architecture of Digital Manufacturing System

From the formative background, definition and connotation of digital manufacturing, and the operation reference mode of the digital manufacturing system, the architecture of digital manufacturing system can be easily established and should include the basic theories of digital manufacturing science, the key technology of the digital manufacturing system, the network and application fields of digital manufacturing, and so on. The architecture of the digital manufacturing system is shown in Fig. 2.2.

Figure 2.2 shows that the architecture of a, digital manufacturing system should be constructed on the basis of the basic theory of digital manufacturing science. The foundation of digital manufacturing science includes modeling theory of the digital manufacturing system, a system architecture model and discipline basic theories, and so on. Accordingly, the modeling theory of a digital manufacturing system is a scientific method of systematic analysis and synthesis; the system architecture model defines the basic research objects and contents of the digital manufacturing system, and establishes the basic organization structure, function structure, operation and control structure of the digital manufacturing system. Further, it establishes the basic architecture of the entire research subject; the basic discipline theories belong to the discipline theories of digital manufacturing science, and provide theories and methods for the concrete realization of the entire system to ensure its successful implementation. These factors constitute the basic theory of digital manufacturing science and are the cornerstone of the development of all digital manufacturing science. Based on the basic theory, a reasonable digital manufacturing application system can be constructed.

The key technologies of the digital manufacturing system include product description technology, manufacturing process expression and control technology, manufacturing data acquisition, storage and processing technology, networks and grid technology, engineering database technology, virtual and simulation technology, and metadata technology [3]. Accordingly:

1. Product description technology refers to the use of digital technology to describe product information, including description and expression norms, as STEP is a typical product description technology and norm.
2. Manufacturing process expression and control technology includes how to express and control various certain and uncertain manufacturing processes, and the examples of uncertain manufacturing processes include the process of tool wear, market development and the decision-making process.
3. Manufacturing data acquisition, storage and processing, include the acquisition, expression, storage, processing and application of manufacturing knowledge.
4. Network and grid technology refer to the network support technology which guarantees the collaborative design and production of the system in remote, heterogeneous environments. Among them, the grid network technology, which applies and develops network technology, guarantees the independence of network resources, and the sharing of applications in an efficient and safe way.
5. Engineering database technology: there are many problems concerning data storage and a management in a manufacturing system, but there is so far no suitable database technology to meet the corresponding requirements.
6. Virtual and simulation technologies include virtual design, manufacturing process simulation and digital prototyping.
7. Metadata is data about data, by which we can understand the name, purpose and usage of data.

Digital manufacturing systems can be implemented at different levels and in different network environments, including the Internet around the world, industry-wide

Internet and Intranet technologies and the network and digitalization technologies that support the enterprises' lifecycle and the digitalization of the product.

The digital manufacturing system is widely applied and includes the breakpoints in machinery, electronics, the chemical industry, light industry, national defense and a variety of manufacturing and application platforms, and digital manufacturing norms and the implementation of tools. As the concepts of digital manufacturing science are popularized and the theoretical research of digital manufacturing science deepens, breakthroughs in the key technology and application platform in digital manufacturing, and the implementation of digital manufacturing tools and norms, it is realistic to expect that digital technology will become the leading actualizing mean in manufacturing and will support various manufacturing technologies, leading our society into a full digital manufacturing era.

2.2 Modeling Theory and Method of Digital Manufacturing Science

2.2.1 Modeling Theory of Digital Manufacturing Science

The model, which acts a important role in system engineering, is an idealized abstract and simplified method of the system which reflects the main components in the system and the mutual relationship and effects among these components. The modeling theory of digital manufacturing science seeks to establish the modeling idea of the digital manufacturing system, and to set up a suite of modeling methods. Accordingly, it would be the basic theory for analyzing and solving problems in digital manufacturing science.

The modeling idea of digital manufacturing science expresses the digital manufacturing system abstractly, and the digital manufacturing system is analyzed, synthesized and optimized through studying its structures and characteristics. Its specific target is to support the analysis and synthesis of the system through understanding and expressing the system better; to support the design of new systems or the reconstruction of existing systems; and to support the monitoring and control of the system operation.

The digital manufacturing model is an indispensable tool in the whole lifecycle of the digital manufacturing system. This whole lifecycle includes data acquisition, data processing, data transmission, implementation of control, affairs management and decision support, and so on. It consists of a series of models in an orderly manner; these models are generally the product design model, resource model, information model, operation and control model, system organization and decision-making model and so on. Here, the so-called 'orderly manner' usually means that these models are created at different stages of the life-cycle in the digital manufacturing system.

There are many classifications in the digital manufacturing model. Classifying by form, there is the global structure model (such as the architecture of manufacturing system), the local structure model (such as the FMS model), the product structure model and the scheduling model of production planning; classifying by modeling method, there is the mathematical analytical model (such as the state-space model), the graphic conceptual model (IDEF model) and the hybrid diagram—analysis model (such as the Petri net model); classifying by function, there is the structure description model, the system analysis model, the system design and implementation model, and the system operation and management model.

In digital manufacture, the objects that need to be described by model include:

(1) *Product*. The life-cycle of a product needs a variety of product and process models to be described;
(2) *Resources*. Various resources in the digital manufacturing system need the corresponding models to be described, such as manufacturing equipment, funds, various materials, persons, computing devices, and kinds of application software;
(3) *Information*. It is necessary to establish the appropriate information model for information acquisition, processing and usage in the whole process of digital manufacture;
(4) *Organization and decision-making*. This is an important approach for actualizing the optimal decision-making for modeling organization and the decision-making process in digital manufacture;
(5) *Production process*. This is the premise that the modeling production process will realize the optimization of the production and scheduling process in the manufacturing system;
(6) *Network environment modeling*. The various objects mentioned above are modeled when the digital manufacturing system is in a network environment [4].

Digital manufacturing modeling abstractly expresses every object and process of the entire lifecycle of digital manufacturing through an appropriate modeling method, and analyzes, synthesizes, optimizes and simulates them through researching their structures and features. The target that digital modeling is pursuing is firstly to establish the model of the entire digital system and then to establish the important models aiming at one or more objects mentioned above by using a specific modeling method.

Digital manufacturing science is a new discipline and the modeling method of the digital manufacturing system is still in the exploratory stage. Its specific modeling method must therefore be created by following discipline theory to construct its modeling method system. The basic idea is that a generalized model of the whole digital manufacturing system is created by using set theory and relation theory, based on which basic models related to the system architecture, such as the function model, organization model, information model, operation and control model are established. Through rebuilding the existing modeling method of the manufacturing system, the modeling method system of digital manufacturing science can then be established according to the features of the digital manufacturing system. Finally, every link in the digital manufacturing system is modeled by the model system detailed above to create an implementation model, and this is a theoretical basis for the specific implementation of each manufacturing link.

2.2.2 Critical Modeling Theories and Technologies in Digital Manufacturing Science

The related researches into manufacturing modeling and its analyzing method appeared many years ago, and have made rich contributions. The well-known results of this research include GRAI/GIM, CIMOSA, IDEF, ARIS architecture, PERA, TOVE, Petri Net and so on. GRAI is mainly used to model for decision support systems and the IDEF family is mainly used to model for every stage of the life-cycle in the manufacturing system [5, 6]. The IDEF family includes function modeling (IDEF0), information modeling (IDEF1), dynamic modeling (IDEF2), data modeling (IDEF1X), process description access method (IDEF3), object-oriented design (OOD) method (IDEF4), entity description access method (IDEF5), design theory access method (IDEF6), human–computer interaction design method (IDEF8), business restriction found method (IDEF9) and network design (IDEF14) [7–11].

Object-oriented analysis (OOA) and modeling theory and technique have become research hot spots in recent years, and modeling technique can be divided into two major classes. One class is called the “method-driven method”, such as OOA/OOD; the other is known as the “model-driven method”, such as the object-oriented system analysis (OSA) methods by Embley and the object-oriented modeling technique (OMT) method by Bumbaugh. The former emphasizes the analysis of complex systems, and the results of design will be submitted by documents; the latter emphasizes system modeling, and is directed by existing modeling concepts and driven by modeling structure, and takes into account the implementation of model sufficiently. In these model-driven approaches, OSA and OMT both consist of many models which describe the system from different aspects and form a complementary and unified system view. The difference is that the OMT model is formed by the object model, dynamic model and function model, and inherits many of the traditional modeling methods (such as E-R model, the data flow diagram), and describes a complex system fully through a combination of various modeling methods; its model places more emphasis on the concept, so there is still a certain distance from the detailed design of the system. However, the OSA model is formed by object relationship, object action and interactive object model, and the description of objects is full and detailed. It focuses more on the operation of the object, and the object model could almost be implemented by object-oriented programming techniques ([12, 13]; http://osm7.cs.byu.edu/OSA/tutorial.html).

The agent-based modeling method has also become a hot issue in recent years. Agent originates from the discipline of artificial intelligence. Early research on artificial intelligence is mainly based on physical symbol assumption; its main idea is that an intelligent task can be completed by the reasoning process which operates by symbolizing the internal expression of the problems. The reasoning process and internal expression constitute the initial outline of the agent. With the raising of hardware levels and the further improvement of computer science theory, the capacity of the agent has been strengthened more and more in simulating human thinking and behavior. In the late 1980s, agent technique was underwent rapid development and related researches and applications were further extended. With the development of distributed processing technology, object-oriented technology and computer networks, agent techniques have been researched subtly in Mobile Code, Intelligent Routers, Web Search Tools, Robots, Interface and other areas of computer science. With the wide application of artificial intelligence and computer technology in engineering, along with the broad application of artificial intelligence and computer science in engineering, multi-agent system (MAS) technology provides a better solution to the coordination and cooperation of product design, manufacturing and even many fields in the entire lifecycle, and also provides a more effective means for the development and integration of parallel products [14, 15].

These methods mentioned present an understanding and description of a complex system from different points of view. Because the manufacturing system is a research object of the digital manufacturing system, these methods could offer specific modeling techniques and be evolved into a series of modeling methods in digital manufacturing science. However, the digital manufacturing system is a complex system which is difficult to describe comprehensively; therefore, it is necessary to create a global modeling method. Aiming at the characteristics of the digital manufacturing system, this section proposes an abstract modeling theory and method called the generalized modeling method, which constructs the key modeling techniques of the digital manufacture together with other modeling techniques mentioned above. Here, the generalized modeling method and some methods in common use will be introduced.

2.2.2.1 Generalized Modeling Theory and Method

The digital manufacturing system is a large and complex system having many characteristics, such as a large-scale, complex structure, integrated functions, and multi-factors. The existing large-scale system theory inherits the modeling method of control theory and operational research and mainly uses a mathematical model in the system modeling. However, it is difficult to describe complex large-scale systems which contain uncertainty, unknown elements and varied applicability. Therefore, a relationship model could be established by using the abstraction method and collecting set theory to reflect the relation between the system characteristics, score the overall features of the system and grasp the system's overall function and macro features. General system theory as a means of abstraction is a tool of generalized modeling which has made a great contribution to the development of system science.

General system theory is considered to be a theory that researches the general motion law of a system by using logical and mathematical methods which reveal the relationship between businesses and objects from the viewpoint of the system, interactional essence and internal law, and is a transverse integrated discipline which arose at almost the same time as control theory and information theory. Since the concept of general system theory was proposed by von Bertalanffy [16], many scholars have committed themselves to the establishment and research of the theory such as the early pioneers G. J. Klir, M. D. Mesarovic, Y. Takahara, R. E. Kalman, W. Wymore, R. Rosen and others. Mesarovic and Takahara proposed a general theory model about input and output systems using the set theory method in 1970s, with an abbreviation of MT theory [17]. Ma and Lin presented multi-relationship general system theory [18] in 1980s. These research results provide mathematics theory with the foundation and accurate description in mathematical form of general system theory, and provide effective weapons for the application of the theory.

An MT system is the Cartesian product of two sets. S is an MT system, if and only if $S \subset X \times Y$, of which X, Y is non-empty set. According to the conception of Mesarovic and Takahara, such a system is an input–output system with input set X and output set Y (referred to as I/O system). The general system theory established on the basis of this model is referred to as MT theory and has been applied in the researches on the ordinary differential equation system, dynamic system, hierarchical system and information system [17].

MT system is an I/O system, but there is also non-I/O system. For example, suppose (X, r) is a topological space, in arbitrary open set $\eta \in \tau$, the distance of η is 1. Therefore, X is a non-I/O system. Considering this situation and many complex systems, Lin and Ma presented the general model of the system in 1987: S is a system, if and only if $S = (M, R)$, and it is an ordered pair, of which M is a set, R is the relationship-set on M, namely, $r \in R$, which means $r \subset M^{n(r)}$, ordered number $n = n(r)$ and $n(r)$ is the distance of r. Obviously, when $n = 1$, S is a non-I/O system. Therefore, this model expands the MT model. The system-based general model of Lin and Ma exploits and researches the general system method of mathematical basis and multi-relationships, and its results have been used in sociology, set theory, and so on [18].

We can create an abstract model of the digital manufacturing system called the generalized system model by using the theories above. The system modeling principle, modeling methods and modeling steps are as follows.

(1) System Modeling Principle:

  (a) MT theory and the LM multi-relationship model are the basic criteria in general system theory in developing a system model. The complexity of the system is composed of the relationship among system objects and between system objects and the system target, which constitute the system's relationship-set that is characterized by system functions. Therefore, the key elements of the system's abstract description are the system target, system object and system relation.

(b) Primary and Secondary: Complex large-scale systems often have many targets, so how to determine the system target is directly related to the choice of system scheme. Therefore, it is essential for the establishment of an adaptive model to distinguish between primary and secondary targets among those many target factors, grasping the main factors and omitting secondary ones according to the actual needs and possible conditions of system analysis and synthesis.

(c) Separation: Because the objective world is interrelated and mutually restricted, in order to make the system relatively independent of the environment, it is necessary to consider whether the system can be separated and how to separate it from the surrounding environment in the process of system modeling; that is to say, "system" is separated from "environment". In order to make clear the modeling object and its scope and to simplify the modeling problem, we have to further consider the separation of "controller" and "controlled object", and the division of "a whole system" and "subsystem", and other issues.

(d) Causality: Causal relationship analysis is the basis of establishing a "relationship model". The "input" (the effect caused by the environment to the system), the "output" (the effect caused by system to the environment of the system); the input and output of the controller; the input and output of the controlled object; the interaction between the various subsystems in large-scale systems, and so on, must all be determined.

(2) Basic Modeling Method

"Analysis—Synthesis" Method. Practical large-scale-complex systems are often made up of a number of interrelated subsystems. For instance: a manufacturing system is made up of by a number of function systems and support systems. Therefore, the "Analysis—Synthesis" modeling method can also be used in the modeling of large-scale systems.

First step: Analysis. Firstly, the target set of the system should be determined. Then, the large-scale system is decomposed into a number of subsystems, and the primary component elements of the subsystem established to determine a main component set of the system. Finally, a relation set is determined.

Second step: Synthesis. In this step, the analysis results should be synthesized, and it is important to determine the solving scheme and evaluating method.

(3) Integral modeling process of system

The modeling process of the generalized model and its specific meaning are shown in Fig. 2.3.

According to the demands of the organization and the operation process in the system, we can ascertain the target set T and extract the key organizational factors set F_i ($i = 1,2,\ldots,n$) of the system, such as system resource set R, knowledge and

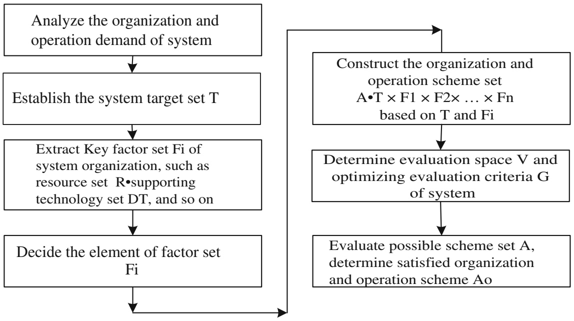


Fig. 2.3 The modeling process of the generalized model

experience set K and support technology set D_T; according to the characteristics of organization and operation in the system, we can establish key factor sets and concrete component elements in each kind of factor set. Each element in the factor set must have main functions and features in this kind of set; the integral organization and operation scheme A with different characteristics of the system is created by the cross-combination of basic functional elements in varieties of key factor sets; the evaluation space V and evaluation criteria G of the system are constructed to evaluate different solutions and determine the satisfied system operation scheme A_o. The generalized model S of the system is constructed by the system scheme that consists of target set T and organizational factors set Fi, and the evaluation process of the solving scheme that consists of set V and set G together.

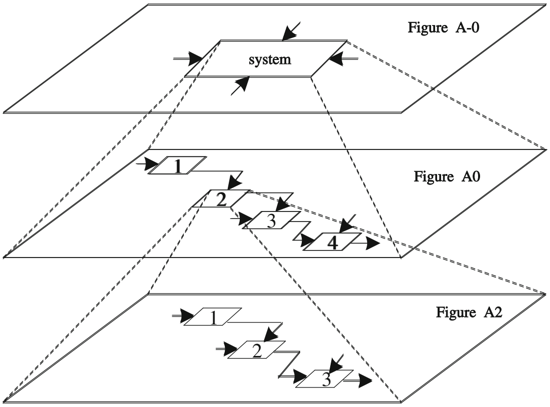
The obtained system model S reflects the relationship of the key elements that make up the system, and any constitutive relationship is on behalf of a state of system constitution. The satisfied relation getting through the evaluation is a selected organization structure, the necessary and sufficient condition of its controllability and stability will reflect the limit of the environment outside the system.

2.2.2.2 IDEF0 and IDEF1X Modeling Method [5–10]

In 1981, the US Air Force published a project—Integrated Computer Aided Manufacturing (ICAM), in which a method named “IDEF” (ICAM Definition Method) was used. The method is applied in the analysis and design of complex systems on the basis of the analysis and design technologies of a structural system. It has five components, from IDEF0 to IDEF5, and involves system function, information and dynamic model, and process description and design method. IDEF0 and IDEF1 have become important tools for establishing the function model and information model of a system through constant improvement and application. These two methods in detail are as follows:

IDEF0. According to a structural method that is decomposed layer by layer from the top to the bottom, IDEF0 describes and establishes the function model of a system using prescriptive figure-type symbols and natural language to characterize,

Fig. 2.4 IDEF0 top-down modeling process



the functional activities and their relationships in the system. IDEF0 is already widely used in the analysis and design of manufacturing systems and computer application systems, and has achieved satisfactory results. The notable features of IDEF0 are that firstly, it describes the system clearly and comprehensively by using simple figure-type symbols and natural language; secondly, it creates a function model by strictly structural decomposition based on layer by layer and from top to bottom. At the same time, it is clear that the difference between system function and system realization is the difference between "what to do" and "how to do it". The integrity and validity of the built model are controlled by the strict division of the staff's work, assessment, document management and other procedures, and the model and recommendation are improved and unified continuously through a repeated review and scrutiny process. The relative results are in pigeonhole management, all of which are beneficial for the user or other personnel in correctly understanding the system and providing complete and correct documentation for the system design.

The modeling process of IDEF0 runs from top to bottom as shown in Fig. 2.4. At the beginning of modeling, IDEF0 uses a box and interface arrows to indicate the origin and the internal and external relations of the whole system, shown as A0 in Fig. 2.4. A single model that expresses the system is then divided into submodules, which are described by boxes, and the link between the submodules or interfaces are denoted by the arrows. Each module could also be similarly broken down into more particular details, as shown in A0 and A2 in Fig. 2.4.

IDEF1X. IDEF0 is used to create a function model of system which reflects the system function or detailed contents and their logic relation, but it does not specify the organization structure and mutual relations of all the information within the system. An information model of the system must be established in order to describe the internal information of the system more comprehensively and exactly. IDEF1X is a useful method for creating the system information model; the information model based on IDEF1X could also be as the main foundation for designing a database system.

IDEF1X based on IDEF1 is a tool for developing a system information model which was published by the project team of the Integrated Information Support System of the US Air Force in 1985. This method expands and improves IDEF1. It has the following characteristics.

IDEF1X is an information model which supports the conceptual model, and is a semantic data modeling technology which supports the concept mode of the database. The perfect IDEF1X model has consistency, expansibility and transformation; the model has a integrated and clear concept set, and expresses information completely and clearly through the entity class, the associated class, attributes and the key class. Each of the classes is further divided into several subclasses. This integral and clear semantic concept set is easy for users to understand and master. The modeling process adopts steps which are extractive and gradual, divided into five stages, and each stage completes a single task that is subsequently decomposed into detail. It provides a rich graphic mark set with clear meaning, thus the expression of the model has more accurate information. This model also stresses the standardized modeling process and provides a set of rules in every stage of modeling so that the modeling work is easy operate and standardize. It also makes the automation of the IDEF1X modeling process possible.

2.2.2.3 GRAI Modeling Method [5, 6]

GRAI can be divided into two parts. One part is to establish a macro view of the top-down decision-making system structure which can be realized by the GRAI grid modeling method. The GRAI grid can clearly express the decision-making functions of each organization in the decision-making system and the mutual relation between them of decision-making and information. The other part of GRAI is to specifically express the operation process of each decision-making center in a bottom-up decision-making system, which can be achieved by the GRAI net modeling method. GRAI net centers on the activities of each decision-making center and describes the conditions, input and output of these activities. Based on these two major modeling tools, it is convenient to use to model a decision-making system.

GRAI grid is a table which is composed of rows and columns. The GRAI row represents the valid period and adjustable period for making decisions, namely, it is the condition of time domain; the columns represent the division of the functions of the decision-making system. Every rectangle formed by crossed rows and columns is a decision-making center. Every decision-making center has its own code (functional code and horizontal code) which will be used in the next step for drawing the GRAI net.

GRAI net is a graphics tool that is used to express the activities of each specific decision-making center. Each decision-making center of the GRAI grid has a corresponding GRAI net to express clearly the formation of their works in further detail. The state of the decision-making center is described with a circle; the resources or supports which depict the conversion of the decision-making center realizing states are described with a rectangle; and the activities which are

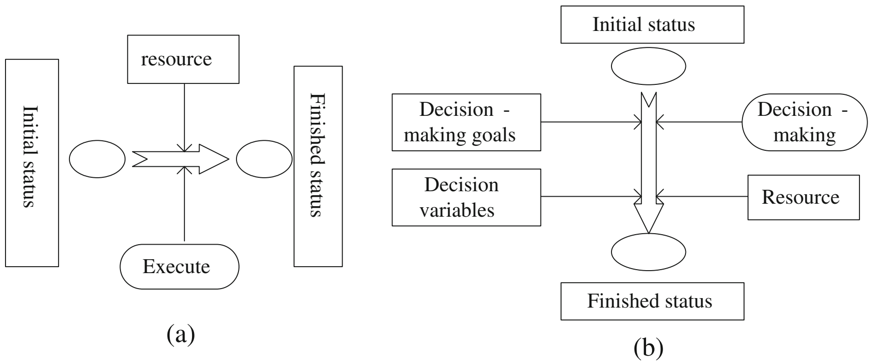


Fig. 2.5 The expressing method of GRAI network activities. (**a**) Executive activities; (**b**) decision-making activities

implemented by the conversion of the decision-making center realizing states are described with a rounded rectangle. Activities are divided into the implemental activities and decision-making activities, as shown in Fig. 2.5. Implemental activities are shown in Fig. 2.5(a). The implemental activities transform a variable from one state into another, which is expressed by using a large transverse arrow. The left side of the arrow is the rectangular box that is the original state, the right is the rectangular box that is the result of the change. The rectangular boxes above and below show the needed and used tools respectively. Decision-making activities are shown in Fig. 2.5(b). The decision-making activities are the primary intelligence of the decision-making center, expressed with a large vertical arrow. The rectangular box above is the basis of the decision-making at the start; the lower one is the result of the decision-making; the right one shows the decision-making support, and the left represents the decision-making variables and decision-making objects. There are logic relations between activities in the decision-making center, and a GRAI net will be formed if the activities are linked by the logical relations. In logical relations, apart from the simple causal relationship (expressed by the arrow), there are some logical symbols: one is the "and" operator, expressed with two parallel vertical lines; the other is the "or" operator, expressed with a vertical line.

GRAI grid and GRAI net, which are the two main parts of the GRAI modeling method, have a close relationship with each other, although their focus is different. Thus, it is necessary to synthesize two methods while modeling the decision-making system. In GRAI, this process becomes the structural process. The structured process is a series of steps to establish the model of the decision-making system, shown in Fig. 2.6. It includes the organization of the modeling team, the establishment of the GRAI grid, the establishment of GRAI net and the result analysis.

GRAI clearly expresses the activities of the decision-making center and their mutual relations, and is an effective modeling method of the process. The GRAI method adapts to analyze the production system and describe the decision-making

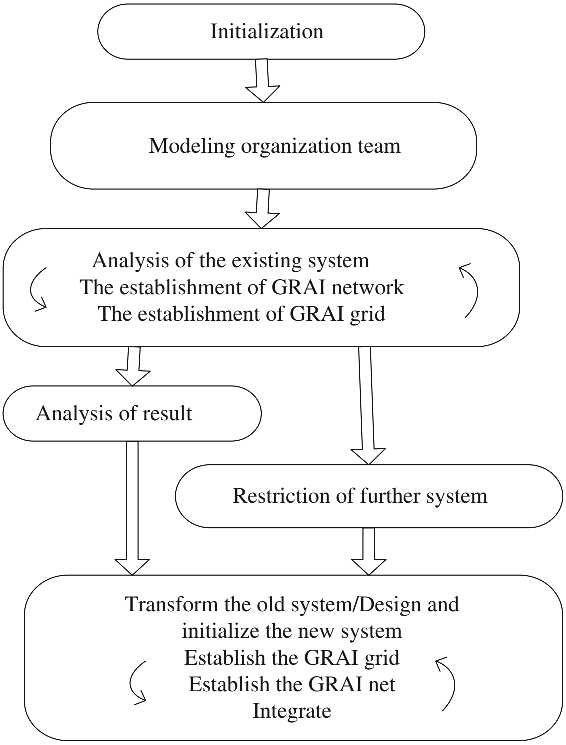


Fig. 2.6 The structured process of GRAI modeling

process of the production system. However, the main purpose of GRAI is to design a decision support system, rather than to design a database system, therefore, it is unsuitable for database design. In addition, it does not introduce timing and realization mechanisms, and is just a logic describing model, so it is difficult to achieve simulation.

2.2.2.4 Petri Net Modeling Method [19]

Petri Net is a modeling tool applied in discrete asynchronous concurrent systems which reveals the dynamic characteristics of a system and other important information by constructing and analyzing Petri Net through practical problems. This modeling method was first proposed by Petri in his doctoral thesis in 1962 [19]. It adapts to graphical and mathematical modeling tools of various systems, and provides powerful means for describing and researching information processing systems with characteristics of parallelism, asynchronism, distribution and randomness and so on. As a graphical tool, Petri Net is regarded as a communication aid method which is similar to data flow diagram and network; as a mathematical tool, it can create state equations, algebraic equations, and other mathematical models describing system operation. Petri Net can be used to research two types of characteristics, one of which is dependent on the initial state and the other of which independent of the initial state: the former refers to the characteristics of the state's behavior, while the latter refers to the characteristics of the structure of the state. The state's behavior characteristics analyzed by Petri Net involve reachability, boundedness, activity, inclusiveness, reversibility, persistency, and so on.

The Petri Net model can be divided into general Petri Net and timing Petri Net. The former is one of the logic models in Discrete Event Dynamic System (DEDS) theory, and the latter is an important timing model in DEDS theory, introducing a timing factor to general Petri Net.

General Petri Net model. General Petri net includes the following contents:

Location set $P : P(P_1, P_2, \ldots, P_n)$ is a limited set of the location point, and represents the state of the system.

Transition set $T : T(T_1, T_2, \ldots, T_m)$ is a limited set of the transition point, and represents events or acts changing system status.

Input $I : I(T_i)$is a subset of P, and represents the set of location point of T_i inputs.

Output $O : O(T_i)$ is a subset of P, and represents the set of location point of T_i outputs.

Tag $\mu : \mu(P_1, P_2, \ldots, P_n)$ is signature vector, and represents the tag distribution of those locations. The transition can only be triggered when every input has a tag after finishing the transition, a tag is taken out from every input and a new tag is produced in every output. In the algebra expression of the Petri Net model, Petri Net is a five element group $G(P, T, I, O, \mu)$ by using the set mentioned above.

In the graphic expression of the Petri Net model, the location set P is marked by "O", and the transition set T is marked by horizontal bar "—" and vertical bar "|", there is a edged "→" for connection of location and transition, marked by a black point, thus "⊙".

Timing Petri Net model. The general Petri Net model clearly describes the logical process of the system, and considers a logical order of the system state and transition, but does not take the time factor into account. Therefore, it cannot analyze the time characteristics of the systems. The timing Petri Net introduces a time factor into the general Petri Net: one is to link a tag on every location with the minimum resident time, referred to as P with timing; the other is to link every transition with duration, that is, T with timing.

Following the introduction of the time factor, the algebraic expression of timing Petri Net is a six element group $G(P, T, I, O, \mu, t)$, of which P, T, I, O, and μ are same as general Petri net, t is time set and the time attribute of transition T.

2.2.2.5 Object-Oriented Modeling Method [12, 13]

Object-oriented technique was formally proposed in the late 1980s, and this technique views the world as a set of independent objects. The object packages operation and data together and provides a limited external interface; its internal implemental details, data structure and their operation are invisible. The objects communicate with each other by message. When an object requests another object for service, the former sends a message to the latter; the latter identifies the message and responds to it in its own appropriate manner.

The characteristics of object-oriented technique emphasize directly mapping the concept of the problem domain to the object and the interface between objects, which is consistent with the usual way of human thinking, and reduces the mapping error from the problem space to the method space in the structural modeling method. After adopting a unified model to express the process from analyzing to designing and to coding, it directly reuses the result of the previous stage, closes the conversion gap from the data flow diagram to the module structure in the structural method, and reduces the mapping error and workload. When the external function changes, it makes the structure of the object relatively stable, and confines the change of object to the inside which decreases the fluctuating effect of the system caused by changes, and makes it easy to extend, modify and maintain. It also has other characteristics, such as inheritance, encapsulation, supporting software reuse, easy expansion and so on, and it could also better adapt to the developing and ever-changing demand in a large system.

Object-oriented system analysis is a common object-oriented modeling method which provides a group of basic modeling concepts and three kinds of OSA models (object relation model, object action model and object interaction model). The system under consideration is described from different angles, such as definition and relationship of the object, action and method of the object, object message transmission and so on, so that a complementary and unified system view is formed. The process of constructing an OSA model is different from the analysis of method drive; it proceeds concurrently with interactional modeling activities, but is not a step-by-step process.

The object relation model of OSA explains the object classes and the relationship between the object classes by using the mark class and object. OSA gives a few of the modeling conceptions for an object relation model as follows:

(1) *Object*. Object is an abstract of the objective world, and is an encapsulation consisting of data and their corresponding operation.
(2) *Object class*. Object class is a set of objects having the same attributes and services.
(3) *Relation*. Relation is a kind of logical connection between objects.
(4) *Relation set*. Relation set is a group of connection, in which each one has the same structure and semantic meaning.
(5) *Constraint*. Constraint is used to describe the other characteristics of the object class and relation set, and consists of basic constraint, participation constraint, concurrent restraint and general constraint. Each has a corresponding and different graphical presentation.

The steps that establish the object relation model are: first, the class and object are marked, namely, the stable class and object are abstracted to be the most basic unit of description of the object-oriented process management by analyzing the conceptual model, the main purpose of which is to make the model more closely fit the conceptual model; second, to establish a relatively stable framework model to describe the relation set between the objects.

The object action model of OSA is used to describe the dynamic structure of each object in the system; that is, to record the perceived state of the object, the conditions under which one state is converted into another state, and the action that object implements and is imposed on. The object action model of OSA uses State Nets to express the method and operation of the object. The main components in the State Nets construction are the model state and transition. State Nets can be looked upon as an action template, and it points out that every instance in an object class has those actions in its template, therefore, concurrency of different objects in the unified object class can be expressed. Because OSA provides the mechanisms of multiple latter state and multiple former state, the concurrency of different actions of a particular object can also be expressed.

The object interaction model of OSA can describe message transfer between objects by combining the object relation model with State Nets to describe the essence of object interaction, action of interaction and message communicated in interaction; in other words, these are services provided by object and message transfer. The basic elements of interaction include the initial object, terminal object and interactive link.

Digital Manufacture is a complex large-scale system and it is necessary to master a set of comprehensive and multi-level modeling methods in order to meet the requirements of manufacturing system development, implementation and optimization. The generalized model is used to establish the global model of the system; IDEF0 and IDEF1X are used to establish the function model and information model; the GRAI modeling method is used to create the corresponding decision-making model; the Petri Net modeling method is applied in establishing the discrete dynamic characteristic analysis model; and the object-oriented modeling method is used in establishing the object model of system. How to choose and use these methods correctly is therefore important for the analysis, design, implementation, operation and optimization of digital manufacturing systems.

2.3 Theory System of Digital Manufacturing Science

2.3.1 Basic Architecture Model of Digital Manufacturing System

According to the issues presented by the architecture of the digital manufacturing system in Sect. 2.1.2, the integral architecture would be constructed by the basic model at its system level, which has great theoretical and practical significance for the development of digital manufacturing science. Because the digital manufacturing system is a complex system, it is hard to describe the global system completely and accurately by using a precise model of system science. The abstract modeling of system science would therefore be used to definitively describe the digital manufacturing system globally in this section. Firstly, the abstract definition of the digital manufacturing system is obtained by using the modeling method of a generalized model. Secondly, according to the definition of the digital manufacturing system and the requirement of a system operation reference mode, the organization model of the digital manufacturing system is constructed through combining relevant theories of management discipline. Thirdly, according to the definition of the digital manufacturing system, and in light of the functional needs of the actual system, a function structure model of the digital manufacturing system will be constructed. Finally, the operation and control structure model will be constituted by combining with the function model, and organization model. The model mentioned above will determine the research object and system architecture of the digital manufacturing system. In practical application, based on this system architecture, the specific contents of each part of the digital manufacturing system could be refined by combining the particular manufacturing contents and distribution characteristics of the members of a practical digital manufacturing system, and using modeling methods such as IDEF, GRAI and Petri Nets.

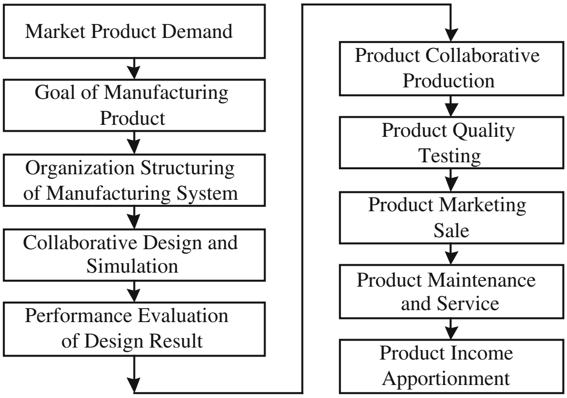
2.3.1.1 The Definition of Digital Manufacturing System

Since the digital manufacturing system is a complex system, it is difficult to describe the global system by using a precise model. In the light of the introduction to Sect. 2.2.1, the abstract model that reflects the characteristics of system can be created by applying a generalized modeling method.

In order to generally understand the digital manufacturing system, it is necessary to analyze the life-cycle of a product. First, the value of product is defined according to the market requirement, and the targets that the new product might achieve are be determined. Second, the techniques and resources for manufacturing the new product are analyzed; if the core competence for the manufacture of the new product is not fully achievable, a virtual manufacturing alliance is created with appropriate manufacturing partners. On this basis, the design, simulation and prototype manufacturing of the product are realized, and the results obtained are then evaluated and amended. The production plan and scheme are then made according to the determined design scheme, and the production process and quality is tested and controlled. Finally, when the product enters the market and is sold, maintenance and service should be provided in accordance with the users' needs until the market goals of the product are completed, and then the next cycle begins. The whole lifecycle is shown in Fig. 2.7.

Based on the above description, considering geographical distribution of the system and its concentration in logic structure, we can abstract the following key factors: suppose that the market's product demand is the system input, and the output is the expected product profit, and suppose that the main compositive elements of the system include the candidate member of the virtual manufacturing alliance, the network supporting equipment for the operation of the principal architecture of the digital manufacturing system, the management software for the operation of network supporting equipment, generalized knowledge (including

Fig. 2.7 Lifecycle of product



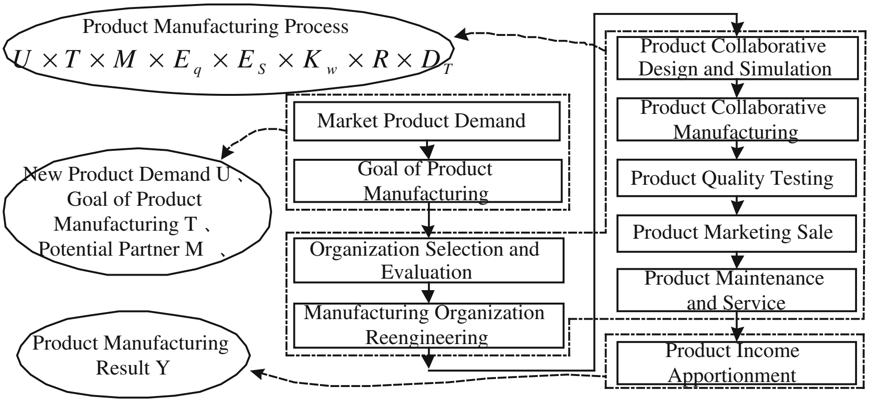


Fig. 2.8 The abstract process of product lifecycle

data, information, rules, methods, etc.), and the distributed resources of digital manufacturing, then any one of the organization, operation and management in digital manufacturing system is a certain combination of the above elements. The abstract process above is shown in Fig. 2.8. Further to the analysis above, the general definition of the digital manufacturing system can be given.

Definition 2.1 Suppose that U is market product demand; M is the member set of potential manufacturing alliance; T is the target set of product manufacturing; E_q is the set of network supporting equipment on system running platform; E_S is the set of software for network supporting equipment; K_w is the set of generalized knowledge; R is the set of product manufacturing resource; D_T is the set of technology supporting digital systems operation; Y is product profit; P is approach solving problem; G is evaluation function; V is evaluation space. The general form of digital manufacturing system is:

$$\mathrm{DMS} = \langle U, M, T, E_{\mathrm{q}}, E_{\mathrm{S}}, K_{\mathrm{w}}, R_{\mathrm{E}}, D_{\mathrm{T}}, P, G \rangle$$

The generalized model is:

$$\left.\begin{array}{l} P : U \times M \times T \times E_{\mathrm{q}} \times E_{\mathrm{S}} \times K_{\mathrm{w}} \times R_{\mathrm{E}} \times D_{\mathrm{T}} \to Y \\ G : U \times M \times T \times E_{\mathrm{q}} \times E_{\mathrm{S}} \times R_{\mathrm{E}} \times K_{\mathrm{w}} \times D_{\mathrm{T}} \times Y \to V \\ S = ((U, M, T, E_{\mathrm{q}}, E_{\mathrm{S}}, K_{\mathrm{w}}, D_{\mathrm{T}}, R_{\mathrm{E}}, Y), P) \end{array}\right\} \tag{2.1}$$

In this equation, S represents the digital manufacturing system.

This definition has the following characteristics. First, the key factors E_{q}, E_{S}, K_{w}, D_{T} reflect that the main feature technology of the system is digital technology, and R_{E} represents the manufacturing system resources. Together, they represent the essential features of the digital manufacturing system and the combination of these factors constitutes a complete digital manufacturing system. Secondly, P which consists of a variety of combination relations of key factors, reflects the diversity and flexibility of the configuration mode of the system, and the general architecture of the whole system with the characteristics mentioned above should be able to adapt to many types of advanced manufacturing systems. Thus, this definition clarifies that the research object of digital manufacturing systems is the manufacturing system with the characteristics of digitalization; the research contents are the detailed constructed contents and changes of key factors, and the system characteristics constructed by these key factors.

In model (2.1), according to the practical operation stage, the different subset can be created by the elements involved in various sets, and the relations between all subsets are able to be assembled into different structures of subsystems. The digital manufacturing system is a complex large-scale system with a number of optimization targets, therefore, it must be described and studied from the viewpoint of system science. The model above shows that the digital manufacturing system is constituted by two or more elements (tache or subsystem) that are different from each other and interrelated. Such correlations construct the structure of the manufacturing system which determines the specialities of the manufacturing system. In addition, the generalized model above provides an analysis foundation for the acquirement of the controllability, accessibility and stability of the system.

Some important inspirations are provided in model (2.1). One is that the system organization structure model should be established according to the key elements of the system composed, and should enhance management effectiveness by breaking away from the bondage of the management mode of entity organization structure. Secondly, to strengthen the openness and compatibility of the system, the system evaluation, decision-making function, system operating process and the knowledge system should be managed at different layers by the function model according to the hierarchical structure. Thirdly, the operation and control structure model should adopt a parallel way of running the multi-function subsystem to improve the stability and operational efficiency of the system. Fourthly, the information resources should be designed, accessed and managed in a unified

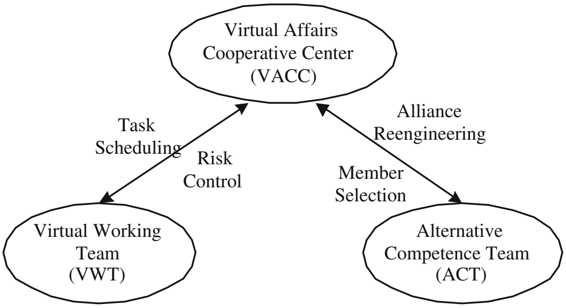


Fig. 2.9 The organization structure model of digital manufacturing system

form, which constructs a generalized knowledge system; the independent access and management of multi-bases in a traditional design are changed to make full use of resources and have rational configuration.

2.3.1.2 Organization Model of Digital Manufacturing System [20]

According to the generalized model of the digital manufacturing system, its organization structure model should be of the constructed in accordance with the key elements of the constructing system and the operation characteristics of the digital manufacturing system, in order to meet the requirements of stability, reliability, expansibility and high efficiency in the operating system.

The composing elements of the digital manufacturing system are: manufacturing target, personnel, manufacturing resources, supporting equipment and technology for operation system platform, generalized knowledge systems and so on. Requirement for the product is first established by analyzing the market, after which the customers are the focus, according to the manufacturing target, personnel are harmonized and resources are scheduled in a scientific management method under the support of network technology and the network environment. Finally, system manufacturing targets will be achieved. The core elements are personnel, knowledge and networks. On the other hand, the organization structure of the digital manufacturing system should also reflect the characteristics of modern manufacturing systems, and its system function could be achieved seamlessly when advanced manufacturing technologies are superimposed on this basic structure and in operation. The common features of advanced manufacturing systems are that they are flexible, parallel, agile and operate in an efficient and stable mode.

A two-layer organization structure model of a digital manufacturing system can therefore be constructed, as shown in Fig. 2.9. This model uses a flat organization management structure, support for which is the network, the means of which is knowledge management and the nucleus of which is the harmonization of human resources.

Figure 2.9 reflects the flexibility, reconfiguration and networks collaboration of the system; its organization structure is in the dynamic changes, and has no fixed entity components, such as a function department on which the traditional entity manufacturing organizations rely, and provides the conditions for the system's rapid response and process reengineering. The core components in this figure either include key elements of virtual organization or embody the characteristics of a virtual organization, and its specific contents are as follows.

Alternative Competence Team (*ACT*). These are the candidates that the sponsor of the virtual manufacturing alliance selects from bidding manufacturing organizations through an evaluation of core competencies. These candidates are divided into different teams in accordance with core competencies, then one or more candidates are selected by each subtask from each team, and an optimal combination is constructed by them in light of the different properties of the task. The outcome is that a Virtual Working Team (VWT) is established at last. ACT has the capability of redundancy to deal with possible risks in the key working procedure.

Virtual Working Team (*VWT*). This is the work team which has the optimal combination from ACT temporarily according to the tasks requirement in the different stages of the chief task. Virtual Working Teams are dissolved after completing the task.

Virtual Affairs Cooperative Center (*VACC*). VACC is the management department of the virtual manufacturing alliance, responsible for the coordination, monitoring and guidance of the ACT, VWT and the entire organizing network, and for outside contact. It is equal to the synthesis of roles, such as the board of directors, general manager and enterprise office in entity organizations.

The VACC is a symbolic representative of virtual manufacturing alliance in Fig. 2.9, and is responsible for the management works, for instance network management, monitoring and coordination of the virtual team. Another very important work of the VACC is that it is responsible for establishing and maintaining internal and external networks, and contacting external business. The thinking behind organizing and establishing a virtual manufacturing alliance is as follows.

Aiming at the market demand for a product, or the market opportunities of customization, the sponsor of the virtual manufacturing alliance, who is able to realize the most core capability of opportunity, posts the demand for partners on the Internet by analyzing market opportunities. After receiving the partners' request, the sponsor evaluates their core competencies and constitutes the ACT and then constitutes the VWT from the ACT through optimized combination according to stage divisions of the task, while other members of the ACT are still in support. On this basis, the VACC is constituted by the VWT; the virtual manufacturing alliance is also constructed by it, along with its management organizations which provides the foundation for the implementation of product manufacturing tasks.

When the manufacturing task is implemented, the VACC is responsible for the task scheduling, coordinating VWT, network management and disposing the exception, and monitors and manages risks of alliance.

After the completion of tasks, VWT is dissolved, all personnel return to their respective ACT and stay in a prepared state. With a new task, the formation of a new VWT or dissolution will be carried out.

The operation process of the virtual manufacturing alliance is shown in Fig. 2.10.

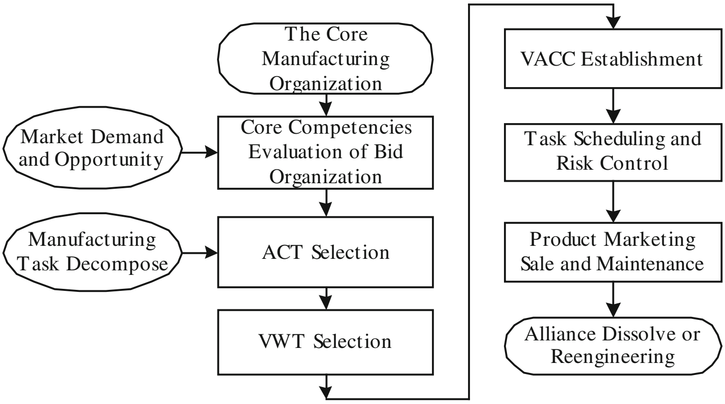


Fig. 2.10 Operation process of virtual manufacturing alliance organization

2.3.1.3 Function Model of Digital Manufacturing System

The purpose of discussing the function model of the digital manufacturing system is to comprehensively analyze the compulsory functions and requirements of digital manufacturing system, to clarify the relationship between the different functions, and to provide direct guidance for the specific design and implementation of the system, which ensures that the operation structure of systems has rationality and robustness. According to the whole lifecycle of product manufacturing, the general function model of the digital manufacturing system can be validated by applying the hierarchy theory of system science and based on an integral model of the system.

As can be seen from model (2.1), the whole digital manufacturing system is a system for solving problems; the market demand of new products is the input, and the benefits obtained by producing the new products is the output. After acquiring the external input information, the integral solution of the system is able to be determined through the generalized knowledge system by the support of the equipment supporting operation platform, supporting techniques and manufacturing resources. A feasible scheme of organization and operation, which is optimal about the entire lifecycle of product, is determined in the evaluation space according to the system evaluation rules. The process of solving problems should be decomposed into different function subsystems which complete the tasks of producing product in different stages. According to hierarchy theory of systems, the problem generation, results evaluation and functions of the organization, decision-making and control of problems should be in the upper layer in the system, and the sub-functions of solving problems should be completed under this layer's guidance. Furthermore, the basic data, methods and knowledge of solving problems and evaluation should come from the corresponding generalized knowledge base of that system, including the database, model base, knowledge base and existing successful decision-making schemes and information base. The organization center and

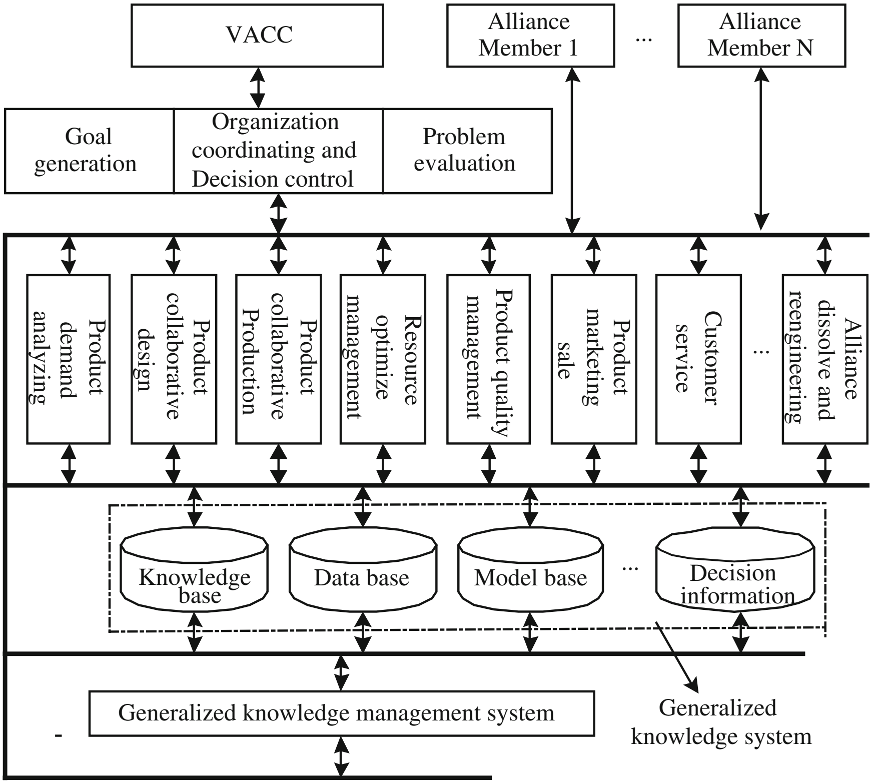


Fig. 2.11 The general function structure model of digital manufacturing system

members are both users, which organize and join the operation and implementation of all functions through the interaction of the system.

Based on the idea above, combined with the integral operation requirements and tasks of the digital manufacturing system, the general function structure model of the digital manufacturing system can be presented, as shown in Fig. 2.11.

In Fig. 2.11, the function of the system is divided into three layers. The first layer is the system management layer constituted by VACC and alliance members. VACC takes charge of the tasks allocation and coordination management of the whole system through three subsystems which are “target generation”, “organization coordination and decision-making control” and “problem evaluation”. The alliance members accomplish the tasks related to their own area through the relevant subsystems in the second layer. The second layer is a layer of problem-solving, constituted by subsystems related to design, production and management of product, and these subsystems work in a parallel way and carry out tasks assigned by the system. The third layer is the generalized knowledge system used to store the manufacturing data, manufacturing methods, relevant models and knowledge of management and manufacture.

Based on the Definition 2.1, the correctness of the model above can be validated by combining with the operating process of the system. The particular contents can be obtained in reference [20]. Moreover, this function model can be constructed by using the IDEF modeling method in the light of the features and demands of a special digital manufacturing system.

2.3.1.4 Information Model of Digital Manufacturing System

The management of the whole system is centralized from a logical point of view, but is a physically distributed form on the topological structure, according to the organization structure model and operation structure model of the digital manufacturing system. The aim of building an information model of the system is to provide reasonable and convenient information storage and use approaches for the optimization of the organization and operation structure mentioned above. Information management can therefore use a management structure with two layers: the inter-domain management of members' information and the intra-domain management of resources information. Here, the domain refers to the management nodes which coordinate and control the nodes of the network members that provides resources for the virtual manufacturing alliance, and the nodes of members domain within the running structure model and their entities are the alliance members and virtual affairs coordination center in the corresponding organization structure, respectively.

The inter-domain information management refers to the basic information of the members' domain node that is managed by the management node, and the whole system forms a virtual organization a logical form according to the information management above; thus, the unified planning and operation control of the whole system can be carried out conveniently. Clearly, the management domain should manage the basic information of the various members domain, including QoS information, registration information, reliability rating, etc., in order to coordinate and control the members in the system. Meanwhile, each member domain also needs to manage the basic information of the management domain, to facilitate the identity testification of the members' domain and management domain and the information transmission of the system.

The intra-domain information management refers to fact that the management domain and the member domain should manage their own resource. The member domain mainly manages the information of the intra-domain resource entity. As the resource entity which one alliance member provides to the virtual alliance may have various types, the resources entity provided should be classified, packaged and managed according to the classification criteria of the whole system resources so as to respond conveniently to the management of the management domain node. In information management inside the management domain, the resource information of the entire virtual alliance system should be considered as a whole for management, therefore, the resources in the whole system should be classified, packaged and managed by using a resources classifier according to the classification criteria.

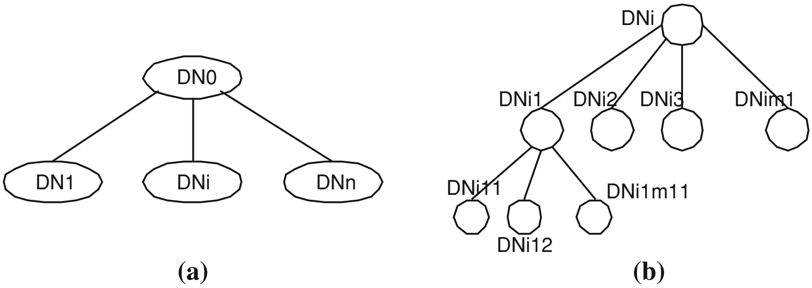


Fig. 2.12 Information structure model of digital manufacturing system. (**a**) The inter-domain information structure; (**b**) the intra-domain information structure

According to the function requirements of information management in the digital manufacturing system, the inter-domain information structure model and intra-domain can be constructed in a two-layer management structure system; together, they constitute the information structure model of the digital manufacturing system and are also the foundation of data structure design while storing specific information of system, as can be seen in Fig. 2.12. The two-layer tree-type structure model of inter-domain information management is shown in Fig. 2.12(a), which is composed of the management domain node (DN0) and the members domain node (DN1…DN*n*). The former is seen as the root node of domain management and the latter as the leaf nodes. This structure is used for the management of the member information of the entire system, which is stored in the information center of VACC. Figure 2.12(b) is the intra-domain information structure model, and DN*i* is the root node of the domain information structure. Assuming the amount of large categories in the system information classification is *m*1, nodes DN*i*1… DN*im*1 in their first layer correspond with the nodes that have the number of *m*1 in this large category. Each large category in the information classification can be further subdivided to construct the nodes of the next category according to the similarity of the information attributes. The leaf nodes in the tree-type structure correspond to the information entities, and each node is composed of a node name and its attributes which represent the particular compositive contents of information entities. The intra-domain information structure model adapts to the management domain and members domain at the same time. The former manages information in the entire system according to the information classification standard, whereas the latter only carries out the corresponding management of resources which are supported for the entire alliance by alliance members according to the system information classification standard.

Taking the resource information management of the digital manufacturing system as an example, a resource information classification criterion of the whole system will be presented according to the lifecycle of the product. Suppose that the system manufacturing resource set R is divided into two major categories: the common resource R_C and the special resources R_S. The common resource can also be divided into human resources R_H and other common system resources R_{OTC}.

The special resources can be further divided into product information resources R_{PI}, information resources of the potential alliance member R_{PMI}, design resources R_{DS} (including design software resources, drawings, documents, etc.), production manufacturing resources R_{PM} (including manufacturing equipment resources and material resources, and the latter corresponding with MRP), customer information resources R_{CI}, other resources R_{OT} and so on. The results of the classification methods above are that the sub-node in the second layer of the intra-domain information structure in digital manufacturing system has two elements, corresponding with two major categories R_{C} and R_{S} in the classification criteria above. The two sub-categories in the third layer include two and six sub-categories respectively. The rest may be deduced by analogy, and each node of the third layer can be divided further in accordance with their different types of the manufacturing product. Specific dividing contents are different according to the different demands of manufactured product, but these nodes should inherit and expand the attributes of their super class. Generally speaking, members of the alliance should have their own resources information management system. These shared resources management mentioned above can be managed in the form of view while participating in the alliance, namely, the original system resources are extracted to be managed separately by the domain according to the virtual alliance resource management standards.

The features of the tree-type information structure model above are as follows:

(1) It is easy to add and delete an information node. When a node is added and deleted, there is no influence on the states of other nodes. Therefore, it is easy for the nodes to join and exit, which guarantees that system functions can be reorganized smoothly.
(2) It is easy to change an information node. When a node moves to the other root node, its sub-nodes will not be changed, which ensures the integrity of the data structure.
(3) The statistics and analysis of historical data will not be affected by the change of nodes. When a node changes, the historical data under the nodes still belongs to the original subsystem, and therefore the results of its statistical analysis will not be influenced.

2.3.1.5 Operation and Control Model of Digital Manufacturing System

The system operation and control structure model is the carrier for implementing the system function and organization structure, and is the basis of designing a specific operation support platform. According to the organization structure of digital manufacturing, the system uses organizations model with two layers, the VACC and the VWT, and the VWT is composed of the alliance members. Therefore, in the actual operation of the virtual enterprise, its organization structure is constituted by a number of running nodes on Internet/Intranet, and these nodes are the VACC and virtual alliance members, as shown in Fig. 2.13.

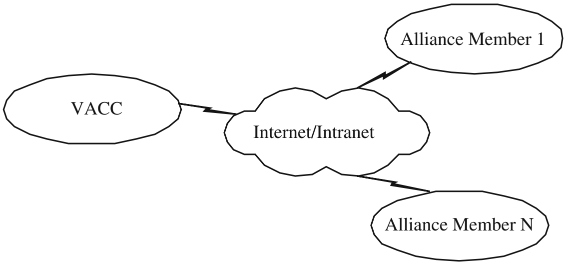


Fig. 2.13 The operation and control structure model of digital manufacturing system

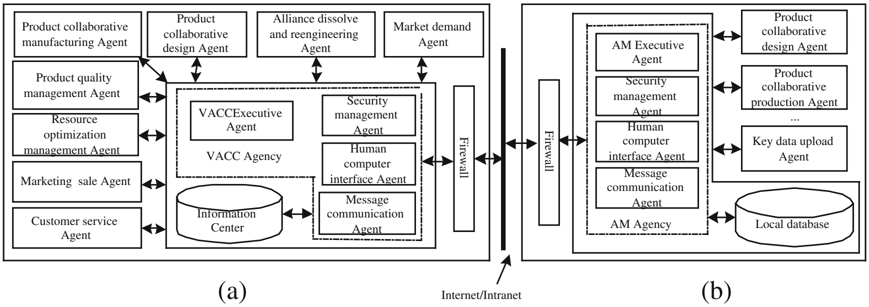


Fig. 2.14 Operation and control structure of Agent-based digital manufacturing system. (**a**) Agent-based VACC; (**b**) Agent-based alliance member

In Fig. 2.13, VACC can be implemented on a network platform, and the platform can be sited at the sponsor's organization of the manufacturing alliance or entrusted to and managed by the Internet agent, while all the members of the manufacturing alliance members operate on their own management platform. The specific implementation of a control function within these nodes and among nodes can be achieved by the application of intelligence Agent technology and grid nodes. Here, the implementation process of the operation and control of system nodes is explained briefly by taking the intelligence Agent as an example.

Multi-agent System (MAS) based on agent is a programming idea and method that has been developed in recent years. Because agents can complete one or several tasks together through organic combination and mutual coordination, they are capable of dealing with problems of environmental complexity and high uncertainty [14, 15]. In recent years, many large MASs, such as internet construction, the balance of complex networks, the realization of network-based mobile software agent, the demand and management for mobile communications, control and management of centralized and distributed system, have appeared and have achieved good practical results. The digital manufacturing system has characteristics of having many objects and complex functions, so it is adaptable to realization by MAS. Figure 2.14 shows the operation and control structure of an agent-based digital manufacturing system, which contains agent-based VACC and the Agent-based alliance members.

The operation and control structure of the Agent-based VACC as shown in Fig. 2.14(a), can be divided into two parts: the VACC agency and the basic function. The former is responsible for the management of the VACC, while the latter takes charge of the implementation of specific business functions and the information center of the VACC. In operation, the two parts are located in the upper and lower levels; the VACC agency lies in the upper level for external contact and internal management, and its specific functions are implemented by the VACC Executive Agent, Message Communication Agent, Human–Computer Interface Agent, and Security Management Agent. Basic functions lie in the lower level, including the Market Product Demand Agent, Alliance Formation and Reorganization Agent, Product Collaborative Design Agent, Product Collaborative Manufacturing Agent, Product Quality Management Agent, Resources Optimization Management Agent, Marketing Agent, Customer Service Agent and other Business Function Agents that correspond to the function of subsystems in Fig. 2.11 and complete their own specific business functions. The information center is responsible for the storage and management of the generalized knowledge in the entire virtual manufacturing alliance, including the common data, evaluation models, computing approach, marketing mode and member information and other kinds of data, models, rules and methods. All these are used for the design, production, operation monitoring, assessment, decision-making and system management, and are the memory center of the whole system.

The operation and control structure of the Agent-based alliance members is shown in Fig. 2.14(b), which can be divided into Alliance Member Agency (AM Agency) and basic functions. The former is responsible for the management of alliance members, and the latter takes charge of the implementation of specific business functions and the information center of alliance members. In practice, the above two parts are also located in the upper and lower two levels; AM Agency is in the upper level for external contact and internal management, and its specific functions are implemented by the Alliance Member Executive Agent, Message Communication Agent, Human–Computer Interface Agent and Security Management Agent. Basic functions lie in the lower level and include Product Collaborative Design Agent, Products Collaborative Manufacturing Agent, Resources and Key business Data Uploading Agent and other business function Agents that correspond to the function subsystems in the function structure diagram and complete their own specific business functions. The local database is responsible for the storage and management of the operation and management information of the alliance members, and meets the needs of local business and the VACC at any time.

The agent-based operation structure has the following characteristics:

(1) *Combination of centralization and distribution*. The entire VACC adopts distributed architecture, which is a node in the network, but the entire digital manufacturing system logically adopts an idea of centralized management . In other words, the VACC is responsible for the unified management of the overall resources and the tasks of virtual enterprises, and the alliance members also have their own management platforms which take charge of the unified

management of local resources and tasks and carry out the execution command of the VACC. The features of this structure are not only convenient for the overall scheduling of the VACC but also beneficial for the independent operation of alliance members.

(2) *Hierarchy of system management and nodes operation*. The whole system has the feature of hierarchical management that is consistent with the feature function structure specifically reflected in the hierarchy division of the operation nodes. Both VACC and Alliance Member are divided into two layers to actualize operation management. In the operation node of the VACC, VACC Agency lies in the upper level and is in charge of external contact and the scheduling of internal functions. Other function agents lie in the lower level and accomplish specific functions of the system. AM Agency lies in the upper level inside alliance member nodes and is responsible for the external contacts and internal operation management of member nodes. The other function agents lie in the lower layer and are responsible for the implementation of specific functions. The hierarchical structure is clear and precise so that the whole system can be easily managed.

(3) *Openness*. Because the system adopts distributed network nodes to operate, the alliance members can be easily added or deleted while reorganizing the system, which increases system stability.

(4) *Maintainability*. Each agent can run as an independent module as a result of using multi-agent technology. Therefore, the corresponding function agent can be diagnosed and maintained when the system is being maintained, which increases the system's maintainability and robustness.

2.3.2 Theory System of Digital Manufacturing Science

As an important part of the global digitalizing wave, the emergence of digital manufacturing brings about a series of profound changes for the core technology of the manufacturing system, equipment, process and products, which have greatly promoted manufacturing technology in the aspects of digitalization, network, intelligence and visualization. Digital manufacturing science is formed by multidisciplines across many fields, such as self-organization theory and synergy theory in system science; the theory and technology of computer networks and computer systems in computer science; the theory and methods of process and system control and intelligence control in automation; the theory of information characteristics transfer and information security in informatics; the theoretical method of design and manufacture of machinery, and the modeling and simulation of mechanical components and electromechanical systems; the theory of the reorganization of enterprise and manufacturing systems, the method of enterprise management and industrial engineering theory in management; bionic mechanics in biology, and more. These subjects provide the theoretic and methodological

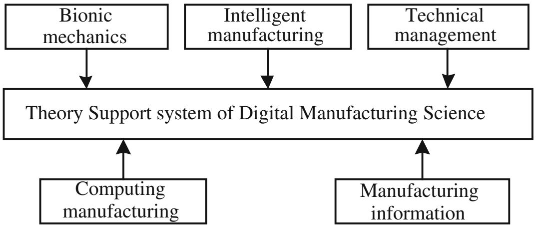


Fig. 2.15 Theory supporting system of digital manufacturing science

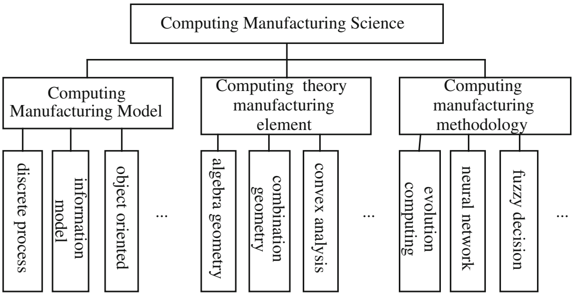


Fig. 2.16 The connotation of computing manufacturing theory

support for the formation of the theoretical system of digital manufacturing science, and its eventual formation of a basic theoretical system comes from manufacturing development and objective demand.

The concept of digital manufacturing indicates that its essence is the digitalization of manufacturing information, that is to say, how to make continuous physical phenomena, fuzzy uncertainty phenomena, physical variables in the manufacturing process and geometrical variables appearing and produced going with manufacturing process, enterprise environment, personal knowledge, experience and capability discrete, so that digitalization can be implemented. The process of discretization and digitalization engenders a series of issues about the theoretical basis, which involves computational manufacturing, manufacturing intelligence, and manufacturing informatics. However the requirement of these basic theories constitute their own discipline within the theoretical system of digital manufacturing science. The overall framework of the theoretical system is shown in Fig. 2.15 [21].

Computational manufacturing and manufacturing informatics are the core of the theoretical basis in digital manufacturing science and the other elements constitute a crucial theoretical support (Fig. 2.15).

The connotation of computational manufacturing covers is shown in Fig. 2.16. It seeks to establish various manufacturing calculation models through calculating the theoretical elements in manufacturing, and the relevant intelligence method used is based on numerical calculation. The digital expression, qualitative or quantitative reasoning and formal processing happens to a series of events in the manufacturing process and manufacturing system, such as the physical variables, geometrical variables, relevant calculating problems and solving complexity by computer. The physical variables include mechanics, thermodynamics, acoustics, vibration, speed, error and so on. The geometric variables consist of processing error and displacement, etc. The calculation problems involve process modeling, control planning, scheduling and management, etc. Ultimately, the various issues in the manufacturing system and process come down to the calculation models that are able to be formal and numerical. Moreover, a manufacturing process with computability, controllability and predictability can be achieved.

Manufacturing informatics pays attention to several relevant scientific issues of the manufacturing process and manufacturing system information; for instance, reasonable representation, optimal configuration and effective operation. The main contents include the principle, attribute, measurement and materialization of manufacturing information and its self-organization and synthesis. In a sense, digital manufacturing is information-driven and the digitalization of manufacturing information makes the manufacturing process and human–computer interaction visible and controllable. The digitalized manufacturing information can be transferred safely by protocol on the WAN, so that we can actualize resources sharing and rapid collaborative manufacture. However, due to the many characteristics in the manufacturing system such as complexity, unconventionality and heterogeneity many scientific issues need to be studied and developed in the future. As shown in Fig. 2.17, this is the main connotation of manufacturing information science.

Manufacturing intelligence mainly researches on artificial intelligence tools and intelligence computing methods (such as expert system, neural network, fuzzy logic and genetic algorithm) in digital manufacturing, and solves the problems of intelligence digital scheduling, intelligence digital design, intelligence digital processing and intelligence digital control, intelligence digital process planning and intelligent digital maintenance and diagnosis in the process of digital manufacturing. Digitalization is the basis of intelligence, and the digital manufacturing system realizing the intelligence enables itself to a new level of artificial intelligence.

Bionic mechanics is an interdisciplinary element of digital manufacturing science and life science. There are strong similarities between the manufacturing process and life process, and between the manufacturing system and life system. Both the manufacturing system and the life system have a lifecycle. The biology copies their basic genetic characteristics to the next generation through genetic inheritance, and the new product produced for the target is often developed on the basis of the old product. The life system and manufacturing system both have a brain (calculating, thinking and controlling system), four limbs (operating system), and nervous system (information system). The life system and manufacturing system are self-organizing and have, self-adaptability, coordination, adaptability to change and intelligence. Almost every element or concept in the manufacturing process, especially in the digital manufacturing process, has its counterpart in the life phenomenon. Therefore, it is apparent that the establishment of a new digital manufacturing mode and the new bionic processing methods and mechanical devices will greatly enrich the connotation of digital manufacturing science as long as life science research results are combined with digital manufacturing science.

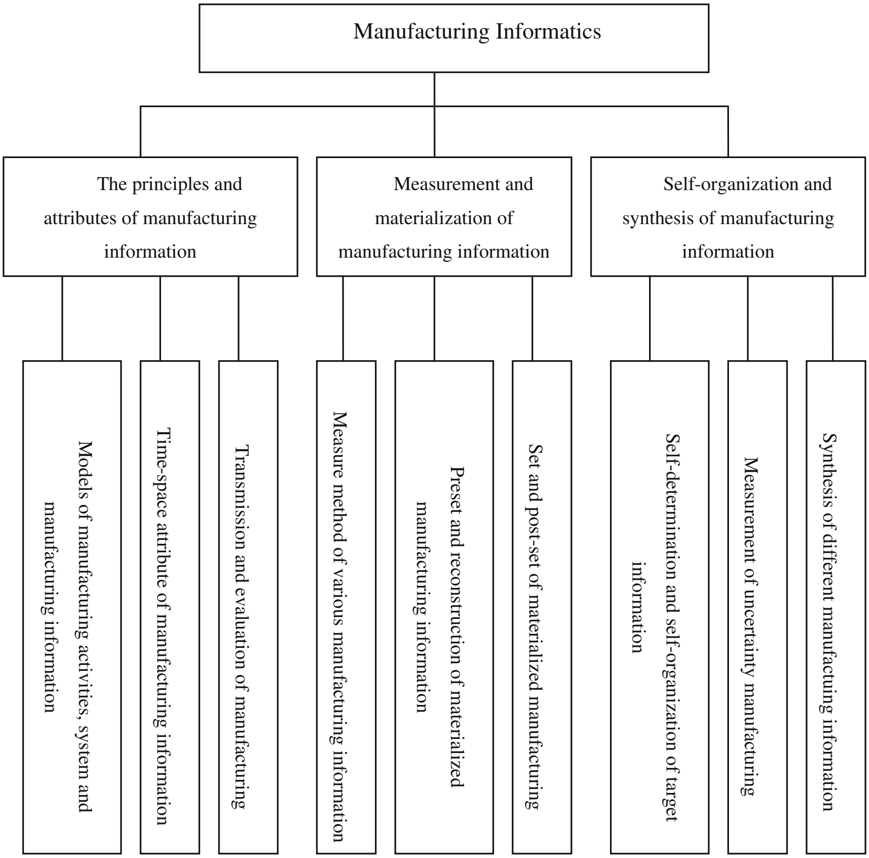


Fig. 2.17 The basic connotation of manufacturing informatics

The management of technology is the fusion of digital manufacturing science and management science. In order to establish a better mechanism of market competition inside and outside digital enterprises, the organization management mode and the management level of digital enterprise must be improved and innovated. This is related to some scientific issues, such the most efficient economic operation of the digital enterprise, production organization and management, cooperation and competition between enterprises, coordination and sharing of digital manufacturing resources, quality assurance system of manufacturing products, mechanisms of rapid response to market and human–computer-environment coordination, and so on. Digital manufacturing science will be further improved if it is closely integrated with the research results of management of technology and social science.

In summary, each part of the theoretical supporting system of digital manufacturing science is constantly being enriched and developed. They support each other and depend on each other, and will continuously develop and improve along with the progress of scientific technology.

2.4 Summary

Digital manufacturing science is a new discipline. In order to construct an integrated system, it must be researched from the aspects of the digital manufacturing process and digital manufacturing system, as well as from the microscopic and macroscopic aspects. This chapter introduces the operation mode and architecture of the digital manufacturing system, which is considered to be a requirement of constructing the theory system of the digital manufacturing system. It goes into detail about the modeling theory of digital manufacturing science and, introduces the critical modeling technologies of digital manufacturing science, which include generalized modeling, IDEF modeling, GRAF modeling, Petri Net modeling, object-oriented modeling and so on. It also establishes the basic model system, including the generalized model, organization model, function model, operation and control model. Lastly, the scientific foundation of digital manufacturing science is discussed and the theoretical supporting system of digital manufacturing science is presented.

Digital manufacturing science is the fundamental discipline of the modern manufacturing system. As a new type of interdisciplinary, constructing its disciplinary system comprehensively is the scientific problem confronted by the modern manufacture. The content of this chapter will be further improved with the constant enrichment and development of the theory and methods of digital manufacture.

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Chapter 3
Computing Manufacturing in Digital Manufacturing Science

Digital manufacturing concerns systematically researching the manufacturing processes, equipment, technology, organization, management, marketing and control of a series of problems from discrete, systematic, dynamic, non-linear and time-varying viewpoints. The discrete and numeral processes involve a series of basic theory problems, such as how to synthetically consider different kinds of computation problems about manufacturing systems and processes with regard to digitization, how to establish formalization representations, construct effective computation models and propose highly effective computational methods, which is one of the basic theory problems that must be researched and solved in digital manufacturing. Computing manufacturing aims to integrate computational geometry, processing principles, sensor information fusion, network control and maintenance and computational intelligence methods by using the computer to represent, compute, reason and process the manufacturing process and manufacturing system (including geometric representation, computation, optimization and reasoning of manufacturing), to solve feature and geometric modeling, reasoning, control, planning, scheduling and management of complex calculation and analysis in the manufacturing process. Thus, computing manufacturing science is the core of digital manufacturing.

Computing manufacturing mainly includes computing manufacturing methodology, a computing manufacturing model and computing manufacturing theoretical units. Its essence is the establishment of various manufacturing computing models. It uses computational geometry and other theoretical foundations, adopts intelligent methods based on a numerical calculation, and applies computers for numeral representation, computation, qualitative reasoning and processing of physical quantities including force, heat, sound, vibration, speed, and error of the manufacturing process and manufacturing system, processing errors and the displacement of geometry, process modeling, control planning, scheduling and management of the relevant calculation and analysis of complex issues. Ultimately, the problems in the manufacturing system and process can be summed

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up as the formal models computed by computers which make the manufacturing system and process computable, controllable and predictable.

From the connotation of computing manufacturing science, the theory, application and research results of computing manufacturing methodology, model and theoretical units are introduced.

3.1 Computing Manufacturing Methodology

Computing manufacturing, through manufacturing system and manufacturing process modeling, qualitative reasoning and quantitative analysis, solves complex parts measurement, assessment, processing path generation, interference checking, space layout, assembly planning, removable and other issues, in order to achieve reconfiguration and scheduling of the manufacturing system, improved product quality, reduced costs and a shortened development cycle. Here, some main methods in computing manufacturing are introduced, including configuration space theory, virtual prototyping and reverse engineering.

3.1.1 C-Space and Screw Space

Configuration space (C-space) is an abstract mathematical structure describing the position and attitude of a robot, processing tools, measuring head, and so on. The position and attitude of the rigid body on the coordinates consolidated with the rigid body of a reference system represent a kind of shape and position. The combination of these shapes and positions forms the C-space [1]. Configuration space theory is an important theoretical basis for positioning and testing in computing manufacturing [2].

3.1.1.1 The Configuration Space Theory Based on Lie Group and Li Algebra

(1) Rigid Euclidean Transformation

The transformation $g : \Re^3 \rightarrow \Re^3$ is called rigid transformation satisfying the following conditions:

(1) Any point $p, q \in \Re^3$, having $| |g(p) - g(q)|| = ||p - q||$;
(2) Any $v, w \in \Re^3$, having $g * (v \times w) = g * (v) \times g * (w)$.

Rigid body movement includes rotation and translation of two parts, as shown in Figs. 3.1 and 3.2. According to agreement, the pan transformation group in one-dimensional, two-dimensional and three-Dimensional Euclidean space are separately recorded as $T(1)$, $T(2)$and $T(3)$. The rotation transformation group in two-

Fig. 3.1 Rigid body rotation transform

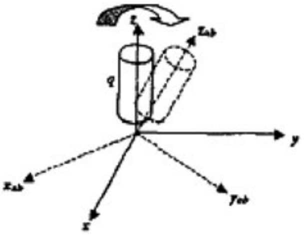
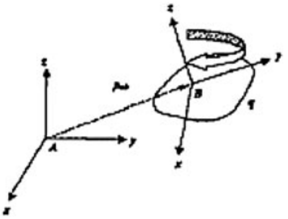


Fig. 3.2 Pan and turn transform of rigid body



dimensional and three-Dimensional Euclidean space are separately recorded as $SO(2)$ and $SO(3)$. The Euclidean transformation in one-dimensional, two-dimensional and three-Dimensional Euclidean space are separately expressed as $SE(1)$, $SE(2)$and $SE(3)$.

As showed in Fig. 3.1, assuming A as inertial coordinate system and B as the dynamic coordinates of the rigid body, $x_{ab}, y_{ab}, z_{ab} \in \Re^3$are the coordinates of the coordinate B relative to the coordinate A. The matrix $R_{ab} = [x_{ab} y_{ab} z_{ab}]$ is called as rotation matrix. Assuming $R \in \Re^{3\times3}$ as rotation matrix, $r_1, r_2, r_3 \in \Re^3$ are its line vectors. Due to the orthogonal feature of line vectors, we have $R^T R = RR^T = I$. The right-handed coordinate system has $r_2 \times r_3 = r_1$, so we know that $R = r_1^T r_1 = 1$. All meeting these two properties 3×3 matrix collection is expressed as $SO(3)$. The definition is:

$$SO(3) = \{R \in \Re^{3\times3} : RR^T = I,\ \det R = +1\} \tag{3.1}$$

According to matrix calculation, $SO(3) \subset \Re^{3\times3}$ is a group meeting the closure, unit, reversible and integration. It is called a 3D rotation group. $SO(3)$ is a 3D Lie group. The rotation transformation meets the two conditions of the rigid transformation.

Assuming that $w \in \Re^3$ represents the unit vector of rotation direction and $\theta \in \Re^3$ represents rotation angle, R can be written as a function of w and θ. That is, $R(w, \theta) = e^{\hat{w}\theta}$. Establishing the mapping:

$$\wedge : R^3 \to so(3) : w = (w_1, w_2, w_3) \mapsto \hat{w} = \begin{pmatrix} 0 & -w_3 & w_2 \\ w_3 & 0 & -w_1 \\ -w_2 & w_1 & 0 \end{pmatrix} \tag{3.2}$$

where, $\hat{w}$ is anti-symmetric matrix meeting $\hat{w}^T = -w$. And

$$e^{\hat{w}\theta} = I + \frac{\hat{w}}{\|w\|}\sin(\|w\|\theta) + \frac{w^2}{\|w\|^2}(1 - \cos(\|w\|\theta)) \tag{3.3}$$

All the anti-symmetric matrices are recorded as $so(3)$ and it is Lie algebra of $SO(3)$. The index of anti-symmetric matrix is the orthogonal. With anti-symmetric matrix $\hat{w} \in so(3)$ and $\theta \in \Re$, we have $e^{\hat{w}\theta} \in SO(3)$. The index transformation is surjection transformation in $SO(3)$. That is, for a given $R \in SO(3)$ letting $w \in \Re^3$, $\|w\| = 1$ and $\theta \in \Re$ making $R = \exp(\hat{w}\theta)$.

The rigid movement in 3-D Euclidean space is shown in Fig. 3.2. We assume the position vector of the origin of the coordinate A to the coordinate B as $p_{ab} \in \Re^3$ and the position and attitude of B related to A as $R_{ab} \in SO(3)$. Knowing the position and attitude of A, the position and attitude of B can be determined by $(p_{ab}\,\text{and}\,R_{ab})$. The system configuration space is the product of $\Re^3$and $SO(3)$, and it is expressed as $SE(3)$. It is called a 3D Euclidean transformation group and is a 3D Lie group. It is expressed as:

$$SE(3) = \{g = (p, R) : p \in \Re^3, R \in SO(3)\} = \Re^3 \times SO(3) \tag{3.4}$$

Any $g \in SE(3)$ meeting the distance invariance and attitude invariance of rigid transformation and assuming $g = (p, R) \in SE(3)$, the homogeneous coordinates are expressed as $\bar{g} = [R, p; 0, 1]$.

Defining

$$se(3) : se(3) = |(v, \hat{w}) : v \in \Re^3, w \in so(3)| \tag{3.5}$$

In an homogeneous coordinate, one element $\hat{\xi} \in se(3)$ can be written as $\hat{\xi} = \begin{pmatrix} \hat{w} & v \\ 0 & 0 \end{pmatrix} \in \Re^{4\times4}$. Elements in $se(3)$ are called a movement screw and $se(3)$ is Lie algebra of $SE(3)$.

(2) Symmetric features and their configuration space

Asymmetric C-space is its Euclidean transformation space $SE(3)$. Symmetrical C-space must be studied using the concept of quotient group. Assuming that $G_0 \subset SE(3)$ is a symmetric sub group of $SE(3)$, the left accompanying collection $SE(3)/G_0 = \{gG_0 | g \in SE(3)\}$on multiplication still constitutes a group called $SE(3)$, the quotient group of G_0. Define the differential structure in $SE(3)/G_0$ and make it as differential streamline of $6\dim(G_0)$. Then make $SE(3)/G_0$ affected by the accompanying function μ of $SE(3)$,

$$\mu : \begin{array}{c} SE(3) \times SE(3)/G_0 \to SE(3)/G_0 \\ (g, hG_0) \mapsto ghG_0 \end{array} \tag{3.6}$$

According to the definition, “the group is affected by the accompanying function of Lie group G to get the differential streamline, which is called the odd

Table 3.1 Common features of the subgroup of symmetry and spatial configuration

Features	G_0	G_0 description	Configuration space C	C^n
$3D$ Point	$SO(3)$	Arbitrary rotation	$SE(3)/G_0 = T(3)$	3
$2D$ Circle	$SO(2)$	Rotation around the center of the circle	$SE(2)/G_0 = T(2)$	2
$2D$ Line	$T(1)$	Translation along a straight line	$SE(2)/G_0$	2
$3D$ Circle	$SO(2)$	Rotation around the axis perpendicular to the center of the circle	$SE(3)/G_0$	5
$3D$ Line	$SO(2) \times T(1)$	Rotation around a straight line and translation along a straight line	$SE(3)/G_0$	4
Sphere	$SO(3)$	Rotation around the center of the sphere	$SE(3)/G_0 = T(3)$	3
Plane	$SE(2)$	Rotation around the normal of the plane and translation in the plane	$SE(3)/G_0$	3
Column	$SO(2) \times T(1)$	Rotation around the axis and translation along the axis direction	$SE(3)/G_0$	4
Conical surface	$SO(2)$	Rotation around the axis	$SE(3)/G_0$	5
Rotary plane	$SO(2)$	Rotation around the axis	$SE(3)/G_0$	5
Fingerprint surface	$T(1)$	Translation along the scanning direction	$SE(3)/G_0$	5
$2D$ asymmetrical curves	I	Unit transform	$SE(2)$	3
$3D$ asymmetrical curves	I	Unit transform	$SE(3)$	6
Asymmetrical free surface	I	Unit transform	$SE(3)$	6

space of Lie group G”. All the odd space of $SE(3)$ is the form $SE(3)/G_0$ of one $G_0 \in SE(3)$, which could represent any C-space. For symmetric C-space, there is the following proposition.

Proposition 3.1 If $se(3)$ is Lie algebra of $SE(3)$ and g_0 is Lie algebra of G_0, then we can choose the mend space M_0 of G_0 to make $g_0 \oplus m_0 = se(3)$, where m_0 is Lie algebra of M_0.

The basic characteristics of Machinery Manufacturing can be divided into symmetrical features and asymmetrical features. Common characteristic G_0, configuration space and configuration space dimension are shown in Table 3.1.

(3) Multi-features and their space configuration

Common parts are the combination of finite basic geometric features. The basic geometric feature is represented by F_i, and G_i is the corresponding symmetric group, and $Ç_i$ is its Lie algebra. According to different applications, the handling of a multi-feature work-piece is also different. For example, when taking the combination of every feature as a whole to realize a function, it needs to be handled as

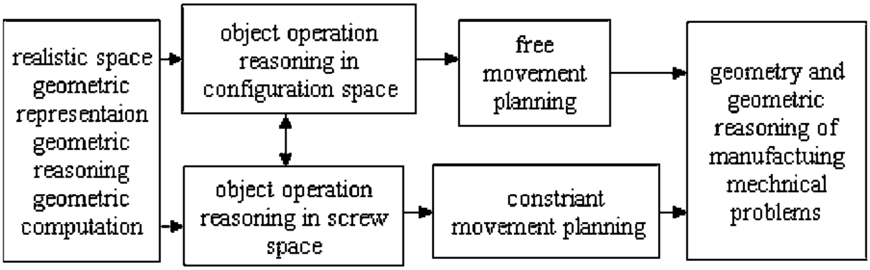


Fig. 3.3 Operation reasoning in C-space and screw space

a combinative feature. The combination of features is defined as the set of every feature $F = \bigcup_{i=1}^{n} F_i$. When every feature needs to be distinguished, every feature must be followed to deal with. For example, considering the differences of the characteristics impacting on the positioning results, the positioning could be in accordance with the descending order of the positioning order. The establishment of benchmarks and error assessment in position tolerance is similar to positioning a problem by order of multi-feature work-piece.

3.1.1.2 Screw Space

Screw space is the tangent space of C-space. It is widely applied in areas that include machine science, robotics, CAD and surface reconstruction and flight control. In the manufacturing system, we should effectively integrate and exchange the operations reasoning information in C-space and screw space to achieve freedom of movement and restraint campaign planning, as shown in Fig. 3.3 [1].

3.1.1.3 Application of C-Space and Screw Space in Manufacturing

The concept of C-space has been widely used in robot motion planning and path planning, such as C-space subdivision and integration in feature-sensitive motion planning, C-space evaluation for mobile robots in large workspaces and Haptic rendering of compliant motions using contact tracking in C-space. The C-space is applicable for solving collision problems. A method of collision avoidance using 2-dimensional C-space in the automatic tool path generation for 5-Axis control machining is devised in Ref. [3]. The objective of the method is 5-axis NC-milling with ball end mills. In the milling operation, the cutter location is represented by the tool center point and the tool-axis vector. The tool center point is obtained by shifting the cutting point in the normal direction at each cutting point by the amount of the tool radius offset, and the tool-axis vector starts from the tool center point. A local orthogonal coordinate system at each cutting point is assumed. At a point in the 2-dimensional C-space, the distance between the point and the origin of the C-space corresponds to the inclination angle θ between the X-axis and the tool-axis vector, and the rotation angle around the origin corresponds to the angle ϕ. Those points in the C-space are called "tool-attitude points", and the whole area of the C-space in which the tool-attitude point can exist is called the "definition area". In particular, in the case in which there is no necessity to consider a collision between the tool and the cutting surface, the definition area is represented by a full circle radius $\pi/2$. By projecting the obstacles onto the C-space, the possibility of collision at each cutting point is clearly represented. The area corresponding to the tool collision is called the "collision area", and the area without collisions is called the "free area". That is, when a collision occurs, the corresponding point in the C-space lies within the collision area. In addition, when the tool contacts obstacles, the tool postures are represented by points on the boundaries of the collision areas.

3.1.2 Virtual Prototyping

3.1.2.1 Introduction to Virtual Prototyping

Virtual prototyping (VP) is an emerging technology and is the simulation of a physical prototype in a virtual environment. Virtual prototyping refers to the analysis of a product without making a physical prototype of the part; a computer model (virtual prototype) allows the user access for observation, analysis and manipulation. This prototype does not necessarily have all the features of the final product but has enough of the key features to allow testing of the product design against the product requirements. It allows people from different technical backgrounds to directly interact with the design of a product and to evaluate its functionality in a virtual environment. Moreover, a virtual prototype can be generated quickly and modified frequently in the early stages of the design process, which means that the designer can consider other alternative designs throughout the design process and make better design decisions. The framework of virtual prototyping is shown as Fig. 3.4.

Compared with traditional design methods based on physical prototypes, virtual prototyping has the following features [4]:

(1) It is a new development mode. Virtual prototyping technology achieves a product optimization perspective from the aspect of system. It is based on concurrent engineering, so that the concept of the product design stage can be rapidly analyzed and various design options compared to determine the impact of sensitive parameters and, through visualization technology design, forecast for products in real conditions and the characteristics of the response, until the optimal performance of the work.

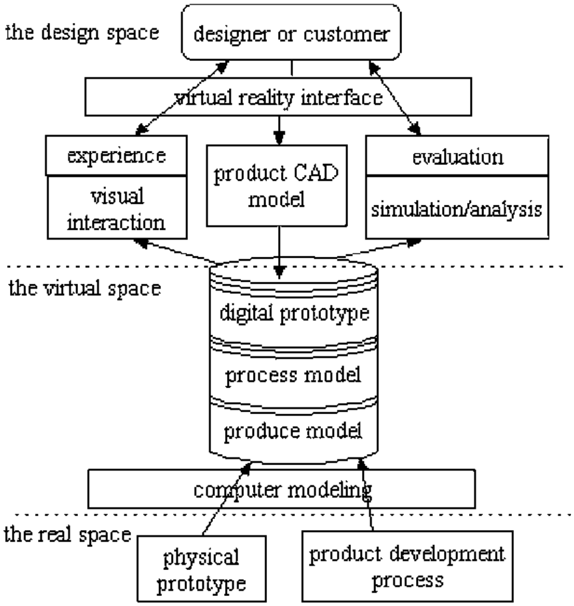


Fig. 3.4 The framework of virtual prototyping

(2) It has lower development costs, shorter development cycles and higher product quality. The establishment of a digital model of a product using computer technology can overcome the cost and time constraints. It can complete the virtual test that a physical prototype cannot, which removes the need for manufacturing and testing a physical prototype to obtain the optimal program. Thus it will not only overcome the cost and time conditions restrictions, but will also shorten the development cycle and improve product quality.

(3) It is an important means to achieve dynamic alliance. A virtual prototype is a digital model. The product information is transmitted through the network with rapid delivery and timely feedback characteristics, thus enabling the dynamic alliance's activities with a high degree of parallelism.

3.1.2.2 Basic Theory of Virtual Prototyping

Virtual prototyping means the process of using virtual prototypes instead of, or in combination with, physical prototypes, for innovating, testing and evaluating specific characteristics of a candidate design. The following aspects are dominant [1, 5].

(1) Product representation and modeling

Virtual prototyping models offer an entirely new perspective, in particular for Internet trading partners, and provide a strong sense of reality and the means to test the model of a product through meaningful interaction. Therefore, in order to

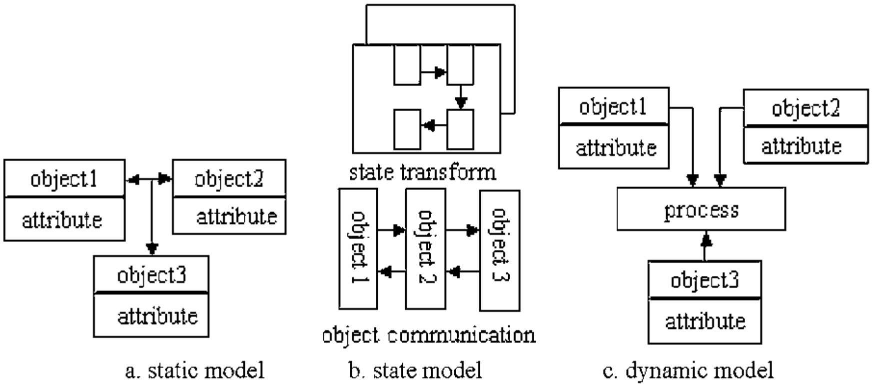


Fig. 3.5 Models in virtual prototyping

integrate the product development process in all activities, the virtual prototype system should establish a comprehensive product data model which includes the product development process in the different types of information. A virtual prototype system contains a number of simulation and analysis applications. Product information must be understood by all applications to meet different application needs entering different abstract levels of product information requirements. At the same time, virtual prototyping is not limited to design evaluation, which involves the manufacturing, production planning, training, marketing and service of all downstream activities, and requires a product model that is suitable for related fields in the form of reasoning.

Zouping et al. [6] point out that the virtual prototype whole model should include a prototype of the static object model, state model and dynamic model, as shown in Fig. 3.5. The static model of the prototype object is the composition of the prototype object, object properties and the links between the objects. It reflects the static object attributes of the current domain. The state model represents the description and other information about the prototype of the current domain and its associated geometry and physical characteristics. The dynamic model is the prototype of objects in a state of the specific content.

(2) Human–machine interaction

The main characteristic of virtual prototyping is using virtual reality in this new interactive mode to allow users to design or image, touch and hear, so that people can truly feel the relevant information about the product's data model as much as possible. To meet the requirements of industrial applications, virtual reality should make breakthroughs in collision detection, on-line analysis/simulation, the advanced visual and interactive ways and new input/output equipment. The human functions involved must be realistically simulated, or a person must be included in the simulation (that is, a real-time operator in the loop simulation).

(3) Simulation and analysis

Product development in the virtual manufacturing system includes the design process simulation, manufacturing process simulation and manufacturing analysis, the design results evaluation, the early feedback from the design process, reducing or avoiding physical changes and reworking. The ideal situation is for all simulation and analysis modules to be integrated in a virtual environment in a plug-and-play manner, and able to run in realtime, but this is restricted by the computer's computing power and resource. At present, the majority of simulations and the analysis of the real-time interactive process cannot be achieved. Even complex geometric visualization of the real-time environment still needs to be further studied.

3.1.2.3 Application of Virtual Prototyping in Manufacturing

Much of the research work on virtual prototyping (VP) and its application has now been done. In the paper titled "Virtual Prototyping" [7], Michael Eccleston used two stories to show that properly modeled 3D simulation techniques can be employed both as a useful risk-management tool and as a tool to fine-tune the final design, especially when planning an investment in a complex, interactive system. This is true not only in the field of manufacturing but also in process systems, transport systems and other service-related activities. VP plays an important role in the design and manufacture of the entire process. Before manufacturing, VP manufacturing is a useful visual means to check the planning and conduct manufacturing, to support the feasibility analysis, and determine the shape, assembly and engineering of the human body. After manufacture of the product, it can analyze the performance of the product and its reliability. VP provides a basic tool for development from the initial concept until the whole process is finished. VP can be used in the product design stage to provide a way to see the results of the design, enabling feedback which can be used to modify the design. VP technology in product manufacturing can therefore play a role as follows:

(1) VP can replace part or even all (in some special circumstances) the demand for physical prototypes. In some cases, a physical prototype is no longer necessary. A computer-aided design (CAD) tool is used to shorten design cycles and reduce costs. Before manufacture, design engineers can easily use VP to modify the design.
(2) Through the provision of testing the design at every stage, VP is able to provide meaningful evaluation of future products for testers.
(3) Through the use of VP, the design of technical requirements, manufacturing performance, maintainability and their realization becomes possible and easy. In addition, for the project's preliminary research and model development, VP provides a program for verifying subsystem "assembly" to support the whole process.

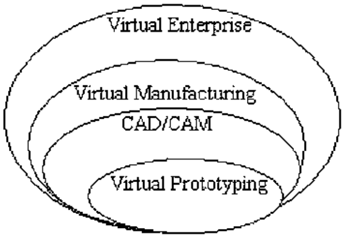


Fig. 3.6 Widening virtual manufacturing towards hyperspace dimensions from virtual manufacturing prototyping to virtual enterprise

3.1.2.4 Virtual Prototyping and Virtual Manufacturing

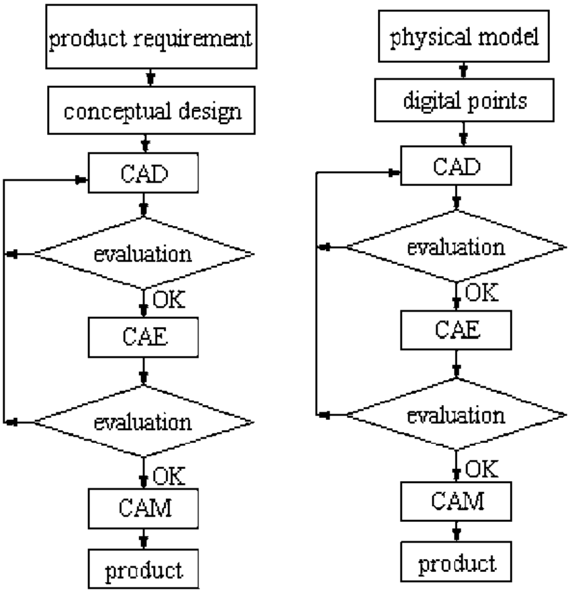
Virtual prototyping aims to use the powerful advantages of virtual reality technology in visual aspects as well as the interactive function of exploring virtual objects to carry out product design, interactive modeling and analysis functions in the aspects of geometry, function and manufacturing. Virtual Manufacturing (VM) may be defined as an integrated, synthetic manufacturing environment to enhance all levels of decision and control. The vision of VM is to provide a capability to "Manufacture in the Computer". This vision could be updated to "Manufacture in networked computers". The virtual manufacturing system (VMS) focuses on the cost of manufacturing products, manufacturing and the benefits and risks, with the goal of product design and manufacturing of the world-class standard. VMS coves the entire product design and manufacturing fields. Figure 3.6 illustrates a widening of virtual manufacturing toward hyperspace dimensions.

3.1.3 Reverse Engineering

3.1.3.1 Introduction to Reverse Engineering

Reverse Engineering (RE), also known as reverse project, is a description of the product design process. In the general concept of engineering and technical personnel, the product design process is a process conducted from scratch. That is, first designing a concept of the product configuration, performance and generally the technical parameters, and then using CAD technology to build a three-dimensional digital product model. It will eventually takes the model into the manufacturing process, to complete the entire design and manufacture of the product cycle. We can call the product design process "forward design". Reverse engineering is a process that analyzes the structure of an existing product in order to recreate that product. It is especially useful for complex, irregular free-form products. It uses 3-D digital measuring instruments to accurately and quickly measure the outline of coordinates, and to build the surface. After revision and edit, the data is transferred to the general CAD/CAM system. The NC tool path generated from the CAM is sent to the CNC machining processing for the required production of the mold, or to a rapid prototyping machine for the production of

Fig. 3.7 Reverse engineering compared with forward engineering



product models or samples. The comparison of reverse engineering and forward engineering is shown in Fig. 3.7 (forward engineering is on the left and reverse engineering on the right).

3.1.3.2 Basic Theory of Reverse Engineering

Reverse engineering consists of three main stages: data measurement, data processing and model reconstruction. The system framework is shown in Fig. 3.8 [8]. Corresponding to these phases of reverse engineering are three basic theories: data measurement theory, data processing theory and model reconstruction.

(1) Data measurement theory

Data measurement is the 3-D digitalization of products. The process is also known as data acquisition and uses digital equipment to measure the prototype surface using three-dimensional coordinates of points. Prototype data measurement has a close relation with many disciplines. With the advent of sensing technology, control technology, computer technology, manufacturing technology, and other related technology development, a variety of data measuring digital technology and digital methods appeared. In accordance with the operation form of the probe and measured work-piece, the methods are classified into contact and non-contact measurement. In accordance with the measurement of whether having been damaged, they are divided into non-destructive and destructive measurement. Contact measurement method often uses a CMM (coordinate measuring machine) or robot to measure. This measurement requires contact with

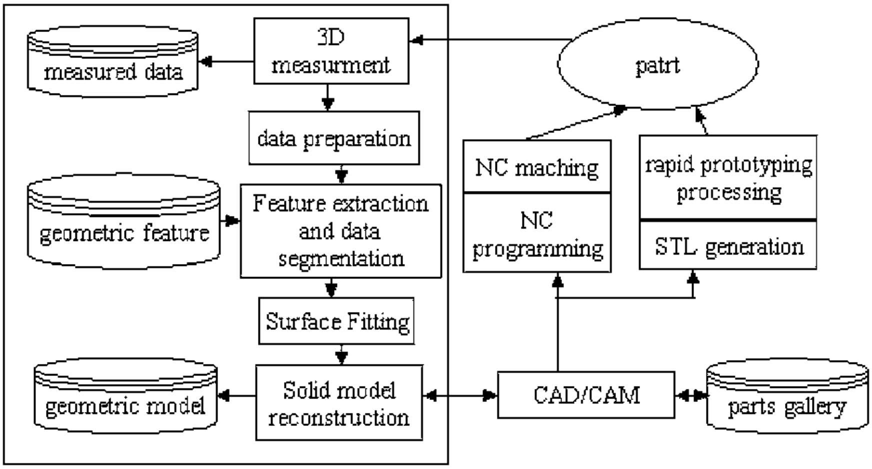


Fig. 3.8 The system framework of products reverse engineering

the surface of detected objects and has high accuracy, but it is slow and restricted to measured material, which is not suitable for measuring soft or easily scratched product. The non-contact measuring method uses sound, light, electricity or magnetic phenomena to measure. While measuring, the product surface has no mechanical contact. The measuring speed is high and operation is simple. It is applicable to the measurements of various quality products. It can be quite intensive in product surface measurement and the large-scale collection of data points. Commonly used non-contact measurement methods are triangular laser projection and grating law. The data measurements and their classification used in reverse engineering are shown in Fig. 3.9. Table 3.2 gives several commonly used methods of measurement [9].

(2) Data processing theory

Survey data processing in reverse engineering occupies a very important position. Data obtained by means of different measurements vary. The data points measured by the CMM or laser scanners and other measurements are usually not among the corresponding display topology, and are only a large group of scattered points. This is the "point cloud" of data. The data need to be pretreated before renewal of the CAD model in order to make it use the CAD software for accurate and fast reverse engineering. Pretreatment includes sorting the data points, the simplification of data points and data points smoothing [8].

(a) Multi-view synthesizing

Multi-view synthesizing generally uses the approach based on reference points or datum mark. There are three ways based on point including the point method, fixed-sphere and plane method. The point method needs to determine three non-line points in the measurement points, which are taken as the detaching standard of the local

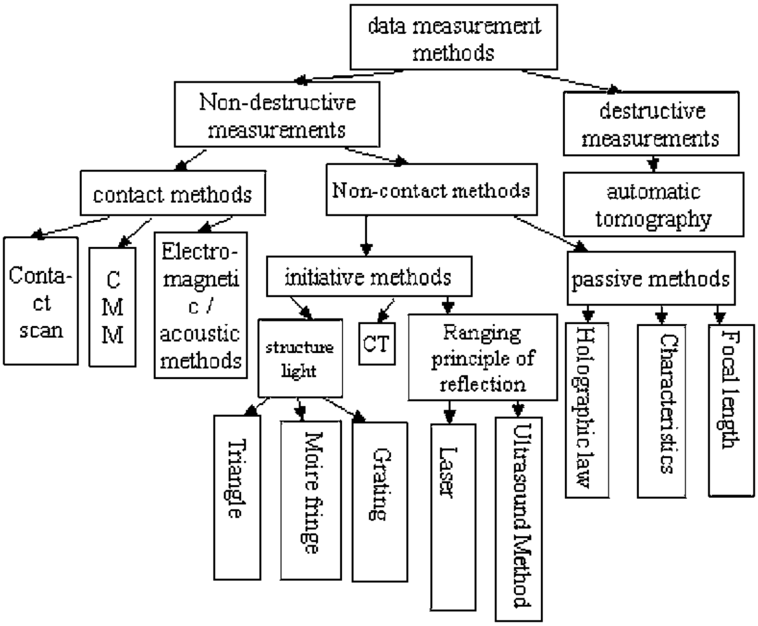


Fig. 3.9 Classification of data measurement in reverse engineering

Table 3.2 Several commonly used comparative methods in reverse engineering

Measurements	Precision	Speed	Data array	Measure within contour	Shape constraint	Material constraint	Cost
CMM	High	Low	Scattered	No	Limited to measuring head size	Hard materials	High
Contact scan	High	Lower	Scanning beam	No	Limited to measuring head size	Hard materials	Higher
Grating	Lower	High	Grid shape	No	Surface flatter	No	Higher
Laser triangle	Higher	High	Related to the light source shape	No	Surface not too smooth	No	Higher
CT	Low	Lower	Section line	Yes	No		Very high
Automatic tomography	Lower	Lower	Section line	Yes	No		Higher

coordinate system. The fixed-sphere method generally associates relatively fixed non-line balls for the measurement of the work-piece. Otherwise, it uses the measured work-piece's own characteristics to measure separately in many multi-view circumstances. The plane method seeks the extension of the normal cross-plane.

(b) Data streamlining and optimizing

Data simplifying is based on the characteristics of a measured "cloud" of data and the actual demand, using different criteria to simplify the huge set of measurement points to simplify and reduce the data processing capacity and improve the efficiency of the surface reconstruction and quality. Streamlining often uses the sampling method and the chords difference. The sampling method by computing the curvature retains fewer points in the flat region and more points in the region having more features. At the same time of simplification, it effectively saves the characteristics. String difference uses the maximum deviation and the largest distance between two points to streamline the point cloud. At the same time, the average or median filtering algorithms of the Gauss standards can be applied to smooth and filter the measured "point cloud" in order to reduce or eliminate the noise effect on quality, following modeling. The small area that cannot be scanned still needs to be filled according to the curvature changes around the point cloud.

(c) Triangle mesh generation and optimization

The point cloud data multi-view that is synthesized and optimized with the multi-lateral model reconstruction technology can be directly generated as a triangular grid model, which is usually saved in STL file format and can be used for rapid prototyping of inputs. In the formation of the STL file, rightly establishing the relationship topology between the points and the formation of films are the key. The basic process is the triangulation of the point cloud data and the goal is to make the scattered data points in space form the optimal triangular grid, as close as possible to Delaunay triangulation. To meet a certain precision, STL data are usually big pet to be optimized to reduce data redundancy. The basic principle of optimization is to reasonably reduce the number of triangle tablets in the relatively flat surface region.

(d) Data segmentation and characteristic curve extraction

For a large number of scattered data points, a surface fitting often does not work. Data will be separated into different regions to be fitted and the surface transition method is then used to splice the surface. There are two ways of splitting: manual and automatic. The automatic segmentation method mainly uses the numerical differential of the point cloud properties and the curvature to extract the boundary or aggregate points. Since the software system in the area of automatic segmentation is limited, a combined manual and automatic split is generally adopted.

(3) Model reconstruction theory

From measuring the point cloud to building a surface is a fitting process. Surface reconstruction is the most complex and the most important part in reverse engineering. The surface modeling mainly uses NURBS surface forms, and some software systems also use Bezier surface-based surface modeling methods. Based on separating data, according to the needs of the cloud features of different regions, a different approach for building surfaces is chosen. The types of point cloud can be broadly classified into regular type, free surface type and mixed type. The regular point cloud is composed of the plane or other simple known geometric shapes. The regular data can be rapidly analyzed using the software analysis functions on the geometric shape. It is then directly used to create the surface or to manually direct modeling. The free surface point cloud can be fitted directly into the point cloud surface, the surface features constructed into the surface, construction of the point cloud and the boundary line. The fixed type includes both regular type and free-surface. The approach taken was in the possible place to directly create a simple plane and geometry. Curve is generated after the creation of the simple geometry. Finally, using plane and curve creates a surface. To ensure the quality and accuracy of the reconstructed surface, it is necessary to conduct surface error analysis and processing. Smoothing is an engineering concept, which is both smooth and pleasing to the eye. 'Smooth' refers to space curves and continuous surfaces and 'pleasing to the eye' is the subjective evaluation of feeling.

3.1.3.3 Application of Reverse Engineering in Digital Manufacturing

With the rapid development of computer technology and CAD technology, reverse engineering technology, measurement-based technology and surface reconstruction technologies have been widely applied in the steam/locomotive, aerospace, footwear, mold and consumer electronics products and other manufacturing industries. The practical application of these technologies in the industrial manufacturing area of reverse engineering includes the following aspects [8]. They are used in the design of new parts, mainly for imitation or modified product design, copying and imitation of parts, and to reproduce the original product design. They are also used in the imitation of complex products, and in the reduction of damaged or worn parts in order to repair or re-use. They are used for product testing, such as product deformation, or welding quality testing, as well as in the analysis of errors between the processed products and its 3-D digital model.

Reverse engineering is a multi-area, multi-disciplinary project. Its implementation requires a high degree of staff and technical coordination, and integration. At present, reverse engineering software is commonly used. Some large CAD software is gradually provided for reverse engineering design module. The development of the software provides the software conditions for the implementation of reverse engineering.

3.2 Manufacturing Computational Model

The manufacturing computational model is a description and representation of the whole or partial practical system in certain forms. Usually, the applied form is simple. There are various describing and representing forms. Thus, the models are different. The simple level of model depends on the level of abstraction of the system. With higher level of abstraction, the system model may be much simpler. Moreover, the level of abstraction of one model is dependent on its practical purpose. The analysis of the whole or partial system can be conducted at different levels or layers. The higher the layer, the higher the level of abstraction, and the corresponding model is much simpler [10].

3.2.1 Discrete Model of Manufacturing Computing

The essential difference of digital manufacturing from conventional manufacturing is that it is the systematic study of manufacturing engineering, equipments, technologies, organization, management, marketing and control via discrete, systematic, kinetic, non-linear, time-varying methods. The essence of digital manufacturing is the digitization of manufacturing information, and the core of digitization is discretization. Its purpose is to discretize the manufacturing continuum of the physical phenomenon, fuzzy or indeterminacy phenomenon, quantity of manufacturing process and geometric sense, condition of business, individual knowledge, experience and capability that emerge in the manufacturing process. The implementation of digital manufacturing is based on discrete models.

3.2.1.1 Discrete Model of Controlled Process in Manufacturing

The practical manufacturing process is composed of dynamic and static elements. Usually, the complex process is analyzed from basic process characteristics. The uppermost research method on process is building a mathematic model to describe the input/output relation [11]. In a specified controlled process equation, input and output or initial value at one time $t = 0$ (or $t = n$), we expect to compute the output after one sampling period that is $t = T$ (or $t = n + T$).

(1) Integral process

The integral process can be defined as:

$$\frac{\mathrm{d}y}{\mathrm{d}t} = kx \tag{3.7}$$

where, x represents input, y represents output and k is proportionality constant. Given $y_{t=0} = y_0$ and when $0 \le t \le T$ inputting the constant value x_0, the corresponding solution of Eq. (3.7) is:

$$y(t) = \int_{-\infty}^{0} kx(t)\mathrm{d}t + \int_{0}^{t} kx_0\mathrm{d}t \tag{3.8}$$

Table 3.3 Basic discrete model of controlled process in manufacturing

Defining equation	Discrete model: the procedure input is constant during the sampling period and T represents the sampling period)
1. $\tau\frac{\mathrm{d}y}{\mathrm{d}t}+y=kx$	$y_{n+1}=e^{-T/\tau}y_n+k(1-e^{-T/\tau})x_n$
2. $\tau\frac{\mathrm{d}^2y}{\mathrm{d}t^2}=kx$	$y_{n+1}=2y_n-y_{n-1}+\frac{kT^2}{2}x_n+\frac{kT^2}{2}x_{n-1}$
3. $\tau\frac{\mathrm{d}^2y}{\mathrm{d}t^2}+\frac{\mathrm{d}y}{\mathrm{d}t}=kx$	$y_{n+1}=a_0y_n+a_1y_{n-1}+b_0x_n+b_1x_{n-1}$
	$a_0=1+e^{-T/\tau};\ b_0=k\left[T-\tau(1-e^{-T/\tau})\right]$
	$a_1=-e^{-T/\tau};\ b_1=-k\left[Te^{-T/\tau}-\tau(1-e^{-T/\tau})\right]$
4. $y(t)=x(t-D)$	$y_n=x_{n-d},\ d={}^D\!/_T$ (the integer or the next largest integer)
5. $\frac{1}{\omega_n^2}\frac{\mathrm{d}^2y}{\mathrm{d}t^2}+\frac{2\xi}{\omega_n}\frac{dy}{dt}+y=kx$	$y_{n+1}=a_0y_n+a_1y_{n-1}+b_0x_n+b_1x_{n-1}$
Over damping ($\xi>1$)	$a_0=e^{P_1T}+e^{P_2T},\ b_0=k\left[1+\frac{P_2e^{P_1T}-P_1e^{P_2T}}{P_1-P_2}\right]$
	$a_1=-e^{(P_1+P_2)T},\ b_1=k\left[e^{(P_1+P_2)T}+\frac{P_2e^{P_2T}-P_1e^{P_1T}}{P_1-P_2}\right]$
	$P_1=-\xi\omega_n+\omega_n\sqrt{\xi^2-1},\ P_2=-\xi\omega_n-\omega_n\sqrt{\xi^2-1}$
Critical damping ($\xi=1$)	$a_0=2e^{-\omega_nT},\ b_0=k(1-e^{-\omega_nT}-\omega_nTe^{-\omega_nT})$
	$a_1=-e^{-2\omega_nT},\ b_1=ke^{-\omega_nT}(e^{-\omega_nT}+\omega_nT-1)$
Low damping ($\xi<1$)	$a_0=2e^{-\xi\omega_nT}\cos\omega_dT,\ a_1=-e^{-2\xi\omega_nT}$
	$b_0=k\left(1-\frac{\xi\omega_n}{\omega_d}e^{-\xi\omega_nT}\sin\omega_dT-e^{-\xi\omega_nT}\cos\omega_dT\right)$
	$b_1=ke^{-\xi\omega_nT}\left(e^{-\xi\omega_nT}+\frac{\xi\omega_n}{\omega_d}\sin\omega_dT-\cos\omega_dT\right)$
	$\omega_d=\omega_n\sqrt{1-\xi^2}$

Doing integral operation and substituting into the initial condition, we have:

$$y(t)=y_0+kx_0t \tag{3.9}$$

To evaluate $t=T$, the Eq. 3.9 could be as the following:

$$y(T)=y_0+kx_0T \tag{3.10}$$

Applying y_n, x_n to substitute y_0, x_0 respectively, and $y_{n+1}$to substitute $y(T)$, we get the first order difference equation as follows:

$$y_{n+1}=y_n+kx_nT \tag{3.11}$$

The integral process expressed by the Eq. 3.11 possesses universal character for auto-control.

(2) First order process, double integration and pure delay process

The defining equations of first order process, double integration and pure delay process and their corresponding discrete models are shown in the Table 3.3.

(3) Other processes

To get discrete models of other processes, we can follow the steps below, which are similar to the above solution procedure. The important precondition is that the procedure input is constant during the sampling period.

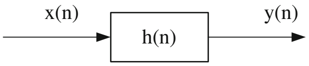


Fig. 3.10 The system transfer function

Step 1: Analyzing the process physical nature to get differential equation;
Step 2: Solving the differential equation to get function about variable t;
Step 3: Making $t = T$ to get discrete solution;
Step 4: Given $y(T) = y_{n+1}$, $y_0 = y_n$ to build discrete model.

3.2.1.2 Discrete Transfer Function and State Variable Method

The system transfer function reflects the relation between its input and output. Its function is to pay close attention to the system's external behavior. The transfer function can be expressed as shown in Fig. 3.10. Its discrete mathematical model is:

$$Y(z) = X(z) * H(z),\ H(z) = \frac{Y(z)}{X(z)} \tag{3.12}$$

where, X(Z), H(Z) and Y(Z), respectively represent Z-transform of system input, system function and output.

In many cases, we are required not only to know the system's external character but also to understand its internal character. The state variable method is used to know the system by combining its internal and external character to create understanding and enable study of the system in depth. Consequently, the analysis and synthesis theory of system are moved up to a new level. A discrete system can be expressed using a state variable method as follows:

$$X(k+1) = AX(k) + BF(k) \tag{3.13}$$

$$Y(k) = CX(k) + DF(k) \tag{3.14}$$

where $X(k)$, $F(k)$and $Y(k)$, respectively represent system state, input and output. Formulas (3.13) and (3.14) are separately called the system state equation and the output equation.

The simple manufacturing process can be analyzed by the transfer function and state variable method. When the manufacturing process is complex and there is interference from noise and other external factors, however, it can only be studied using statistical methods which will be described in the following section.

3.2.1.3 Discrete Model of Computing Intelligence

Computing intelligence is an important researching part of digital manufacturing. It is an intelligence method based on numerical computation, mainly including

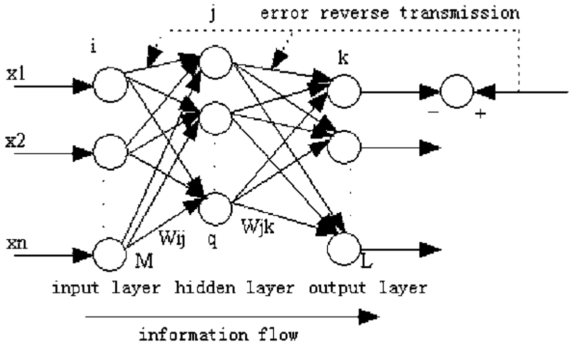


Fig. 3.11 BP training procedure

evolutionary computation, neural networks and fuzzy systems. The flexibility, versatility and tightness of the computing intelligence are clearly superior to knowledge-based artificial intelligence technology.

(1) Neural Network Discrete Model

Neural network is composed of a large number of highly interconnected processing elements (neurons) working in parallel to solve a specific problem. A simple neural network (BP network) is shown in Fig. 3.11.

Mathematically, the neuron model can be expressed as:

$$\sigma_i = \sum_j w_{ij} x_j + s_i - \theta_i \tag{3.15}$$

$$u_i = g(\sigma_i) \tag{3.16}$$

$$y_i = h(u_i) = f(\sigma_i) = f\Big(\sum_j w_{ij} x_j + s_i - \theta_i\Big) \tag{3.17}$$

where x_1, $x_2 \ldots x_n$ are inputs and u_i represents internal state of neuron, θ_i represents the threshold value of the neuron, w_{ij} represents the weight of the j to i interconnection, s_i represents the external teaching or input signal, y_i is the output of the neuron, $f(\cdot)$ is active function and $f = h \times g$. Usually, there are three types of active function:

(1) Linear activation, in which the output activity is proportional to the total weighted output.
(2) Threshold activation, in which the output is set at one of two levels, depending on whether the total input is greater than or less than some threshold value.
(3) Sigmoid activation function, in which the output varies continuously but not linearly as the input changes.

Neural networks have been applied widely in manufacturing problems including diagnostics, tool condition monitoring, design optimization, group technology, collision detection, process modeling and control, flexible

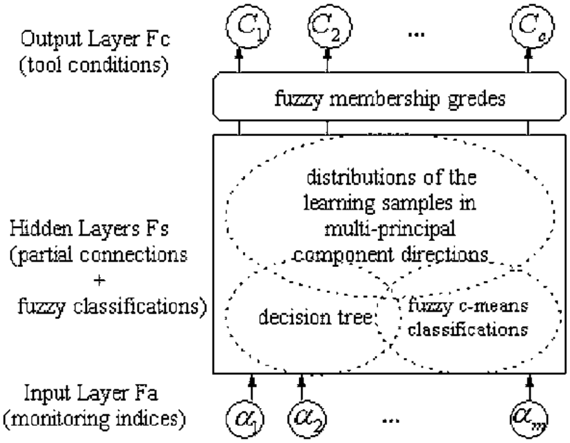


Fig. 3.12 Tool condition monitoring system based on fuzzy neural network

manufacturing control, quality control, robotics, and process planning and scheduling. Here we give several examples to illustrate neural network application in manufacturing.

(1) Tool condition monitoring

The purpose of automated tool condition monitoring in machining is to relate the process signals to the tool conditions, and detect or predict tool failure. Automated tool condition monitoring implies identifying the characteristic changes of the machining process based on the evaluation of process signatures without interrupting normal operations. Figure 3.12 is a tool condition monitoring system structure based on the multiple principal component fuzzy neural network [12].

The input layer, FA $= (\alpha_1, \alpha_2, \ldots, \alpha_m)$, has m processing elements, one for each of the m dimensions of the input pattern x^. The hidden layer of the network, FB, consists of the neurons that use the fuzzy classification to separately address the subsets of the original data set while invoking necessary information from other neurons. The probability distribution and the membership function are used for interconnections within the hidden layer and the connections to the output layer. The neurons of the output layer and FC, represent the degrees to which the input pattern x^ fits within each class.

(2) Process control

The typical example is NN combined with PID controller to realize its self-adapting parameters according to variance of the environment or controlled object. Two types of NN PID controller are shown in Figs. 3.13 and 3.14 [13]. The neural network input corresponds to the selected system state, such as feedback error or the derivative of error and its output is three parameters (k_p, k_i and k_d) of the PID controller.

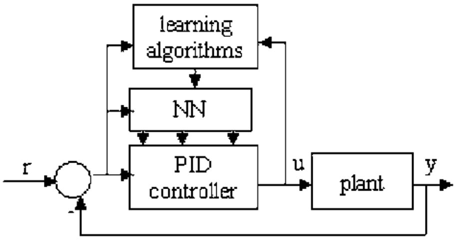


Fig. 3.13 NN PID controller

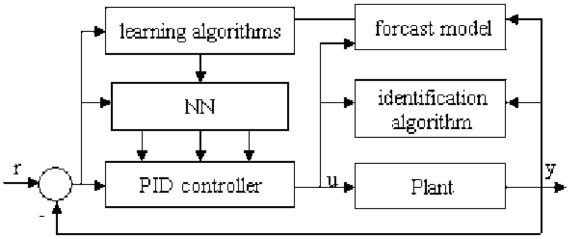


Fig. 3.14 NN PID controller with forecasting model

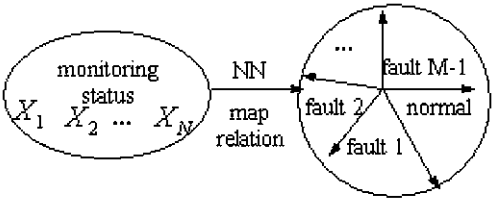


Fig. 3.15 A sketch map of fault diagnosis based on neural network

(3) Diagnosis

Fault diagnosis is virtually the same with pattern classification in that it realizes the mapping from measuring space to fault space. A sketch map of fault diagnosis based on neural network is shown in Fig. 3.15 [14]. In the figure, $X_n = [P_{n1}, P_{n2}..., P_{nj}]$ $(j = 1, 2, ..., J; n = 1, 2, ..., N)$, and P_{nj} represents the number j measured value of the number n set. Suppose there are $M - 1$ kinds of fault in the diagnosed system. To train the neural network, we apply retrieval data which reflect the mapping relation between the measured state and the fault space. Having been trained, the neural network will output the diagnosis result when the measured state data are input in practical diagnosis.

Neural networks are widely applied in digital manufacturing; however, there are some problems in application.

(1) Neural network topology

There is no standard on how to select the optimum NN topology (including NN type, number of layers, number of connections, kind of weight, input function, transfer function, selection of nodes, number of nodes, structure of nodes, scaling of nodes, etc.).

(2) Training data retrieval and training algorithms

These include the number of examples, selection of examples, order of examples, training iterations, learning rate, momentum, initial weight, pattern or epoch training.

How to select or design appropriate neural networks topology, training or learning algorithms and retrieve the training and testing data in applications is a very important scientific problem which affects practical application performance, such as real-time and precision, etc.

(3) Fuzzy logic discrete model

Definition 3.1 (*Membership function of fuzzy set*): In fuzzy sets, each element is mapped to [0, 1] by membership function.

$$\mu_A : X \to [0, 1] \tag{3.18}$$

where [0,1] means real numbers between 0 and 1 (including 0,1). The membership functions of set operations are defined in the same forms as in crisp sets. The operations of fuzzy set include fuzzy complement, fuzzy partition, fuzzy union, fuzzy intersection and other operations.

Definition 3.2 (*Fuzzy Logic*): The fuzzy logic is a logic represented by the fuzzy expression (formula) which satisfies the following:

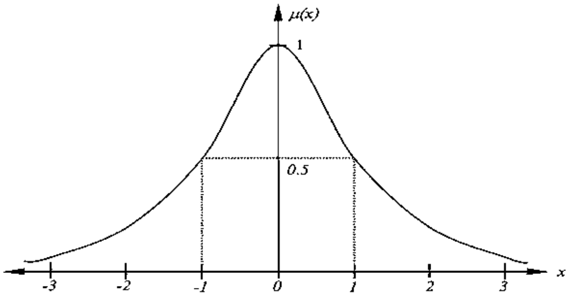
(i) Truth values, 0 and 1, and variable $x_i (\in [0, 1], i = 1, 2, \ldots, n)$ are fuzzy expressions.
(ii) If f is a fuzzy expression, $\bar{f}$ is also a fuzzy expression.
(iii) If f and g are fuzzy expressions, $f \wedge g$ (conjunction) and $f \vee g$ (disjunction) are also fuzzy expressions.

Fuzzy logic is a generalization of classical logic and deals with the ambiguity in the logic. When we consider a variable, in general, it takes numbers as its value. If the variable takes linguistic terms, it is called a "linguistic variable". Fuzzy sets are usually expressed using linguistic variables.

Definition 3.3 (*Linguistic variable*): The linguistic variable is defined by the following quintuple. Linguistic variable $= (x, T(x), U, G, M)$, where x represents name of variable, $T(x)$ represents set of linguistic terms which can be a value of the variable, U means set of universe of discourse which defines the characteristics of the variable, G is syntactic grammar which produces terms in $T(x)$ and M is semantic rules which map terms in $T(x)$ to fuzzy sets in U.

In solving practical problems, we may give express fuzzy sets using linguistic sets, such as {NB, NM, NS, ZO, PS, PM and PB}, where NB, NM, NS, ZO, PS, PM and PB separately represent Negative Big, Negative Middle, Negative Small, Zero, Positive Small, Positive Middle and Positive Big. The membership function of fuzzy set "zero" may be as shown in Fig. 3.16.

Fig. 3.16 Membership function of fuzzy set "zero"



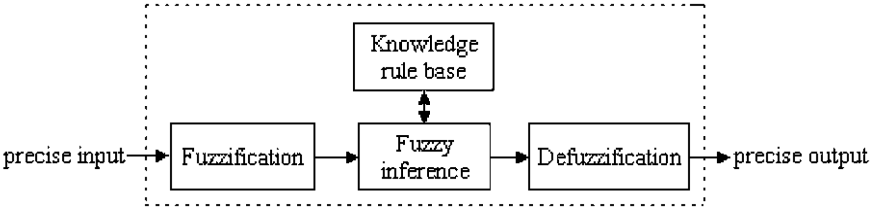


Fig. 3.17 Accurate/exact/vague

The core idea of fuzzy logic or computing used in an application can be described as in Fig. 3.17. There are three important parts.

(1) Fuzzification. This maps a precise input to a fuzzy set and assigns the input precise value to a fuzzy variable such as "PB, PM, etc.".
(2) Fuzzy inference and knowledge rule base. This comes from the prior knowledge or experience of experts or engineers in the applied field which has been accumulated through long experience. Using the decision rules composed of fuzzy rules that represent the fuzzy relation between input and output, fuzzy inference calculates the fuzzy output. In general, the "inference" is a process to obtain new information by using existing knowledge. The representation of knowledge is an important issue in the inference. When we consider the representation methods, the following rule type "if–then" is the most popular form, such as "If x is a, then y is b". When we consider fuzzy rules, the general form is given as follows:

$$\text{If } x \text{ is } A, \ \text{then } y \text{ is } B.$$

The fuzzy rule may include fuzzy predicates in the antecedent and consequent, and it can be rewritten in the form.

$$\text{If } A(x), \ \text{then } B(y)$$

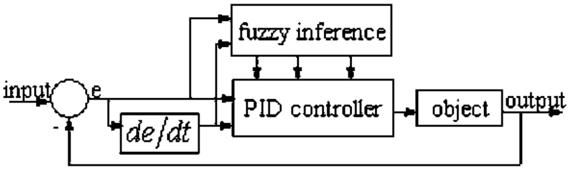


Fig. 3.18 A self-tuning controller using fuzzy logic combined with PID controller

This rule can be represented by a relation R(x, y).

$R(x, y):$ If $A(x)$, then $B(y)$ or $R(x, y): A(x) \rightarrow B(y)$.

If there is a rule and facts involving fuzzy sets, we can execute two types of reasoning.

(1) Generalized modus ponens (GMP)

Fact: *x* is *A*’	$R(x)$
Rule: If *x* is *A* then *y* is *B*	$R(x, y)$
Result: *y* is *B*’	$R(y) = R(x)\ o\ R(x, y)$

(2) Generalized modus tollens (GMT)

Fact: *y* is *B*’	$R(y)$
Rule: If *x* is *A* then *y* is *B*	$R(x, y)$
Result: *x* is *A*’	$R(x) = R(y)\ o\ R(x, y)$

(3) Defuzzification. This translates fuzzy set into precise or deterministic output. Three defuzzification methods are usually available, i.e., center of gravity (COG), average of maximum (AOM) and the modified center of gravity (MCOG).

Fuzzy logic has been widely used in manufacturing including manufacturing process control and decision support systems in manufacturing such as working order and tool selection.

(1) Manufacturing process control

In manufacturing, there are many industry processes which do not permit the accurate mathematical modeling required for classical control theory, or the controlled system is dynamic, complex and nonlinear. A fuzzy logic scheme can be used to realize self-organizing controllers. A detailed example of fuzzy logic applied in the process of manufacturing is given. It is a self-tuning controller using fuzzy logic combined with a conventional PID controller as shown in Fig. 3.18. It is based on the PID control algorithm and accepts error (*e*) and variance of error

EC	=	GA	+	ES	+	EP	+	GP
Evolutionary Computing		Genetic Algorithms		Evolution Strategies		Evolutionary Programming		Genetic Programming
		(Holland, 1975)		(Rechenberg, 1973)		(Fogel, Owens, Walsh, 1966)		(Koza, 1992)

Fig. 3.19 The evolutionary equation

(*ec*) as inputs. Then it uses fuzzy rules to do fuzzy inference and queries fuzzy matrix to tune parameters in order to realize the online automatic tuning of PID parameters. The automatic tuning of PID parameters is to find out the fuzzy relation between three parameters (K_P, K_I, and K_D) and *e* and *ec*. The core part of fuzzy control is to sum up the techniques and practical operation experiences of project designers and to construct appropriate fuzzy control rules separately about parameters K_P, K_I, and K_D.

(2) Fuzzy decision support system in manufacturing

Jiang and Chi-Hsing [15] developed a manufacturability evaluation model and provided a systematic way to analyze manufacturability in the concurrent engineering environment based on fuzzy multiple attribute decision-making (FMADM) methodology. The integrated decision model involves the multi-level and multi-goal requirements of manufacturing. It also considers the functional integration of the total life cycle of the product. An example of high-pressure vessel manufacturing is used to illustrate the proposed model.

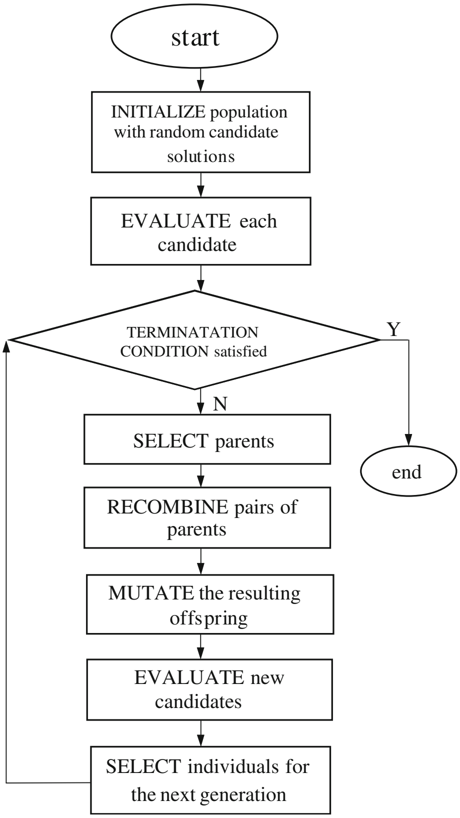
The principal advantage of fuzzy logic is the possibility of studying vague problems. On the other hand, the disadvantage of fuzzy logic in application is the need for an expert's knowledge accumulated through long experience to build the knowledge base manually. It does not have the ability to learn, so in many applications, we can see a fusion of the fuzzy system and neural networks or genetic algorithms.

(3) Evolutionary Computation Discrete Model

Evolutionary Computation (EC) is the general term for several computational techniques which are based to some degree on the evolution of biological life in the natural world. These techniques can be classified into three main categories as shown in Fig. 3.19 [16, 17]. The classification is based on some details and historical development facts rather than on major functioning differences. In fact, their biological basis is essentially the same. The most widely used form of evolutionary computation is genetic algorithms (GA). The general scheme of an Evolutionary Algorithm (EA) is as shown in Fig. 3.20 in the flow chart.

Any evolutionary algorithm is composed of a set of common elements in spite of its differences with respect to other EC algorithms. The most important among these common elements are as follows:

Fig. 3.20 The general scheme of an Evolutionary Algorithm in a flow chart



(1) A population of N strings to work with. The first step in defining an EA is to link the "digital manufacturing real world" to the "EA world" that is, to set up a bridge between the original problem context and the problem solving space where evolution will take place. Objects forming possible solutions within the original problem context are referred to as phenotypes, and their encoding or representation, the individuals within the EA, are called genotypes.

One common approach is to encode solutions as binary strings: sequences of 1's and 0's, where the digit at each position represents the value of some aspect of the solution. Another, similar approach is to encode solutions as arrays of integers or decimal numbers, with each position again representing some particular aspect of the solution. A third approach is to represent individuals in a GA as strings of letters, where each letter again stands for a specific aspect of the solution.

(2) A fitness function to be optimized (either maximization or minimization) for evaluation of a string. It is usual for the fitness function to be called "the environment".

(3) Some selection mechanism in order to simulate the survival of the fittest strings. The types of selection include Elitist selection, Fitness-proportionate selection, Roulette-wheel selection, Scaling selection, Tournament selection, Rank selection, Generational selection, Steady-state selection, and Hierarchical selection.
(4) Some replacement policy in order to keep population size constant. This is normally achieved by replacing the worst individual in the population.
(5) Nature-inspired operators for changing a string into a new string. Such an operator is very frequently a mutation operation (replace a gene by another random gene). Another operator typically found in genetic algorithms is the crossover operator that crosses slices of two strings in order to compute two new strings.

The first and most important point of evolutionary algorithms is intrinsically parallel. Due to the parallelism that allows them to implicitly evaluate many schemas at once, EAs are particularly well-suited for solving problems where the space of all potential solutions is truly huge - too vast to search exhaustively in any reasonable amount of time. Another notable strength of EAs is that they perform well in problems for which the fitness landscape is complex - problems in which the fitness function is discontinuous, noisy, changes over time or has many local optima. EAs can manipulate many parameters simultaneously and know nothing about the problems they are deployed to solve.

Evolutionary Computation is used for manufacturing in the following aspects:

(1) Scheduling and planning in the production process and path planning, such as the job-shop scheduling problem, the flow-shop scheduling problem, the dynamic scheduling problem and process planning, scheduling and planning of flexible transportation.
(2) Optimization in production research, such as optimization problems in cellular manufacturing, optimization of assembly lines, design optimization problems, production planning and control and flexible manufacturing systems.
(3) Manufacturing-related optimization. Evolutionary computation is developed in various manufacturing areas including PID and fuzzy controllers, selection of machining parameters for constrained machining problems, process model identification, machine failure and maintenance, quality control and advanced manufacturing optimization problems such as the problem of designing an optimal integrated production—inventory-distribution system.

In addition, EC is considered to be one of the three most suitable methods, along with chaos theory and fractal geometry, for researching non-linear and complex systems because of its adaptivity, self-learning, parallelism and other characteristics. Evolutionary computation based on natural mutation and natural selection of biological evolution thinking allows a complex manufacturing system to be described as a model of biological evolution, by the use of its reorganization, adaptive and evolutionary characteristics, to study the dynamic reorganization and acts of self-organization in manufacturing systems. However, the following problems are faced in its practical application:

1. The terminology of evolutionary computation is vague for the manufacturing engineer. Despite the fact that the driving logic of evolutionary algorithms is amazingly simple and efficient, the terminology inherited from genetics predisposes manufacturing engineers to think the opposite.
2. Evolutionary computation is a relatively new technique, evolving to deal with more complex real-life problems.
3. There is no standard evolutionary computation toolkit that can be used easily by manufacturing people who are not familiar with evolutionary concepts.

On the other hand, evolutionary computation methods offer solutions that combine computational efficiency and good performance. This significant feature will certainly continue to attract the interest of engineers.

3.2.1.4 Other Discrete Model

Other discrete models include Discrete Time Markov Chain (DTMC), Petri net, Queuing Theory, stochastic state-charts and Discrete Event System Model. They are also widely used in the analysis and design of a manufacturing system or process, such as in reference [18–20].

3.2.2 Information Model of Manufacturing Computing

3.2.2.1 Introduction to Information Model of Manufacturing Computing

The subjects of informatics are used at three levels of manufacturing systems or in manufacturing processes. At the lowest level, many control computers regulate a single production process; at the middle level they control, analyze and test a group of production processes with a common factor; and finally, at the upper level of the manufacturing process, they support planning, business activities, logistics, management and many other high-level manufacturing activities. All the above-mentioned activities must be carefully projected by means of information engineering. An information model in manufacturing provides a sharable, stable and organized representation of information in a selected domain area. The specification of the information model defines elements, attributes, constraints and relationship between elements for the domain context.

3.2.2.2 Information Model of Product Whole Life Cycle

In the information model of manufacturing computing, the product information model is very important because the product is the core of manufacturing and

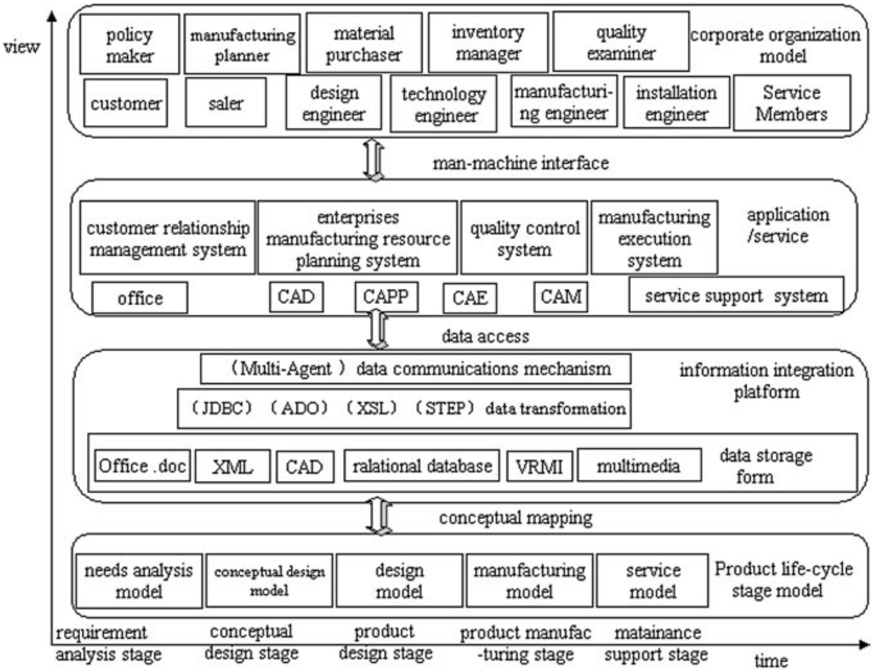


Fig. 3.21 The system framework of product lifecycle model

digital manufacturing. Product is the main target and the ultimate goal to pursue in the manufacturing activity. The product life cycle framework of the system is shown in Fig. 3.21. There are five different stages in the product life cycle, including needs analysis, conceptual design, engineering design, manufacturing and service support. At each stage of the corresponding information models are the product demand model, conceptual model, design model, manufacturing model and service support model, which compose the product information model. The product demand analysis model describes the demand of the customer or market on product functions, performance, usage environment and so on. It is the foundation of product innovation, improving customer satisfaction and realizing the rapid development of products. The product conceptual model describes the conceptual products in the minds of design engineers, including product functions, principle and structure information, the design, manufacture and assembly information of the basic components, cost information and its maintenance services. The product design model includes product geometry information with CAD files as the core and relation data expressed by the concept of the object, and it is the core model of the product life-cycle model. The product manufacturing model, based upon the design model, focuses on describing the necessary information in the manufacturing process, such as materials, processing technology, the assembly sequence and so on. The product service model mainly describes information

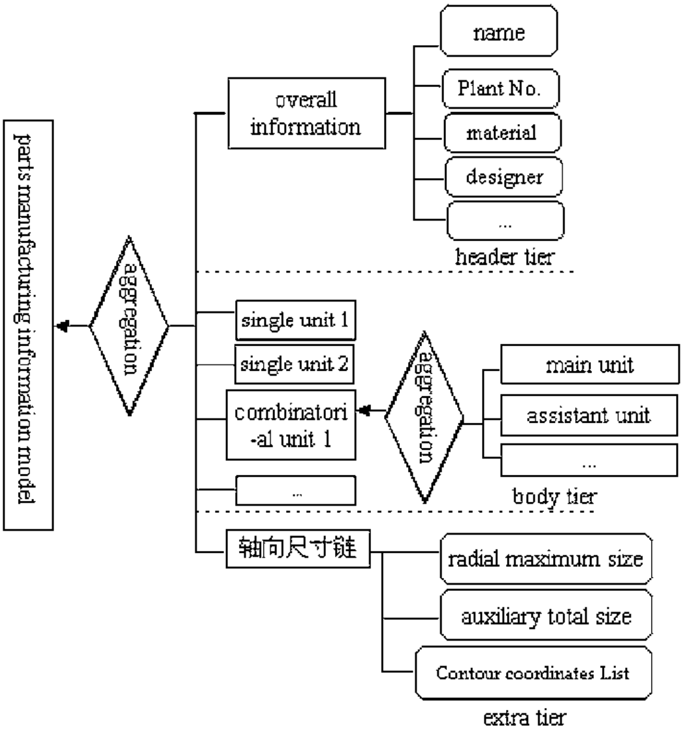
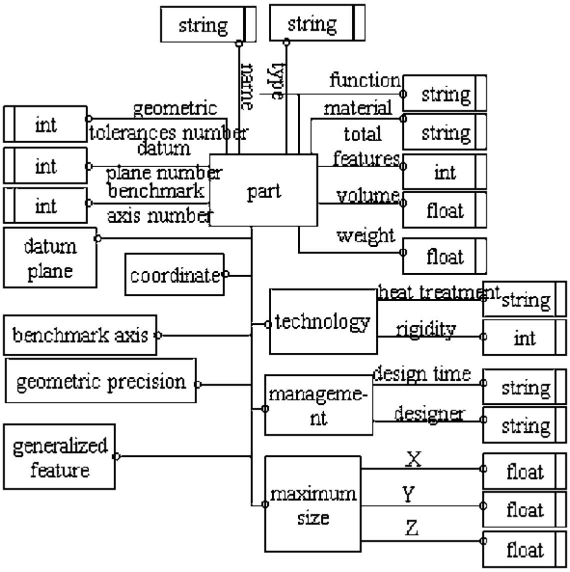


Fig. 3.22 Parts manufacturing information EER model of processing unit

about the delivery state, installation, usage, training, diagnosis and maintenance service [21]. At present, there are three types of product information model: the geometry-oriented model, feature-oriented model and integrated product information model. They represent the product model and the relevant modeling technique from simple to complex, from local to global, and from single function to covering the whole life cycle process.

Parts are the basic component unit and basic processing unit of a product. The parts information model is the medium used by the Integrated Manufacturing System (CIMS) to transmit information between the CAD, CAPP and CAM. It is also used to resolve the exchange and reunification of the geometry, technology and resources information of parts in the manufacturing process. Parts information includes management information (type, name, materials, number, bulk, designers, etc.), geometric information (geometric shape and size) and technology information (rough features, parts materials, precision machining, surface roughness, heat treatment, surface treatment, and meshing relations, etc.) [22]. Figure 3.22 exploits the ERR method to establish the manufacturing information model of a part, which includes the geometric information, technology information and processing resources of parts. Figure 3.23 is a part information model based on generalized features and built by applying EXPRESS- G [23]. The information includes the

Fig. 3.23 Part information model based on generalized feature



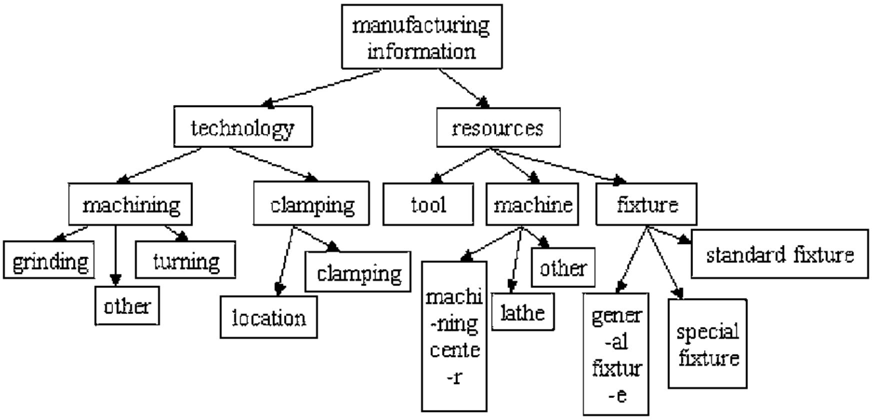


Fig. 3.24 Manufacturing technology resources

part name, type, function, material, volume, weight, feature set, position tolerance set, reference axis set, datum plane set, frame axes of the part, designer, designing time, heat treatment mode and rigidity and generalized feature set.

3.2.2.3 Information Model of Manufacturing Technology Resources

Manufacturing technology resources include manufacturing resources and manufacturing technology, as shown in Fig. 3.24. Manufacturing technology resources

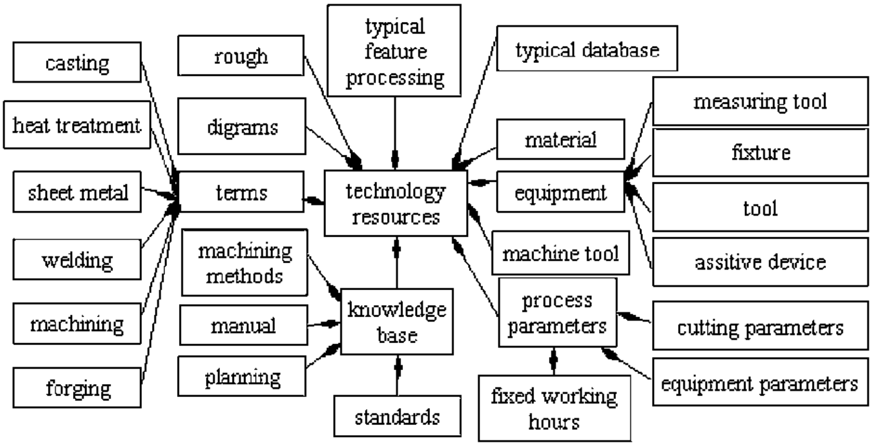
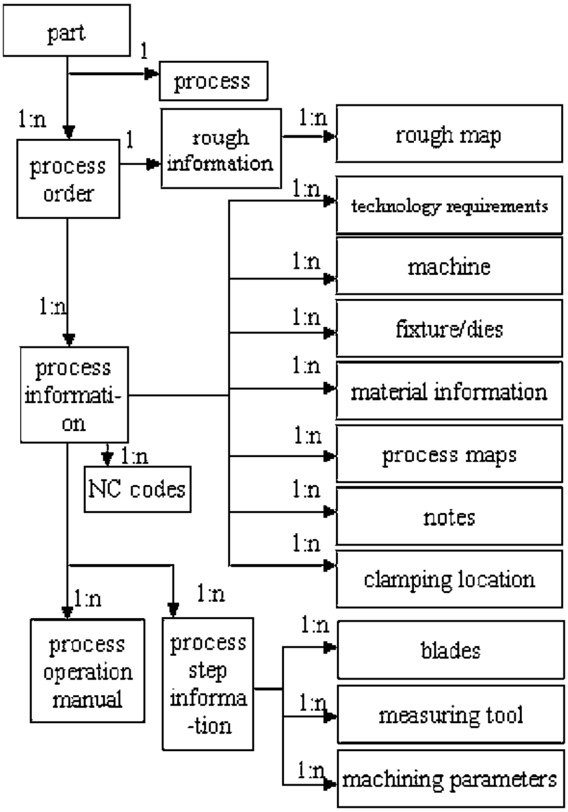


Fig. 3.25 Technology resource information model of manufacturer

run through the whole manufacturing process concerning the design and manufacture of products. They include the blank for manufacturing, materials, machine equipment, equipment (tools, measuring tool, fixture, assistive device, etc.), the standard process name, the contents of corresponding procedures, cutting parameters (feed rate, cutting depth, cutting speed, etc.), the method of calculating the fixed working hours, fixed working hours and materials standards, various knowledge of technology, typical technology and so on. Figure 3.25 is a model of a technology resource information model. The usual processing flow of manufacturing parts: rough workshop => main system workshop => auxiliary system workshop => assembly workshop. Each processing flow must have a point of order, the specific parts information model shown in Fig. 3.26. The product assembly process information model shown in Fig. 3.27 clearly indicates the assembly structure and assembly order in the form of an assembly tree. The literature [24] has studied assembly process planning and simulation of the assembly tool information model, and demonstrated the method of establishing an assembly tool information model. The strategy of establishing an assembly tool information model has also been studied by the same authors. The literature [25] demonstrated a method of large and complex pieces of stamping process design and knowledge expression, and established a complete technology knowledge information model about integration expertise, parts information, knowledge of the design process and environmental knowledge. Through control mechanisms to ensure the efficient inheritance, innovation, utilization and management of knowledge, it also achieved the expression of high-level overall information.

Networking and information technology are key parts of digital manufacturing. With a wide range of integration and development of networks and information technology, the manufacturing resource information model should also consider the sharing, collaboration and coordination of manufacturing resources in the circumstance of the networking environment. The literature [26], based on

Fig. 3.26 Processing information model of parts



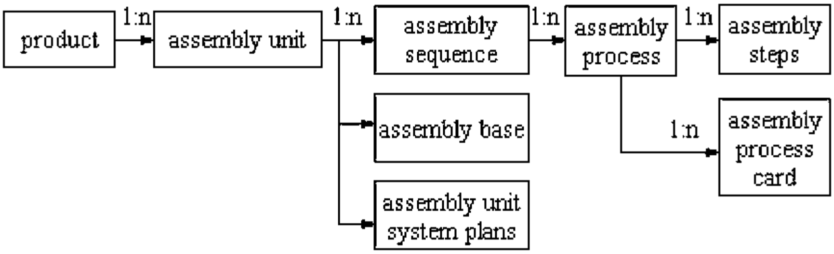


Fig. 3.27 Assembly process information model of products

EXPRESS-G, established a networking resource information model. It not only includes the resources name, type and other basic information, but also includes capacity, cost, constraints and association which are necessary for network cooperation. The information model almost covers the required resource information of all stages, including preparation, operation, implementation and the disintegration of network manufacturing. The information model includes the type

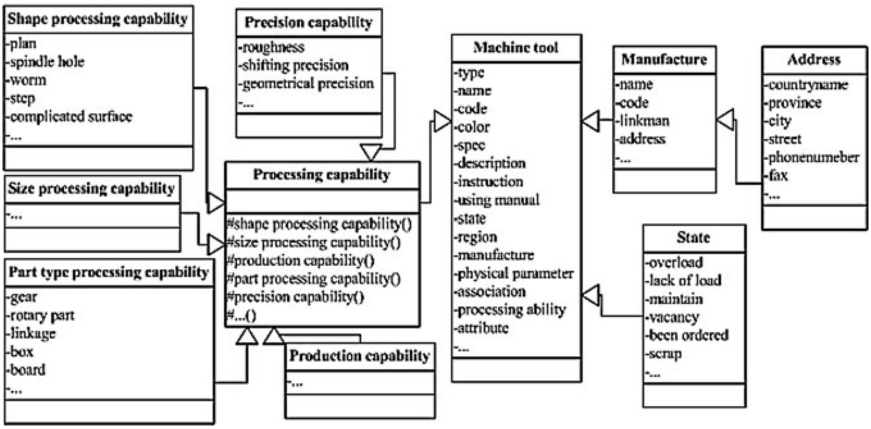


Fig. 3.28 Machine tool model expressed by UML

of resources, capacity and sharing attributes and resources links. Figure 3.28 is a machine tool model in a manufacturing grid by UML [27]. The literature [28] demonstrated the manufacturing resource information model, which is based on sharing and collaboration.

3.2.3 *Geometric Modeling and Reasoning in Manufacturing Computing*

Geometric Modeling is the branch of Computer Science concerned with the efficient representation, manipulation and analysis of geometry on a computer. It attempts to provide a complete, flexible and unambiguous representation of the object, so that the shape of the object can be easily visualized and modified, increased in complexity, converted to a model that can be analyzed computationally, manufactured and tested. In manufacturing, geometry plays an important role in shape design, in the production of input for engineering analysis tools and in the simulation of different manufacturing stages.

3.2.3.1 Theoretical Foundation for Geometric Modeling

The geometric foundations of the geometric model are differential geometry and computational geometry. The differential geometry is about definition, computing formula and application of basic geometry sense. The geometrical property of studying an object can be understood intuitively through computing and analysis of its geometry senses. The associated field of computational geometry is concerned with the development, analysis and computer implementation of algorithms encountered in geometric modeling. It is mainly used to solve geometric problems including convex hulls, intersection, distance and geometry searching. The mathematical techniques include singularity analysis and resolution, birational mappings, modular techniques, power series and localizations, ideal theoretic methods and approximation in solid modeling and how the merging of results form algebra, geometry and approximation theory into effective tools to lead to a higher level of performance in solid modeling.

3.2.3.2 Geometric Modeling Forms

There are several different geometric modeling forms, such as wire-frame modeling, surface modeling, solid modeling, and non-two-manifold modeling.

(1) Wire-frame modeling.

Wire-frame modeling, developed in the early 1960s, is one of the earliest geometric modeling techniques. It represents objects by edge curves and vertices on the surface of the object, including the geometric equations of these entities (and also possibly, but not always, adjacency information).

(2) Surface modeling

Surface modeling techniques allow the graphic display and numerical control machining of carefully constructed models, but usually offer few integrity checking features (e.g, closed volumes). The surfaces are not necessarily properly connected and there no explicit connectivity information is stored. These techniques are still used in areas where only the visual display is required, e.g., flight simulators.

(3) Solid modeling

Solid models, unlike surface models, enable a modeling system to distinguish the outside of a volume from the inside. This capability, in turn, allows integral property analysis for the determination of volume, center of volume or gravity, moments of inertia, etc. Typical solid modeling systems also offer tools for the creation and manipulation of complete solid shapes, while maintaining the integrity of the representations. Solid modeling techniques exclude the two previous modeling forms (wire-frame modeling and surface modeling). The reason is that the solid modeling forms are traditionally constrained to work only with two-manifold solids.

Current computer-aided design and manufacturing (CAD/CAM) systems used for solid object representation are generally based on three different types of modeling methods:

(1) Decomposition models that represent solids in terms of a subdivision of space. The representing methods of a decomposition model include exhaustive enumeration, boundary cell enumeration, space subdivision and cell

Fig. 3.29 Alternate classification of geometric modeling forms

Unevaluated Class

	boundary based	volume based
spatial based	Half space	Octree
object based	Euler operators	CSG

Evaluated Class

	boundary based	volume based
spatial based	Boundary Cell Enumeration	Cell Enumeration
object based	Boundary Representation	Non-parametric Primitives

decompositions. The idea of cell decompositions is based on the entity as a continuous point set.

(2) Constructive models that represent solids by Boolean (set) operations on primitive solids such as rectangular boxes, cylinders, spheres, cones and torus (appropriately sized, positioned and oriented). Constructive Solid Geometry (CSG) is the Boolean combination of primitive volumes that include the surface and the interior. Constructive models could be defined by CSG tree as following
<CSG tree > ::= <basic body element >|<CSG tree ><set operation>
<CSG tree >|<CSG tree > <rigid transform > ...

(3) Boundary models that represent solids in terms of their bounding faces, which are themselves bounded by edges and the edges by vertices.

(4) Non-two-manifold modeling

Non-two-manifold modeling is a new modeling form which removes constraints associated with two-manifold solid modeling forms by embodying all of the capabilities of the previous three modeling forms in a unified representation. Overall, non-two-manifold representations have superior flexibility, can represent a larger variety of objects and can support a wider variety of applications than two-manifold representations, but at a cost of a larger size and more complex data structure.

The wire-frame model is good at drafting. The surface model is proper to the design, which mainly contains curved surfaces, and is not suitable for handling the elimination process, volume calculation, center of gravity calculation and such geometric processing. The solid model is mathematically well constituted in detail, and the good formality of the model is consistently endorsed. It derived from many automated processing functions.

Figure 3.29 is an alternate classification of geometric modeling forms. The various representation techniques developed are differentiated based on boundary based or volume based, object based or spatially based, evaluated or unevaluated in form.

3.2.3.3 Geometric Modeling in Manufacturing Computing

Geometric modeling is widely used in digital manufacturing, including the field of design, analysis and manufacture.

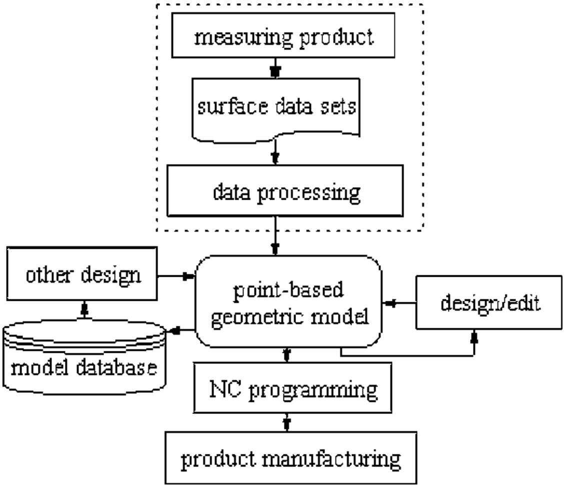


Fig. 3.30 Point-based geometric model applied in CAD/CAM

(1) Design and manufacture

Point-based Geometric model is a point set of 3-D space [29]. It is called point model for short and expressed as $P = \{p_i(x, y, z)|1 \leq i \leq N\}$ to describe a product with a complex surface configuration. The detailed flow-sheet in application is shown in Fig. 3.30. It first gets the data point set of a surface by measuring the definite product. Then the point-based geometric model is built after processing the measured data. A new point-based geometric model is obtained using CAD to design and alter. A numerical control machining program is generated to manufacture the product through CAM operation on a point-based model.

Many manufacturing processes deal with deformable objects such as rubber tubes, sheet metals, cords, leather products and paper sheets. Modeling of deformable objects is necessary so that we can evaluate the shape deformation of deformable objects on a computer in advance and can derive task strategies that carry out manipulative operations successfully. Reference [30] develops a systematic approach to the modeling of deformable linear objects such as cords and tubes.

(2) Machining process simulation

Reference [31] has presented a novel approach for machining process simulation. It combines solid modeling and curve modeling to accurately, completely and explicitly represent all the geometric entities involved in any machining process (i.e., part shape, tool shape, tool swept volume and cutting edges), as shown in Fig. 3.31. In the approach, for each implemented tool shape and path motion, a tool swept volume is generated. The swept volume is then intersected with the current part to obtain the machined material. The part is updated by subtracting the swept volume. Solid model representations are used in each case. Cutting-tool edges are represented by 3-D space curves in Bezier form and the machining

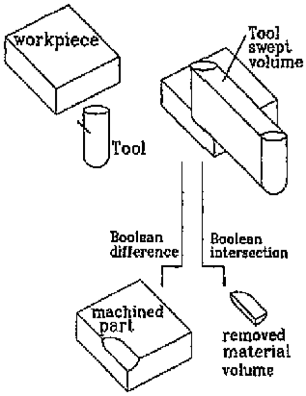


Fig. 3.31 Solid modeling-based machining process simulation

immersion extracted by intersecting these curves with the machined material. By bringing the simulation to the level of the cutting edge, this approach allows the basic cutter immersion, which is required to predict any process parameter, to be a natural output of the geometric simulation. Additionally, the approach is not process-specific.

3.2.3.4 Geometric Reasoning in Digital Manufacturing

Geometric reasoning is also known as spatial reasoning. It originated from the justice system of ancient geometry, and its development is associated with modern artificial intelligence. On one hand, the generation of automatic geometric reasoning is because of the actual needs in engineering, such as computer graphics, geometry, pattern recognition, intelligent manufacturing, adaptive fixture design, robot motion planning, machine assembly, multi-finger snatching and so on. All provide broad applications for geometric reasoning. As one enabling technology of computing manufacturing, geometric reasoning is widely used in product design, intelligent robots, NC, auto assembly, precision measurement and many other areas. It provides the geometric reasoning and methods for solving problems in those areas.

The literature [31] demonstrated a geometric reasoning algorithm that identified robot kit attitude, which is based on the plane polyhedron object model. The algorithm is based on the geometric model of objects and analyzes the spatial relationship between the surface, edge and vertex of the object. Through solving all non-collisions that can crawl kit gesture of the location of a vector, near vector, direction and the opening of vector, it considers the stability of the crawling type and spatial location of the object's gravitation as inspiration information to determine the optimal robot kit posture. Point pattern matching is widely used in image registration, object recognition, motion detection and target tracking, autonomous navigation and attitude determination. Geometric reasoning has also been widely used in the field of CAD; for example, in the design of CAD parameters, the design technology of CAD parameters has a strong technical draft, size drives and other functions which make it an effective method of conception and series design.

3.3 Theoretical Units in Manufacturing Computing

Theoretical units in manufacturing computing are the most basic theory and mathematical foundation. They are used to support geometric representation, computation, optimization and reasoning of computing manufacturing, to solve features of the geometric modeling, reasoning, control, planning, scheduling and management of the relevant computing problems and complexity analysis in the manufacturing process. Through the first two quarters of the computing manufacturing methodology and manufacturing computational model, we can see that the computational geometry, algebraic geometry, combinatorial geometry and convex analysis are the theoretical foundation of manufacturing computing, and they cover almost every process and aspect of computing manufacturing.

3.3.1 Computational Geometry

"Computational geometry" was originally put forward by Minsky and Papert (1969) as a synonym for model identification. A.R. Forrest (1972) gave the formal definition of computational geometry: "The computer representation, analysis and synthesis of geometry." Geometry information refers to some of those identified as plane geometry or the type of surface, or polygons. Computational geometry is formed as a convergence of disciplines by function approximation theory, differential geometry, algebraic geometry, mathematical calculations and the NC. Computational geometry is the study of curves and surface targets.

3.3.1.1 Mathematical Representation in Computational Geometry

As we know, geometric modeling deals with the mathematical representation of curves, surfaces, and solids necessary in the definition of complex physical or engineering objects. Computational geometry is concerned with the development, analysis, and computer implementation of algorithms encountered in geometric modeling.

(1) Points

The Points can be expressed as follows:

1. Explicit: $R = R_0$; $R = [x, y, z]$
2. Algebraic: $f(R) = g(R) = h(R) = 0$, where f, g and h are polynomials.

(2) Curves

Space curves can be expressed as the intersection of two surfaces such as $f(R) = g(R) = 0$. Their explicit and parametric expression are described separately as $y = y(x), z = z(x)$and $x = x(t), y = y(t), z = z(t), t_1 \leq t \leq t_2$. When $z = 0$ and$f(x, y) = 0$, they will be Planar curves. In 1963, Ferguson at Boeing developed a polynomial representation of space curves:

$$R(u) = a_0 + a_1 u + a_2 u^2 + a_3 u^3 Z \tag{3.24}$$

where $0 \leq u \leq 1$ by convention. A parametric non-uniform B-spline curve is defined by

$$P(u) = \sum_{i=0}^{n} P_i N_{i,k}(u) \tag{3.25}$$

where, P_i are $n + 1$control points; $N_{i,k}(u)$ are piecewise polynomial B-spline basis functions of order k (or degree $k - 1$) with $n \geq k - 1$. The parameter u obeys the inequality $t_0 \leq u \leq t_{n+k}$.

(3) Surface

A surface can be expressed as $R = R(u, v)$ or$f(R) = 0$, where u, v vary in some finite domain f which is a polynomial. More topics include Coons surface, Blending surfaces and Developable surface.

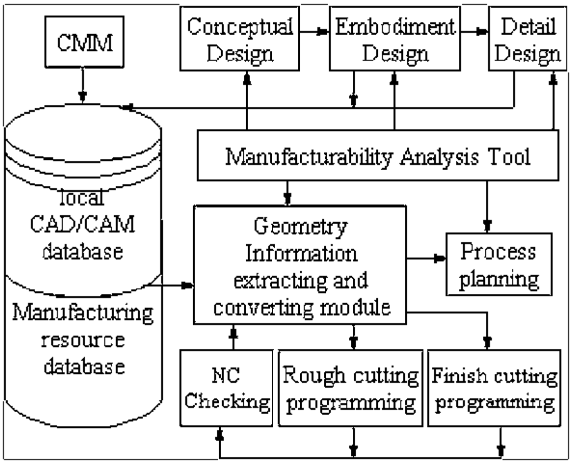
3.3.1.2 Computational Geometry Operation

In a narrow sense, computational geometry is concerned with computing the geometric properties of sets of geometric objects in space such as the simple above/below relationship of a given point with respect to a given line. In a broader sense, computational geometry is concerned with the design and analysis of algorithms for solving geometric problems. In a deeper sense, it is the study of the inherent computational complexity of geometric problems under varying models of computation. Computation Geometry (CG) is mainly used to solve geometric problems including convex hulls, intersection, distance and geometry searching. In detail, it includes the Jordan Curve Theorem, Convex Polygons, Polygon Triangulation, Art-Gallery Theorems, Polygonizations of Point Sets and Generating Random Polygons, Distances between or within Sets, Triangulations and Quadrangualtions, Convex Hulls, Hidden-Line Problems, Intersection Problems, Voronoi Diagrams and Degeneracies.

3.3.1.3 Computational Geometry in Digital Manufacturing

Geometry arises in many, if not most, of the computational problems of manufacturing, due to the inherent geometrical nature of form design, of manufacturing processes, and of the physical products themselves. Mitchell [33] has pointed out

Fig. 3.32 A framework for sculptured surface manufacturability analysis



that the field of computational geometry should be keenly involved in the development of new advanced manufacturing technologies. The motivation for many problems studied by computational geometers are certainly relevant to manufacturing—solid modeling, robotics, VLSI, computer graphics and visualization.

(1) Tool path generation

In the manufacturing process planning problem, the vast majority of current CNC machine tools have only the straight line and circular interpolation function. When processing the parts or dies containing a non-circular curve, the first problem is that it must be converted to a straight line or arc. That is, within the given precision range, using a series of lines or arcs to construct and approximate the non-circular curve. The reference [34] adopts the same double arc fitting plane to approach various parameter curves, and it is applied to the NC Cutting Machine CAD/CAM system. Evaluating manufacturability involves finding a way to manufacture a proposed design, and to estimate the corresponding production cost and quality. Reference [35] proposed a method for the manufacturability evaluation of 5-axis sculptured surface machining through geometric constraints analysis, represented by the aggregate of all visible directions which were computed using a convex hull computation algorithm. The framework for sculptured surface manufacturability analysis is shown in Fig. 3.32.

(2) Geometric modeling

Woodwark [36] has illustrated that it is now widely recognized that the foundation for all software in highly automated processes in manufacture has to be a geometrically complete model of the product. In most branches of engineering, the geometry of both components and tools has a large influence on manufacturing processes; in order to computerize manufacture, computer-based representations of shape and efficient programs to utilize them are essential. Modeling techniques can grossly be classified into two categories: the static and the dynamic approaches. In the static approach, object models are built by either interpolatively conjoining sampled points together or by approximately fitting patches to sampled points. Both paradigms are grounded in computational geometry design.

As we know, the objective of solid modeling is to represent, manipulate and reason about the three-dimensional shape of solid physical objects by computer. Technically, solid modeling draws on diverse sources including computational geometry; thus, computational geometry is the foundation and theoretical unit of solid modeling. In geometric modeling, geometric operation, representation and the corresponding data structure depends on computational geometry to some extent because computational geometry provides mathematical techniques. The solid modeling operations such as intersections involve a number of basic computational problems in mathematics which should be solved efficiently and robustly in order to realize an effective and higher level of performance in solid modeling.

The role of computational geometry in manufacturing can be seen in many sources of related journals and conferences, such as Computer Aided Design, International Journal of Computational Geometry and Applications, Journal of Mechanical Design (ASME Transactions), CG International Proceedings, IFIP Conference Proceedings on CAD, CAM, CAE and so on.

3.3.2 Combinatorial Geometry

3.3.2.1 Introduction to Combinatorial Geometry

Combinatorial Geometry was originally developed to simplify the complex mathematical description of armored military vehicles in conventional and nuclear vulnerability studies. It is modeled on set theory and describes complex three-dimensional shapes in terms of the unions, intersections and differences of simple geometric bodies. A complex problem reduces to a series of zones involving the combination of simple shapes.

Combinatorial geometry is the study of order and incidence properties of groups of geometric features. János Pach and Micha Sharir in the lecture "Combinatorial geometry with algorithmic applications" introduced combinatorial geometry, starting with Sylvester's problem on the existence of "ordinary lines". They surveyed many aspects of the theory of arrangements of surfaces in higher dimensions and studied arrangements of curves in the plane, with special emphasis on Davenport–Schinzel sequences and the role they play in the theory of arrangements. The topic of incidences between points and curves and their many relatives are included. They have also described some open problems. Some combinatorial properties of arrangements of spheres, boxes, etc. are discussed and discrete variants of the "piano movers' problem" on graphs and grids are covered [37].

3.3.2.2 Combinatorial Geometry in Digital Manufacturing

Combinatorial geometry plays an important role in the geometric modeling of Digital Manufacturing. Reference [38] concerns combinatorial geometry for shape representation and indexing. It gets a common framework for metric and qualitative representations using combinatorial geometry to define qualitative shape properties and does general recognition using the invariant properties of order and incidence relations. Reference [39] described 3-D external world modeling based on sensor derived data using combinatorial geometry for autonomous robot navigation. In combinatorial geometry (also known as Constrictive Solid Geometry (CSG) in computer graphics and CAD literature), solids are represented as combinations of primitive solids or "building blocks" (such as spheres, cylinder and boxes) using the Boolean operations of union, intersection and difference. The storage data structure is a binary tree where the terminal nodes are instances of primitives and the branching nodes represent Boolean operators.

3.3.3 Convex Analysis

3.3.3.1 Introduction to Convex Analysis

Convex analysis (or convex set and convex function) is a young branch in mathematics. In the 1930s, the more systematic book researching on convex set came into being. Between 1940 and 1950 especially, many applications were found in the field of optimizing and promoting the development of this theory. With mathematical programming theory, game theory, mathematical economics, approximation theory, variation study, optimal control theory and the development of other disciplines, convex analysis attracted growing attention. In the late 1960s, the cornerstone of convex analysis theory, "Convex Analysis" by R.T. Rockafellar, was published, and convex analysis in the infinite dimensional space in this period was fully developed. It is the branch of mathematics devoted to the study of properties of convex functions and convex sets, often with application in convex optimization, a subdomain of optimization theory.

Convex analysis, including convex, convex function, convex cone, normed space convex, positive solutions and other aspects, researches basically on is convex set and convex function, and the basic tools are convex separation theorem, and these concepts and theorems can be purely researched by Algebra that is not the introduction of a topology of linear space to study. On its basic contents, convex analysis can be completely represented as "convex algebra." Convex function as the basic research of convex analysis plays an important role. Its definition and features are often used as the solution of mathematical programing, game theory, mathematical economics, approximation theory, variation study and optimal control theory. Convex analysis theory mainly includes convex set theory, the fundamental nature of convex function, convex sets and the dual relation of convex function, the differential computing of convex function, etc. Here we simply introduce convex sets and functions based on [40, 41].

Definition 3.7 (*Convex Sets*): Given $C \subset \mathbb{R}^{\ltimes}$, it is called convex if

$$\alpha x + (1-\alpha)y \in C \quad \forall x, y \in C\,, \forall \alpha \in [0,1] \tag{3.26}$$

Simple Properties of Convex Sets are:

1. Intersection of an arbitrary collection of convex sets is convex;
2. A set C is convex if and only if it contains all convex combinations of points in C.

Definition 3.8 (*Convex Functions*): Let C be a convex subset of $\mathbb{R}^{\ltimes}$. A function $f : C \mapsto \mathbb{R}$ is called convex if

$$f(\alpha x + (1-\alpha)y) \leq \alpha f(x) + (1-\alpha) f(y) \quad \forall x, y \in C \tag{3.27}$$

The properties of convex functions, extended real-valued convex functions and recognizing convex functions are not introduced here. Knowledge about these and convex functions and their minimization (semi-continuity, minimization), convex functions in duality (the duality relation, the conjugation operator), separating convex sets separation theorems and affine minorization of convex functions can be found in books about convex analysis. Further reading will provide detailed and deep knowledge about convex analysis, such as differentiable convex functions, convex and affine hulls, Caratheodory's theorem and Farkas' lemma, Null variables, Strict Complementarity, Closure, relative interior and continuity.

3.3.3.2 Convex Analysis and Digital Manufacturing

At present, convex analysis has been mainly applied in the area of automatic control, such as system identification, system analysis and control problems.

System identification deals with mathematical modeling of an unknown system in a model class from noisy data. Reference [42] presents a numerical procedure based on convex analysis and optimization to calculate the minimum-norm solution that minimizes the 2-norm of actuator forces in cable-based parallel manipulators (CPM) using Dykstra's alternating projection algorithm. Convexity is often a desired property for a function or a set. In stability analysis, the invariant sets are usually used to estimate the domain of attraction and whether an invariant set is convex or the convex hull of an invariant set is still invariant are of interest to us.

Computational Geometry, combinatorial geometry and Convex Analysis are interrelated and the basis of theory for computer-aided design. They are mainly used in the CAD/CAM of manufacturing.

3.4 Summary

With the continuous development of intelligence and network, the computing complexity of manufacturing systems and the manufacturing process has become a key issue in constraining rapid product design and rapid manufacturing. As one of the basis theoretical systems of digital manufacturing science, the research area of computing manufacturing has involved the whole process of the manufacturing system and all levels, and has covered multiple disciplines and a wide range of research areas.

Computing Manufacturing Methodology mainly includes the configuration of space theory, virtual prototyping and reverse engineering. Configuration space theory is an important basis and theoretical basis of computing manufacturing in positioning and testing. Virtual prototyping is designed to use the powerful advantages in the visual aspects as well as the interactive exploration of virtual objects function of virtual reality technology to do product design, interactive modeling and analysis in the geometry, functions, manufacturing and other aspects. Reverse engineering is a product design process description. Reverse engineering and virtual prototyping are both key methods in product digital design of computing manufacturing.

The manufacturing computing model is described from the three aspects of the manufacturing computing discrete model, the information model, geometric modeling and reasoning. The discrete model is the basis of digital manufacturing and the key point of computing manufacturing. The information model provides a shared, relatively stable and organized model to describe products, resources and the environment in manufacturing activities. Geometric modeling and reasoning in computing manufacturing play a key and core role. The origin of geometric models and geometric modeling is closely related to manufacturing.

Theoretical units in computing manufacturing are used to support geometric representation, optimization and reasoning of computing manufacturing, to solve the relevant computations and complexity analysis of the geometric and features modeling, reasoning, control, planning, scheduling and management arising in manufacturing processes. They are the most basic theory and mathematical foundation.

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Chapter 4
Manufacturing Informatics in Digital Manufacturing Science

The high speed development of computer networks and information technology has enabled manufacturing enterprises to enter the Information Age. To adapt to such competition, we should rethink the information science problems in manufacturing, which give rise to the technology and techniques of manufacturing informatics. Manufacturing informatics is a new interdisciplinary area, which synthesizes manufacturing science, information science, system science, control science and management science. It mainly researches the logical expression of information, optimal distribution, and the effective operation of manufacturing processes and manufacturing systems. The digitization of manufacturing information makes manufacturing processes and manufacturing decisions controllable and visible. Moreover, since the digitized manufacturing information can be transmitted through a wide area network (WAN) with a certain series of protocols, the manufacturing information can usually be shared and collaborative. Digital manufacturing is driven by information, and manufacturing informatics is the core and basic theory of digital manufacturing science.

The main content of manufacturing informatics involves the principle and properties of manufacturing information, the measurement and materialization of manufacturing information, self-assembling and the synthesis of manufacturing information and information security. Specifically, it mainly researches the properties, measurement, acquirement, transmission, storage and exchange of manufacturing information. In this chapter, the contents mentioned above will be discussed separately.

4.1 Principal Properties of Manufacturing Information

Before the introduction of manufacturing informatics, it is useful to understand principal properties of manufacturing information. Manufacturing is a kind of social output activity driven by needs and profits, that is, a kind of information-intensive

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output activity. In this sense, information and manufacturing activities are highly integrated; therefore information property is one of the basic principles in manufacturing activities. In order to fully leverage the effectiveness of manufacturing information and to escalate the competitiveness of manufacturing enterprises, the discussion of rules in manufacturing information—the information principle of manufacturing—is imperative. This section will begin with the characteristics of manufacturing activities, then discuss the structure and principles of manufacturing information, and reveal further properties of manufacturing information. Information pervades all manufacturing activities, and the main characteristics are that manufacturing information is an indispensable product element, and that a part of manufacturing information can be seen as a manufacturing product [1].

4.1.1 Information Characteristics of Manufacturing Information Activities and Manufacturing Informatics

1. The significance of manufacturing activities

Manufacturing activities, which are considered in the lifecycle of products, include the requirement analysis of products, design, material stocking, assembling, selling, reclaiming and so on. Activities in these processes can all be described as manufacturing activities. Most manufacturing activities exist in sequential and parallel form with information, control and object. These activities include after-sale service, device debugging, operation of the NC (Numerical Control) machining tool, workshop operation, enterprise operation and so on.

In the market, a manufacturing sales activity at least involves the demander, supplier, intermediate, government and manufacturing enterprise, among which there exists bidirectional information and material flow, as shown in Fig. 4.1. The five entities in Fig. 4.1 shows these characteristics as:

(1) Any entity has a bidirectional relationship(s) with one or more entities.
(2) The information acquired by each entity is generally unequal. The information inequality between two entities is called the information difference.

To reduce the risk of transactions with the existing information difference, some strategies can be implemented, such as: (a) enterprises should abide by the related laws and regulations; (b) enterprises should exchange their information to reduce the information inequality; (c) the intermediate could be induced to assure the equality of the transaction. In fact, related research has been carried out in the domain of Economics of Information [2, 3].

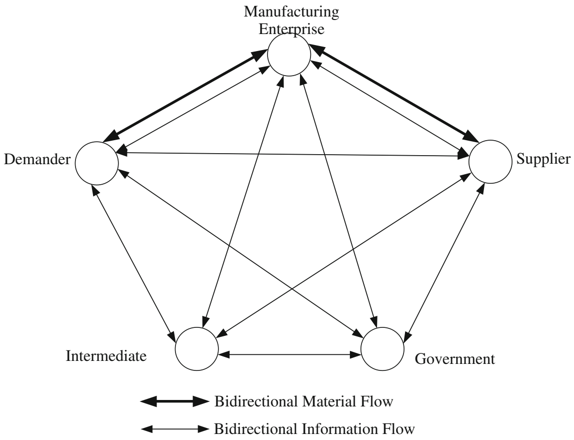


Fig. 4.1 Illustration of the relationship among the entities involving sales activities

2. The characteristics of manufacturing activities

Manufacturing activities have the fundamental characteristics of:

(a) Purpose feature. All manufacturing activities have a clear purpose. Because the production aims to satisfy customers' needs and benefit enterprises, all subactivities should also have a clear purpose.
(b) Human feature. Manufacturing activities are output activities involving human activities to satisfy social needs.
(c) Material feature. The traditional definition of manufacturing is to transform raw materials into substantial products. Modern production includes not only substantial products but also insubstantial products, such as software products, services, etc.
(d) Information feature. The information feature of manufacturing is decided by the three features above; no manufacturing activity can proceed without manufacturing information.

3. The Information Property of Manufacturing Activities

The information property of manufacturing activities means that no manufacturing activities can leave out manufacturing information—they are all driven by information (Fig. 4.2).

By output form, manufacturing activities can be categorized as two major classes: substantial output activities and insubstantial output activities. The substantial activities include three types of processing methods: material reduction (e.g., cutting process), material constant and accumulation (e.g., rapid prototyping).

The compound proposition of manufacturing activities is:

$$\begin{aligned} \text{manuf ACT} &\rightarrow \text{manuf-matl ACT} \cup \text{manuf-info ACT} \\ \text{manuf-matl ACT} &\rightarrow \text{ctrld-matl ACT} \cap \text{manuf-ctrl ACT} \end{aligned} \tag{4.1}$$

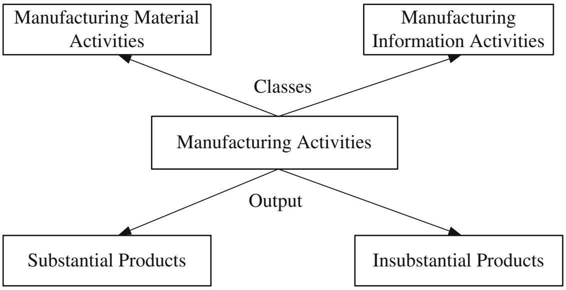


Fig. 4.2 The classes and output forms of manufacturing activities

$$\text{manuf-ctrl ACT} \rightarrow \text{manuf-info ACT} \cup \text{manuf-cstr ACT} \tag{4.2}$$

Combining Eqs. 4.1 and 4.2, we could derive:

$$\begin{aligned}\text{manuf ACT} \rightarrow {} & \text{ctrld-matl ACT} \cap \text{manuf-info ACT} \cap \text{manuf-cstr ACT} \\ & \cup \text{manuf-info ACT}\end{aligned} \tag{4.3}$$

In the above equations, manuf ACT means the manufacturing activities; manuf-matl ACT means the manufacturing material activities; manuf-info ACT means manufacturing information activities; ctrld-matl ACT means controlled material activities; manuf-ctrl ACT means manufacturing controlling activities; manuf-cstr ACT means manufacturing constraint activities.

In (4.2), manufacturing activities are the disjunction of manufacturing material activities and manufacturing information activities. Equation 4.3 interprets both the manufacturing material activities and manufacturing information activities because the manufacturing information activities cannot be left out. They are both driven by information.

4. Properties of manufacturing information

No human activities can get away from information because of the rapid development of networks and the features of the information society; therefore, neither can manufacturing activities, especially for global requirements in manufacture.

(1) Manufacturing is driven by information

All manufacturing activities are carried out under the manufacturing information, therefore manufacturing is driven by information.

Today, manufacturing engineering technology approaches such a level that once there is a demand, the product can be manufactured if the advanced manufacturing method, resources and sufficient manufacturing information can be obtained. With the support of computer and network technology, the information increasingly impacts on the manufacturing. Information-driven manufacturing technology and manufacturing activities are more and more important.

(2) Value of manufacturing information

In the digitized age, manufacturing information is different from that of limited land, factory, equipment, raw material, energy, funding, staff, etc. Although manufacturing information is time-constrained, it is also an inexhaustible, disposable, duplicable and creatable resource.

The reason why manufacturing information is inexhaustible is, on the one hand, that the continuous object is itself endless, and, on the other hand, that the information is related to subjective recognition, while the recycle of practice and recognition is the root of subjective creation. In this sense, it can be said that manufacturing information is the source of creating value, directly or indirectly. In order to render enterprises sustainable to development, it is imperative to punctually and reasonably configure enterprise resources, so manufacturing information becomes the new strength and provides a new chance of making profit.

The implementation of manufacturing hangs on a series of decision-making processes. To update the prior probability, the processes must be based on manufacturing information. The output of manufacturing decision-making is also information, and the decision-making risk is dependant not only on the information, but also on the decision-maker's recognition, decision strategy and decision environment, which can be described as information. In addition, manufacturing activities rely on decision-making manufacturing information.

(3) Principles of manufacturing information

a. The Inconsistence between Manufacturing Information Investment and 'Decreasing Benefit' Principle

In the enterprise operation, the benefit caused by constant investment will be decreased. It is notable that the investment of manufacturing information will not follow the 'decreasing benefit' principle.

The aggregation, update, disposal, fusion and creation and investment of manufacturing information, together with enterprise resources, staff morale and initiative spirit, can be the way to break the bound of the 'decreasing benefit' principle, and make an enterprise subject to constant development.

b. The Importance of the Manufacturing Information/Capital

Since the manufacturing information is a dominating strength rather than a direct strength, the constant increase of benefit is mainly decided by the dominating resources in an enterprise and the will to operate is dominated by information. In this sense, it is important to establish the mechanism of transforming manufacturing information into benefits, consolidating the driving capability of advanced manufacturing information and making the manufacturing information part of an enterprise's assets.

c. Materialization ability of manufacturing information

In order to obtain a substantial product, manufacturing information should be applied to substantial products.

Materialization means the manufactured substantial object is changed (e.g., size, shape, hardness and material) following the manufacturing information, as a result, the manufacturing information is solidified into the object being manufactured with allowance (some kind of uncertainty). Generally, the process of materialization is irreversible, and the quality and production rate should be considered in the process. Broadly speaking, materialization relies on the information, and the information makes materialization possible.

(4) Manufacturing information as acceleration factor of manufacturing enterprise development

Firstly, manufacturing information can expedite obtaining information from the market. Manufacturing information is now mainstream in the development of global manufacturing, and the progresses and application of information technology quicken the speed of updating knowledge, decreasing the cost of spreading knowledge, improving the level of sharing information and knowledge and accelerating the application of scientific technique in practical manufacture. Information is gradually becoming an important factor in manufacturing development. For instance, the ability of an enterprise's forecasting market and decision-making can be improved by focusing on supply and demand information of products, which also can provide exact guiding information and resist the risks of the market. The rapid progress and application of information technology make information-getting more and more convenient. Furthermore, it favors sustained decision-making, taking opportunities, opening up the market, decreasing trade cost and enhancing the efficiency of enterprise.

Secondly, it speeds the development of products and shortens the period of products coming into market. Informatization and digitalization become the dominant ingredients in manufacturing technology. Experiment and trial-produce can be achieved at lower cost, consequently the validity of the decision-making process and virtual design will be promoted if we can obtain a precise digital model. Through public manufacturing information that is shared on the network, the capacity of manufacturing activities could be improved maximally. Therefore, manufacturing activity will be able to further impel the improvement of the manufacturing enterprise.

Finally, it encourages personnel to communicate with one another and trains them, and also propels scientific technique advancement in the enterprise. Along with more and more information technology such as networks used in education and study, it is more and more necessary that enterprises make use of computers and networks to train their personnel, so as to promote the performance of the whole team. For example, the performance of the whole team can be examined effectively by using e-Training, e-Learning and e-Performance. Personnel in different departments or in the virtual organization can communicate conveniently and effectively, and can explore and define their work, role, team and organizational practice. Meanwhile, the information technology is made use of in transforming and upgrading the traditional manufacturing industry, changing its design, production and circulation, which is conducive to promoting the reengineering and organizational restructuring of the business process, improving the technological content of traditional products, lowering resource consumption and improving production efficiency.

4.1.2 Information Principles of Manufacturing

1. Duality of information

Information itself is abstract and represents a non-physical phenomenon. On the other hand, information can be issued, transmitted, stored and perceived. Therefore, it must be bound to some physical carrier, i.e., information must be transmitted by using some material or energy-based structure. Such a representation is called a message. Because manufacturing activities involve the characteristics of social output by people, manufacturing systems hold not only an objective attribute but also a subjective attribute. Understanding this duality of manufacturing systems helps us comprehend the objective and subjective attributes in manufacturing systems. Therefore, manufacturing systems can be classified as the following three types:

(1) Subjective and objective manufacturing systems. Such systems include human-operated manufacturing facilities, CAX systems by designers and computers, etc.
(2) Objective manufacturing systems. These systems consist of various types of objects, such as machining tools and flexible manufacturing systems (FMSs) controlled by predefined programs, industry robots programmed with codes, etc.
(3) Subjective manufacturing systems. These consist of cognitive subjects, such as the directorate in an enterprise and the leading board in a factory.

In the real world, these three types of manufacturing systems often exist at the same time. Also, they can dynamically change their roles. For example, at the maintenance stage, the FMS is a type of subjective and objective manufacturing system; as soon as it finishes maintenance to go back to a production line, it belongs to the objective manufacturing systems.

Because of the existence of cognitive entities and the constant changing among the three types of manufacturing systems, manufacturing system behaviors become very complicated, which causes difficulty in modeling and expressing manufacturing systems. The complexity also indicates why many current modeling techniques (Markov chain-based queuing models, Petri Nets, etc.) consider the manufacturing system as a black box. Furthermore, the exact and simplified dynamic models can be built for merely the objective manufacturing systems such as the milling system because the cognitive entities' joining is not related.

2. Characteristics of manufacturing information
(1) Transmission characteristic of manufacturing information

Different from communication transmission, the transmission of manufacturing information has its own characteristics:

(a) In many situations, transmission is not accessible. The classical manufacturing activities, in particular the materialized manufacturing information, consume substantial resources. Therefore, the process is irreversible. Also, if a large error in manufacturing information occurs during transmission, great economic loss will occur. Such transmission, for example, includes the transmission of numerical machining instructions, of CAD data, of logistic instructions, and of decision-support information. However, in order to curtail the time to market and to reduce cost, transmission errors in a certain range are permitted.

(b) The interference from the ontology and subject is unavoidable. Because the manufacturing activities often relate to the participation of society and enterprise, the variety of transmitting manufacturing informations (e.g., the transmission of electronic signals, optical signals, file, video and audio) and sociality of manufacturing results in this interference not only coming from itself but also from the external environment of transmission.

(2) The evaluation of manufacturing information quality

As with normal information, as an insubstantial expression, the manufacturing information is vulnerable to actions such as addition, deletion, modification, aggregation, conversion and interference. The assurance of manufacturing information quality is either difficult or important. Therefore, the definition of manufacturing information quality is the basis for scientifically evaluating quality information. In objective and practical conditions, manufacturing information evaluation can be used in the multiple stages of the product lifecycle, such as information quality evaluation in the process stage, evaluation of manufacturing process, marketing evaluation and profit evaluation. The definition of manufacturing information quality is given as follows:

Definition 4.1 The manufacturing information quality is the degree of how much the information of product manufacturing that meets requirements.

In the definition, the requirements come from the expectation of customer and society, and the publicly recognized needs. Within manufacturing systems, the definite, unified expression of manufacturing information is the basic requirement, thus there are several factors to assuring information quality.

Firstly, it is important to establish the connection between the ontology of an object and symbol for its description. For example, an ERP system will be dependant on accurate information in each department. If not, accurate information quality may not be calculated.

Secondly, time is also required to describe the information. For example, the load of a facility, storage information of material, and the order sheet from customers all need the time data in an information system; otherwise the related information will lose its meaning.

Thirdly, the spatial information is also essential to the information quality in a manufacturing system. For example, if the spatial information about the material and products is known in advance, the storage time and delivery time can be estimated.

Fourthly, the quantitative and qualitative expression of information should be considered. In addition, the other elements involve the source of information, information carriers and the way to express information. Gauging the information

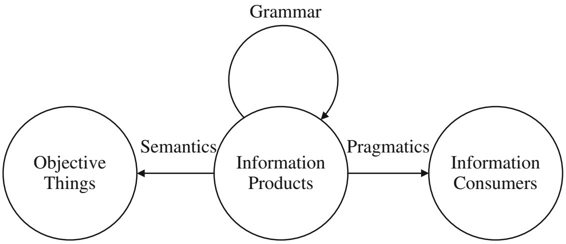


Fig. 4.3 The relationship of grammar, semantics and pragmatics of manufacturing information

quality in view of comprehensive information, we can analyze it in three parts: grammatical, semantic and pragmatic (Fig. 4.3).

Therefore, manufacturing information quality has the following main characteristics: it has objective and subjective duel attributes; it can be used for quality variable sets; it permits errors; the evaluation of information quality involves the information ontology, users' destination and ability to use information and the environment of the information; the reasonable information quality should be ensure by compromising with multi factors.

In order to quantify the manufacturing information quality, proper categorization is needed. Similar to manufacturing information, the product information can be described by multiple sets varying with time, space, customer demands and dimensions. As for the objective and credible evaluation for manufacturing information, some information is easy to evaluate, such as the overprice of standard parts; the unconformity of accounts; the unconformity between part size and general assembly size. On the other hand, other information, such as competitor information, or information of similar products in the market, should be objectively and credibly described by one of the following four proposed methods: to escalate the credibility and quality of information acquisition or output; to make comparison with multi-channelled input and output (see Fig. 4.4a), with the aim of obtaining a better evaluation; to make comparison with stored information or knowledge, through which to make a judgment; to make re-verification, e.g., re-detection and re-investigation etc.

(3) The quality of manufacturing decision and decision variable

The manufacturing decision decides the manufacturing activities, and the quality of manufacturing decisions to a large extent decides the quality of manufacturing activities. The quality of manufacturing decision DQ is decided by the following criteria: the related manufacturing information quality IQ; the decision strategy and decision method quality AQ; the environment quality EQ; the execution condition and environment quality WQ.

Generally speaking, from the preceding experience, we have:

$$DQ = d\ (IQ, AQ, EQ, WQ), \tag{4.4}$$

where d means the relationship between decision quality and all the decision variables (variables that can affect the decision). The Eq. 4.4 can be difficultly

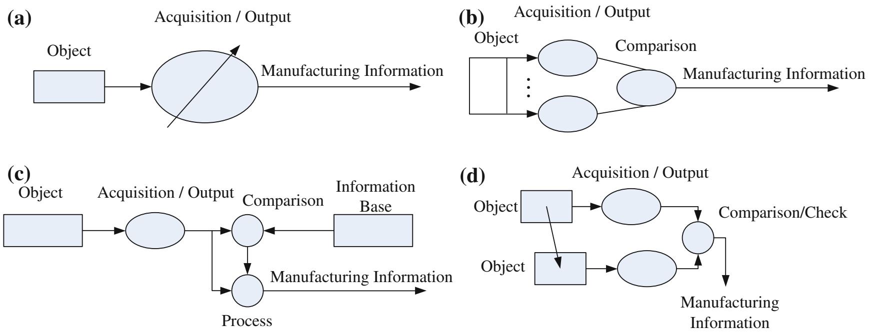


Fig. 4.4 Four objective and credible evaluation methods for manufacturing information. (**a**) Escalation of the credibility and quality of information acquisition/output. (**b**) Comparison with multi-channeled input and output. (**c**) Comparison with stored information or knowledge. (**d**) Re-verification

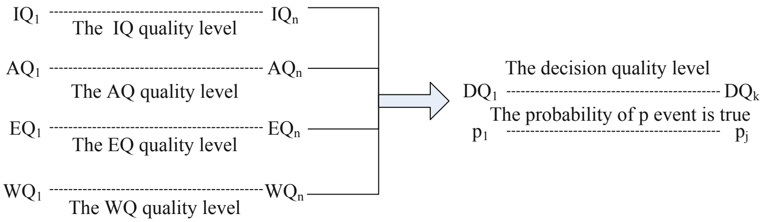


Fig. 4.5 The 4-dimensional relationship between decision quality and decision variables

expressed by explicit formula, while the relation diagram can be achieved by field knowledge as follows:

$$\begin{aligned} \text{if IQ, AQ, EQ, WQ } &\rightarrow \text{IQ}_a \text{ and AQ}_b \text{ and EQ}_c \text{ and WQ}_d \\ &\text{then DQ} \rightarrow \text{DQ}_f(0.85) \end{aligned} \tag{4.5}$$

In (4.5), the value 0.85 in bracket is the probability when the event is true, DQ_f means the level of decision quality. The illustration of Eq. 4.6 can be seen from Fig. 4.5.

The four decision variables have different impacts on decision quality DQ, where the manufacturing information quality IQ can otherwise degrade the decision quality, that is, although high-quality manufacturing information cannot make the manufacturing decision high-quality, poor manufacturing information quality must cause a poor manufacturing decision. High quality manufacturing information is the key resource and output for enterprise competition, so it needs to be contained by rigid acquisition, output, evaluation and management.

3. Self-assembling of manufacturing information

All activities have their own targets, and targets are also information. Manufacturing objects are endowed with target information through production. The manufacturing target is in accordance with the needs of the market, but possibility and efficiency should be taken into account at the same time. Thus, the manufacturing target is other-identified but not self-identified. However, in specific circumstances, the system can identify targets itself. The way that an organization achieves an other-identified manufacturing target is that manufacturing target information is transferred gradually to manufacturing objects through the controlled manufacturing process, which is referred as to other-assembling manner. Under certain conditions, the system can also organize the implementation itself, and gradually achieve the targets, which is called the self-assembling manner.

Yovits [4] indicated that the research on self-assembling started in the late 1950s. In the past half a century, the research has been greatly applied in the fields of biology, automation machine, cognition science, behaviors, and management science, system theory, economics, social science, etc. From the point of view of information, self-assembling is facilitating the positive feedback to increase orders, implementing the open system with self-assembling behaviors. Self-assembling is a process in which the internal organization of a system, normally an open system, increases in complexity without being guided or managed by an outside source.

The idea of self-assembling challenges an earlier paradigm of ever-decreasing order which was based on a philosophical generalization from the second law of thermodynamics in statistical thermodynamics where entropy is envisioned as a measure of the statistical “disorder” at a microstate level. However, at the microscopic or local level, the two need not be in contradiction: it is possible for a system to reduce its entropy by transferring it to its environment. It would appear that, since isolated systems cannot decrease their entropy, only open systems can exhibit self-assembling. However, such a system can gain *macroscopic* order while increasing its overall entropy. Specifically, a few of the system’s macroscopic degrees of freedom can become more ordered at the expense of microscopic order.

Compared with “other-assembling”, the behaviors in self-assembling have some essential characteristics: information sharing, autonomous, short-range communication, microscopic decision (each cell only cares about its own behaviors, disregarding others), parallel operation, whole coordination and iterative optimization. In the manufacturing system, studying how to gain the ability of self-assembling is also an all important task.

(1) The self-assembling problems in manufacturing systems

Along with the rapid development of manufacture and the fast growth of the knowledge economy the modern manufacturing system has become more and more complex. Inside the system, the problems include the fact that modern products require more complex and varied structure, and more accurate processes; and consumer orders are more individual and varied, because products in large quantities, standardization and specification are no longer popular with customers.

Thus, manufacturing enterprises have to turn to the producing mode of various products and small quantity, and must quicken the products' updating. Outside the system, a major problem is that, with the global economic integration environment, cross-industry, cross-region or even cross-country manufacturing enterprises and manufacturing resources are converging into huge and complicated manufacturing networks. These networks suffer from dynamic interference and regulations. All these variations accelerate the process of complication of the manufacturing system.

Additionally, the knowledge, distribution and network trend in modern times fiercely challenges the manufacturing industry, and therefore makes manufacturing systems more complicated than ever.

Summarily speaking, the complexity of the modern manufacturing system has four expressions: (1) its innate nonlinearity, (2) its autonomous and emergent behaviors, (3) its openness, and (4) its non-equilibrium. Finally, the manufacturing system exists in a condition that changes randomly and is difficult to forecast. Therefore, when facing such a complicated system, we should refresh our ideas and conceive new methods to solve the corresponding problems, that is to say, it is necessary to introduce self-assembling for creating a method to solve problems.

We conclude with the emergent scientific and technical problems that are emergent, which are found in each part of manufacturing system and in each link of manufacturing process. The more outstanding ones are:

(a) The self-organized forming technology of products

To date, humans have used mandatory forming to matching parts, which belongs to "other-forming". The growth and development of biology are under the control of the inner gene, which is called "self-forming", or self-organized forming. Biology or mankind itself has proven that "self-forming" can have a very sophisticated and complex structure. The key problems include: macroscopic mode and its mathematical model generated by autonomous behavior of mass elements; new self RP (Rapid Prototyping) methods from the growth of "seeds" controlled by inter genes; fabrication processes of nano or micro parts based on molecule self-assembling; surface fitting and numerical programming methods based on autonomous units.

(b) Principles and methods for self-organized design

Unlike the traditional method, self-organized designing is a bottom-up and parallel method. The product "element", as a "gene", should be designed first, containing the characteristics and information of the full product lifecycle. Then the "element" will "split" (replicate), and automatically "grow" (assemble) a product. Any design and modification will be preformed at the "element" stage. The key problems include: the connotation and characteristics of the "element"; the interaction between the "element" and the environment; the principle and model of the split, separation and the automatic assembly of the "element"; the encoding of characteristic information, in particular the characteristic information of shape, size, structure, material and their applications in the product model and production process; driven by product information model, the automatic generation of self-organization and process parameters in process systems; the application of concepts as genotype and phenotype in the design of a diversified production series; the fault-defense and fault-tolerance methods in the storage, replication, transcription and interpretation of genetic information and the application of quality assurance techniques in production design and process design while replicating individual.

(c) Distributed controlling based on the cooperation of multiple autonomous units

Simulating the organizing structure and running mode of biological individuals and groups, the system researches on the distributed and network system that is based on multiple autonomous units cooperation and its application in network manufacturing. The key problems include: the autonomous unit-based manufacturing systems; the entropy evolution mechanism and dynamic characteristics of manufacturing systems based on autonomous units; the behavior strategy design and "teaching and cultivating" of Agents, the communication relations and communication strength design of Agents; the predication of macroscopic characteristics based on Agents' "individuality".

(d) Optimization strategy based on evolution theory

Because of the complexity of modern products and manufacturing systems, traditional optimal methods are generally incapable of handling them all. Also, all sorts of optimizing methods are carried out in quantitative space, but the optimization of products and manufacturing systems need to be carried out in the feature (semantic) space. Therefore, the self-organization simulation of biological evolution is essential for finding an optimal strategy in the feature space. The key problems include: research on the optimization and its application in product optimization and process optimization during biological evolution, in order to avoid "combination explosion" and "local optimum"; optimization and generic algorithm in the feature space.

(e) The information conversion and entropy equilibrium in the manufacturing process

In the manufacturing process, information from various sources is being exchanged and is fluent. Between manufacturing systems and sub-systems and between manufacturing systems and the environment, either the energy and information, or entropy is exchanged. The conversion of information and the variation of entropy include the essential principles of self-organization, which should be studied seriously and quantificationally. The key problems include: the amount of information and its complexity of computation method in manufacturing systems, manufacturing processes and products.

(2) Application: a self-assembling application in machining accuracy

We take an example to introduce the self-assembling application in machining accuracy. This is the other-assembling materialization of machining accuracy information in the literature [5]. Most machining accuracy information reaches the standard through other-assembling after being other-identified. In the face of inevitable and various error interferences, the accuracy information of the machining object is transferred to the machining object orderly by other-assembling through the accuracy information sources, the accuracy information transferred links and craft links, which can be seen in Fig. 4.6. The transferred method of other-assembling accuracy has open-loop and closed-loop.

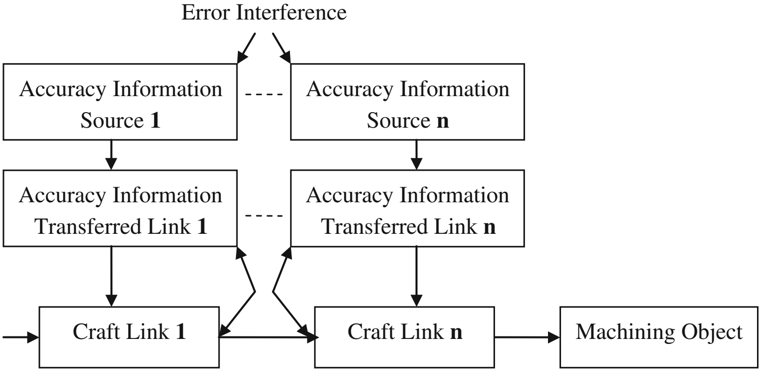


Fig. 4.6 Other-assembling orderly transfer of machining accuracy manufacturing

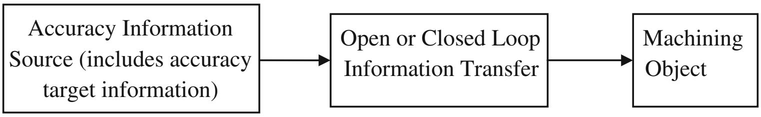


Fig. 4.7 Other-assembling materialization of accuracy information

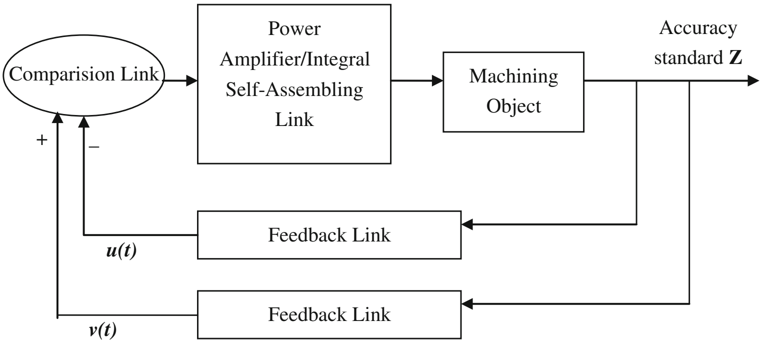
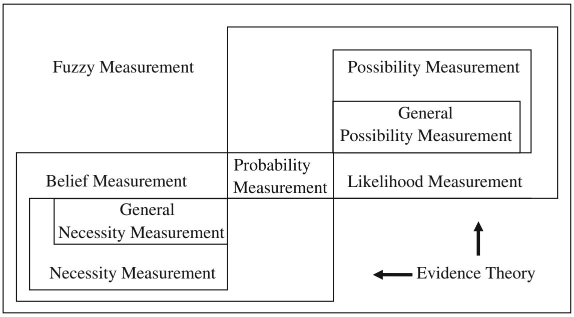


Fig. 4.8 Self-assembling illustrative diagram of accuracy information

In other-assembling materialization of machining accuracy information, the accuracy information is materialized to the machining object in an other-assembling and orderly way, as indicated in Fig. 4.7.

Different from Fig. 4.7, accurate information source that is out of machining object does not exist in self-assembling materialization system of machining accuracy, so the accuracy standard of the machining object is reached by multi-feedback channels. Figure 4.8 is the self-assembling illustrative diagram of objective accuracy information. In Fig. 4.8, there are two feedback channels that

Fig. 4.9 Relationship of measurements in common use



are mutually independent; their outputs are $u(t)$ and $v(t)$, respectively. In the process of its operation, the self-assembling materialization system has the function of close-loop regulation, and can automatically adjust its own machining process while meeting the required accuracy of the system, which greatly simplifies the complexity of the system control and enhances the superiority of self-assembling system.

4.2 Measurement, Synthesis and Materialization of Manufacturing Information

4.2.1 Measurement of Manufacturing Information

Measurement of information is a basic problem which can affect the effectiveness of the organizational structure and decision-making related to the product lifecycle within the product information lifecycle. Due to the variation in measurement methods, this sector mainly discusses the entropy-based measurement of manufacturing information, including entropy-based measurement, measurement of belief in manufacturing information and measurement of complexity in manufacturing information.

Classical measure theory originates from the metric geometry that is used to measure length, area or volume of an objective in the material world. Indefinite phenomenon is an objective reality, and scholars have put forward many calculated formulas to measure the uncertainty of probability theory, fuzzy set theory, possibility theory, evidence theory [6] and so on. Relations of some commonly used measures of uncertainty are shown in Fig. 4.9. In this figure, fuzzy measures provide a big frame that involves a variety of measures including probability measures. The duality is between belief measures and plausibility measures, so one may only identify the other, the two constitute an important though imprecise reasoning model—Evidence Theory in expert systems.

1. The entropy-based measurement

Drestke applies entropy into the measurement of manufacturing systems, suggesting that the more the equipment states, the higher the value of entropy or complexity. Efstathiou et al. [7] proved that the system entropy is equal to complexity, which is used to represent the amount of information that is used to describe the system's descriptive and control states. To discuss how to measure the manufacturing information, the definition of entropy is first given.

- The definition of entropy

Definition 4.2 Suppose the discrete random variable X has n possible values $(x_1, x_2, \ldots, x_n)$, with probability vales $(p_1, p_2, \ldots, p_n)$, then the entropy can be defined as

$$E(X) = -\sum_{i=1}^{n} p_i \log p_i, \tag{4.6}$$

where $p_i \geq 0$, $\sum_{i=1}^{n} p_i = 1$, $\log \sum_{i=1}^{n} p_i = 0$. If X represents a system, x_i and $p_\mathrm{i}(i = 1, 2, \ldots, n)$, respectively represent the n possible states and the probability of each state, E(X) is the entropy of system X. E(X) also indicates the amount of uncertainty. The greater the value of E(X) is, the more uncertainty the system is. From the classical information theory, it is easy to know that

(1) when there is only one value of p_i is 1, and all other 0s, the system has the minimal entropy, E(X) = 0, when the system is definitely known.
(2) when all the states are with an uniform distribution ($p_i = 1/n$), $E(X) = \log n$, when X has the greatest uncertainty.
(3) any change that causes the equal change of p_i will increase the uncertainty of the system entropy.

- Entropy-model-based measurement

(1) Static entropy model (SEM)

SEM comes from Deshmukh et al. [8]. For a distributed parts manufacturing system, the complexity is a function of its structure, subsystems' variable and the strength of association, and following the increasing number of machining parts, machinery, tasks, equipments and increased flexibility of working procedure, it will increase subsequently. SEM shows as follows:

$$H_s = -C \sum_{i=1}^{m} \sum_{j=1}^{m} \sum_{k=1}^{r} \sum_{l=1}^{n} p_{ijkl} \log_2 p_{ijkl} \tag{4.7}$$

In Eq. 4.8, H_s, is a static entropy; C is a constant related to unit of measurement, $C > 0$; m is the total number of operations related to a combination of certain parts and components; n is the number of parts that are processed at the same time in the manufacturing system; r is the total pieces of equipment used for a batch of known parts; p_{ijkl} is the probability of the manufacturing system in a certain state.

The method adapts to a manufacturing system in which parts and processing methods are optional, and can be extended to process a variety of components in a preferential order. It can also be applied to the process of assembling parts or to study the relation between differences of cost structure and static complexity in the system.

(2) Dynamic entropy model (DEM)

SEM can obtain useful data after a long-term measurement, but Frizelle et al. [9] put forward the DEM model, to stress the static (structure) complexity and dynamic (process) complexity in manufacturing system. It has real-time monitoring of the analyzed representative processes and the rule of time interval, to ensure that the system remains stable under the assumption that, when the test system is stable, reliability will decrease after the complexity of the process increases, and the most complex one is the "bottleneck" in the whole process. DEM can be shown as follows:

$$H(S) = \left\{ \begin{array}{l} P\log P + (1-P)\log(1-P) \\ + (1-P)\left[\sum_{M^b}\sum_{N_j^b} P_{ij}^q \log P_{ij}^q + \sum_{M^q}\sum_{N_j^q} P_{ij}^m \log P_{ij}^m \right. \\ \left. + \sum_{M^m}\sum_{N_j^m} P_{ij}^b \log P_{ij}^b \right] \end{array} \right\} \tag{4.8}$$

(3) LEM

Karp and Ronen point out that when the probability of products being on the location of the points in the assembly line is known, the entropy for the position of a set of products in an assembly line can be calculated. They believe that entropy is a function of the scale of batch production; the calculated formula is as follows:

$$H(S) = -\frac{N}{C^2 P}\log\frac{N}{PSC} - \left(\frac{1}{C} - \frac{N}{PC^2}\right)\log\left(1 - \frac{N}{PC}\right) \tag{4.9}$$

In Eq. 4.10, $H(S)$ is batch entropy; S is the total number of all online processing locations; P is the number of parts used to machine a product, N is the number of each batch of machining parts, B is the number of the batch and $P = NB$; C is a constant that is not less than one: its meaning is a ratio of the total production time (time for production and machine + time for the finished product) to a net production time (only including time for production and processing) in a single batch production process.

The model proves that when the number of the batch is not less than 2 and the number of processing locations is more than 2, $H(S)$ is a reduced function; when the number of batches tends to infinite, $H(S)$ is near zero. This model is mainly applied in streamlined production, and is designed to prove that the lower the number of the batch is, the less need there is for information. Its prerequisite is using efficient, high-quality production management tools (such as TQM, JIT and TOC). The method also reveals the important relationship between improved production activities (such as reducing equipment installation and assembly time) and the information needed by the system.

- Composite entropy-based method

Randomicity and ambiguity are two different uncertainties; they cannot replace each other, but are complementary. Therefore, the uncertainty that is caused by randomicity and ambiguity simultaneously in the system can be measured uniformly by a composite entropy or a hybrid entropy. The general entropy *Htot* (A, P), caused by both of the two uncertainties mentioned above, can be expressed as:

$$H\mathrm{tot}(A,\,P)\;=\;H(P)\,+\,M\,(A,\,P) \tag{4.10}$$

In Eq. 4.12, $H(P)$ is the entropy of probability, such as Eqs. 4.11 or 4.12, and the entropy of ambiguity, M (A, P) is:

$$M(A,P) = \sum_{i=1}^{n} p_i S(\mu_i) \tag{4.11}$$

- Fuzzy entropy-based method

Suppose A is a fuzzy subset in domain U, expressed as:

$$A = \sum_{n=1}^{n} \mu_i / x_i, \forall x_i \in U \tag{4.12}$$

in the Eq. 4.13, μ_i is the membership function of x_i, its range is [0, 1]. Suppose $M = (\mu_1, \mu_2, \ldots, \mu_n)$ is referred as to distribution of possibility of fuzzy set A. The formula for calculating fuzzy entropy $m(A)$ pointed out by DeLuca and Termini is as following:

$$m(A) = K' \sum_{n=1}^{n} S(\mu_i) \tag{4.13}$$

in this equation, K' is a normalizing constant, but S (μ_i) is:

$$S(\mu_i) = -\mu_i \log \mu_i - (1-\mu_i)\log(1-\mu_i) \tag{4.14}$$

For continuous variables, there is:

$$M(A) = \int_{-\infty}^{+\infty} \omega(x) S(\mu_i) \mathrm{d}x \tag{4.15}$$

There are other expressions and formulas for the measurement of the entropy of ambiguity, but fuzzy entropy mentioned above is mostly used.

- The general-information-based measurement

The concept of information from Shannon is a purely formal concept (grammatical information), which does not contain the meaning (semantic information) and the value (pragmatic information) of information, therefore its scope is limited. Many scholars establish kinds of measuring formulas for generalized information, and spread the Shannon entropy from a different angle. This generalized information related to grammar, semantics and pragmatics, the three levels of information, is called the general information [10].

The measuring parameter η_n in general information is defined as a function that is a weighted combination of certain degree c, logical reality degree t and validity degree u.

$$\eta_n = f\left(\alpha_{c_n} g\beta_{t_n} g\gamma_{u_n}\right) \tag{4.16}$$

in Eq. 4.17, α, β, γ are grammatical information, semantic information and pragmatic information; f is a certain linear or nonlinear continuous function. In the simplest case, we could suppose the combination is a product, $\alpha = \beta = \gamma = 1$, and f is a linear function that the slope is 1, $\eta_n = c_n t_n u_n$.

The thing X's description model of general information can be expressed as:

$$(X, \zeta) : \{x n, \eta n \,|\, n = 1, \ldots, N\} \tag{4.17}$$

ξ in the equation is X's generalized distribution of general information's parameter. Suppose R is a cognitive host, ξ is R's prior generalized distribution of general information's parameter about X, ξ_3 is its posterior generalized distribution of general information's parameter about X. According to $\sum_{n=1}^{N} \eta_n$ is normalizing or not, we can get different expressions. In the normalized case, there are:

Equation of self-owned general information:

$$I(\varsigma) = \sum_{n=1}^{N} \eta_n \log \eta_n + \log N \tag{4.18}$$

Equation of real obtained general information:

$$I(\varsigma, \varsigma^*; R) = \sum_{n=1}^{N} \left(\eta_n^* \log \eta_n^* - \eta_n \log \eta_n\right) \tag{4.19}$$

- Entropy-based method for 3-D restructure [11]

The information entropy-based method can also be used in 3-D reconstruction, which can be applied in reverse engineering, object recognition, inspection, computer graphics and medical imaging. In the framework of Bayesian statistics, we propose an improved Bayesian information criterion (BIC) for determining the B-spline model complexity. Then, we analyze the uncertainty of the model using entropy as the measurement. Based on this analysis, the information gain for each cross section curve for the next measurement can be predicted. After predicting the information gain of each curve, we obtain the information change for all the B-spline models. This information gain is then mapped into the view space. The viewpoint that contains maximal information gain about the object is selected as the next best view.

2. The measurement of belief in manufacturing information

Evidence in the multiple objective and subject factors is not definite and the decision effect is hard to predict. In order to quantify and measure this objective manufacturing information, statistical and probability methods should be used. In this section, we introduce the Belief-based method to perform such measurement. Inherited from Dempster–Shafer theory (also known as ***evidence*** theory), some existing measurements are introduced as follows:

- The measurement of belief based on indefinite evidence and indefinite deduction

In indefinite deduction that is based on indefinite evidence of uncertainty in the reasoning of uncertainty, a function of belief or trust denotes the degree of trust in an object, which is supported by indefinite evidence. We can use the intervals of probability to express this degree, and have an available D–S synthesized rule with multi-beliefs [6, 12]. Belief Bel is defined as:

Definition 4.3 $\mathrm{Bel}(E) = \Sigma p(e)$, e is E's subset. We define A as the power set of a certain finite set, p is a function of A in [0, 1], and

(1) p (null set) $= 0$;
(2) for all sets: $E \in A$, $p(E) \geq 0$ and $\sum p(E) = 1$The belief $\mathrm{Bel}(E)$ can be obtained by the two belief $\mathrm{Bel}(E_1)$ and $\mathrm{Bel}(E_2)$ through D–S combination rules.

$$\mathrm{Bel}(E) = \frac{\left[\sum_{E_1 \cap E_2 = E} p_1(E_1) p_2(E_2)\right]}{\left[1 - \sum_{E_1 \cap E_2 = \phi} p_1(E_1) p_2(E_2)\right]} \tag{4.20}$$

Obviously, the change in belief of $\mathrm{Bel}(E)$ made by $\mathrm{Bel}(E_2)$ could be denoted conditionally by $[\mathrm{Bel}(E) - \mathrm{Bel}(E_1)]$, and a certain function of $[\mathrm{Bel}(E) - \mathrm{Bel}(E_1)]$ could also express the information that is provided from E_2 to E conditionally.

- Proposition framework, proposition elements and basic probability assignment

In order to measure objective manufacturing information, this section mainly introduces the measure method of Dempster–Shafer evidence theory.

Unit proposition and unit proposition set

Unit proposition e_k is a unit declarative sentence to express the judgment information, and is the particle of information which constitutes information and belief. Unit proposition E is composed of n unit proposition $e_k(k = 1, 2, \ldots, n)$ that is unrepeatable and has nothing to do with the sequence. That E is

$$E = \{e_1, e_2, \ldots, e_n\} \tag{4.21}$$

Typical unit propositions in manufacturing engineering are “quality is eligible”, “quality is not fully eligible”, “status of equipment is normal”, “outstanding performance” or “good performance”.

According to the formal definition of the belief of unit proposition framework elements (p_i), we can define the likelihood and unknown degree of the proposition framework elements (p_i) on the basis of that.

Unit proposition set E involves n unit propositions, and P is power set of E, and

$$P = \{\{p_1\}, \{p_2\}, \ldots, \{p_{2n}\}\} \tag{4.22}$$

P is proposition framework. (p_i) ($i = 1, 2, \ldots, 2n$) are mutually independent proposition elements. P contains the full subsets of E (including the null set), and E is also the proposition element of P. Through the probability transformation, each proposition element (p_i) is given a probability assignment in [0, 1] to get a group of independent uncertainty propositions. The sum of the assignment of all proposition elements should be satisfied with following formula:

$$\Sigma m(\{p_i\}) = 1 \qquad i = 1, 2, \ldots, 2n \tag{4.23}$$

$m(\{p_i\})$ is the basic probability assignment of the proposition elements $\{p_i\}$. Equation 4.24 shows that the basic probability assignment of all proposition elements $\{p_i\}$ should meet conditions of total probability.

- Belief for proposition elements

In manufacturing engineering, belief is defined by the various proposition elements (p_i). In D–S evidence theory, manufacturing engineering belief for any proposition element (p_i) is defined as Bel ($\{p_i\}$), and

$$\mathrm{Bel}(\{p_i\}) = \Sigma m\big(\{p_j\}\big) \tag{4.24}$$

In Eq. 4.25, p_j is the subset of p_i From this equation, Bel ($\{p_i\}$) is the sum of some related basic probability assignments $m\big(\{p_j\}\big)$ on the basis of p_j being the subset of p_i. Due to the total probability condition, so any Bel ($\{p_i\}$) should meet:

$$0 \le \mathrm{Bel}(\{p_i\}) \le 1 \tag{4.25}$$

Obviously, from Eqs. 4.25 and 4.26, we can get:

$$\mathrm{Bel}(E) = \Sigma m(\{p_i\}) = 1 \tag{4.26}$$

3. Complexity of manufacturing information
(1) Static complexity of manufacturing information

The static complexity of manufacturing systems describes the amount of information that is used to anticipate the state owned by various resources in the static state, which is called static complexity C_S. To a certain manufacturing system, the anticipated states of resources are dependant on the production scheduling scheme. Consequently, static complexity can measure the information based on a scheduling scheme.

Suppose a manufacturing system is composed by M resources $(M \geq 1)$, the i-th resource $(1 \leq i \leq M)$ has S_i states, and each state is independent. From (4.6), the static complexity of resource i can be calculated as

$$C_{s,i} = -\sum_{j=1}^{S_i'} p_{ij}' \log p_{ij}' \tag{4.27}$$

where p_{ij} means the probability of state i in state j, and $1 \leq j \leq S_i'$, $\sum_{j=1}^{S_i'} p_{ij}' = 1$.

In the light of the characteristic of information entropy, the static complexity of the whole manufacturing system can be calculated as follows:

$$C_{ss} = -\sum_{i=1}^{M} \sum_{j=1}^{S_i} p_{ij}' \log p_{ij}'. \tag{4.28}$$

We should note that the static complexity is in the upper bound. Considering the fact that the probability of each state is not totally random, the real complexity is lower than this upper bound.

The key for computing static complexity is how to define the states. For the discrete manufacturing system, we generally use the discrete states related to the scheduling process (e.g., the state of a machining tool from one type of process to another). For the continual manufacturing system, we can split the different states on demand with a certain meaning. For example, in order to measure the time-out status in a production process, we could set the 0–0.5 h as the light time-out state, and set the 101–200 products as the severe production state.

In essence the static process structure in manufacturing systems decides the possible states and the number of them; therefore the static complexity of manufacturing systems can be obtained. Its value increases with the number of resources, types of parts, number of processes, the flexibility of processes, and otherwise. Also, the value of static complexity is constantly ignoring the categorical processing of machined parts.

(2) Dynamic complexity of manufacturing systems

Static complexity only considers the states followed by predefined the production scheduling scheme, while the dynamic complexity concerns the real state during operation. The dynamic complexity of manufacturing systems is defined as the amount of information C_d of various resources during the operation. The real status during the operation can be categorized into two classes: (a) the normal state followed by anticipated scheduling (referred to as controllable state), and (b) the malfunctioning status outside the anticipated scheduling (referred to as uncontrollable state). The real state can be obtained by the direct observation during the operation.

Following Eq. 4.7, the dynamic complexity of the manufacturing system in resource i can be calculated as:

$$C_{d,i} = -\sum_{j=1}^{S'_i} p'_{ij} \log p'_{ij} \tag{4.29}$$

where S'_i means the number of real states of resource i during the operation, which can be gained by observation; p'_{ij} means the probability that the resource i is in the state j. Besides,

$$\sum_{j=1}^{S'_i} p'_{ij} = 1,\ 1 \le j \le S'_i. \tag{4.30}$$

If we define the state of controlled state in real state as S'_i (with the occurring probability P_i), the other states are uncontrollable. From Eq. 4.29, we obtain:

$$C_{d,i} = -P_i \log P_i - \sum_{j=2}^{S'_i} p'_{ij} \log p'_{ij} \tag{4.31}$$

where p'_{ij} is the probability of resource i in uncontrollable state which is equal to

$$j \sum_{j=2}^{S'_i} p'_{ij} = 1 - P_i$$

Note the resource's probability in controllable state is P, the uncontrollable state of resource i is denoted as N_i; therefore, the complexity of the whole manufacturing system is

$$C_{ds} = -P \log P - \sum_{i=1}^{M} \sum_{j=1}^{N_i} p'_{ij} \log p'_{ij} \tag{4.32}$$

where M denotes the number of states in the system; the right second part denotes the complexity caused by the deviation of the scheduling states (the required amount of information to describe the uncontrollable states), which depicts the amount of uncertainty in the running process of manufacturing systems.

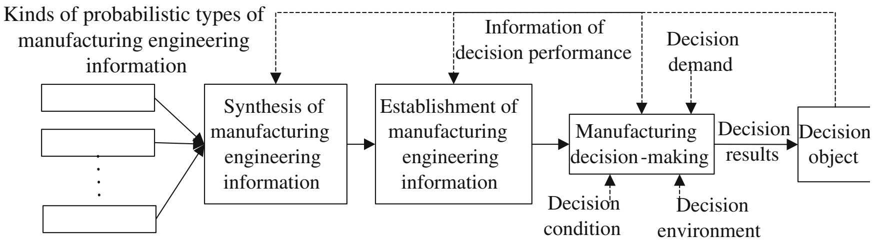


Fig. 4.10 Synthesis, belief establishing and decision-making of probabilistic type manufacturing information

The analysis complexity can be used in the scheduling process (that is, the scheduling in statistics, not the general specific scheduling process), and can be applied to select the optimal scheduling scheme. The evaluation index in common use includes the features that the average operation time is the lowest, Makespan is lowest, the average operation delay is lowest, the maximum equipment is in use, and so on. In the absence of an effective evaluation index, people are less concerned about the actual state of implementation and the final results of scheduling, which is the validity of scheduling. The entropy-based complexity measuring model provides important methods and tools for analyzing the validity of scheduling.

4.2.2 Synthesis of Manufacturing Information

Belief and proposition-based measurement, those concepts introduced in the sections above, will also be used for the synthesis of manufacturing information presented below. The type, form and quantity of information in manufacturing engineering is varied, but until now has not been formalized and there is no general formulation. Therefore, this section will introduce the formulation of the unit proposition of probabilistic type manufacturing information and the comprehensive synthesis of decision-oriented and the unit-proposition-based probabilistic type manufacturing information (shown as Fig. 4.10). The characteristic of this method is that, for the different manufacturing information in the same proposition framework and for different proposition frameworks, the method can synthesize both the common part and the different part (difference of manufacturing information) of that information.

In order to make a decision, firstly we need to synthesize two different pieces of multi-information that support decision-making. The evidence theory provides a method of synthesizing two evidences. However, in the face of various different information, a decision-maker should know both the common part and the different part of the different information in decision-making. This is because not only the common parts in the different information are important to decision-making but also the different parts. For instance, some different information have ability to deny in one ticket, and different part with fairly large probability should be considered, etc. It is obvious that to support decision-making, a method to comprehensively synthesize both the common part and the different part of probabilistic type manufacturing information at one time is required.

1. Comprehensive synthesis of probabilistic type manufacturing information in the same proposition framework

(1) Formulation of probabilistic type manufacturing information supporting decision-making

E, proposition framework P, and its basic probability value set M can state probabilistic type manufacturing information I that supports decision-making, source formula of I is:

$$\left.\begin{array}{l} E=\{e_1,e_2,\ldots,e_n\} \\ P=\{\{p^1\},\{p^2\},\ldots,\{p^{2^n}\}\} \\ M=\{m(\{p^1\}),m(\{p^2\}),\ldots,m(\{p^{2^n}\})\} \\ \sum m(\{p^i\})=1,\ i=1,2,\ldots,2^n \end{array}\right\} \tag{4.33}$$

This formulation is consistent with classical information theory.

First, we will introduce a comprehensive synthesis of two probabilistic types of manufacturing information, and then spread into a synthesis of probabilistic type multi-manufacturing information on the basis of the equation above. According to the source formula of I, in the same proposition framework $P=\{\{p_1\},\{p_2\},\ldots,\{p_{2n}\}\}$, the unit proposition of manufacturing information I_1 and I_2 can be stated:

I_1:

$$\left.\begin{array}{l} P_1=\{\{p_{11}\},\{p_{12}\},\ldots,\{p_{1b}\}\} \\ M=\{m(\{p_{11}\}),m(\{p_{12}\}),\ldots,m(\{p_{1b}\})\} \\ \sum m(\{p_{1i}\})=1,\ i=1,2,\ldots,2^n \end{array}\right\} \tag{4.34}$$

I_2:

$$\left.\begin{array}{l} P_1=\{\{p_{21}\},\{p_{22}\},\ldots,\{p_{2b}\}\} \\ M=\{m(\{p_{21}\}),m(\{p_{22}\}),\ldots,m(\{p_{2b}\})\} \\ \sum m(\{p_{2i}\})=1,\ i=1,2,\ldots,2^n \end{array}\right\} \tag{4.35}$$

The two pieces of probabilistic type manufacturing information I_1 and I_2 are in the same proposition framework and should meet the total probability condition, its synthesizing information I_{12} involves common part $I_{12\text{com}}$ and different part $I_{12\text{dif}}$. $P_{12\text{com}}$ in $I_{12\text{com}}$ is defined as set of intersections which is not null set and symmetrical difference set of P_1 and P_2 sets' elements; $M_{12\text{com}}$ is defined as a set of product of the corresponding elements in M_1 and M_2 set. The specific algorithm is:

$I_{12\text{com}}$:

$$\left.\begin{array}{l} P_{12\text{com}} = \{\{p_{12\text{com}}(ij)\}\}_{a\times b} \\ M_{12\text{com}} = \{m_{12\text{com}}(ij)\}_{a\times b} \\ \{p_{12\text{com}}(ij)\} = \left\{\{\{p_{1i}\} \cap \{p_{2i}\}\}^2, \{\{p_{1i}\} \cap \{p_{2i}\}\}^1\right\} \end{array}\right\}\} \tag{4.36}$$

$P_{12\text{dif}}$ in $I_{12\text{dif}}$ is defined as a set that is composed of elements in intersection of P_1 and P_2 sets' elements and intersection is not null set. $M_{12\text{dif}}$ is also defined as a set of product of its corresponding elements in M_1 and M_2 set. The specific algorithm is:

$I_{12\text{dif}}$:

$$\left.\begin{array}{l} P_{12\text{dif}} = \{\{p_{12\text{dif}}(rs)\}\}_{a\times b} \\ M_{12\text{dif}} = \{m_{12\text{dif}}(rs)\}_{a\times b} \\ \{p_{12\text{com}}(rs)\} = \{\{p_{1r}\} \cap \{p_{2s}\}\}^1 \\ m_{12\text{dif}}(rs) = m(\{p_{1r}\}) \times m(\{p_{2s}\}) \end{array}\right\} \tag{4.37}$$

Equation 4.38 represents the difference of manufacturing information in comprehensive synthesizing information I_{12}; the condition of Eq. 4.38 is $\{p_{1r}\} \cap \{p_{2s}\}$ is a null set, and $r \in \{1, 2, \ldots, a\}$, $s \in \{1, 2, \ldots, b\}$. Because manufacturing information I_1 and I_2 are in the same proposition framework and meet the total probability condition, apparently, the sum of elements in $M_{12\text{com}}$ and $M_{12\text{dif}}$ should meet the total probability condition also.

In summary, the comprehensive synthesizing information I_{12} of manufacturing information I_1 and I_2 which are in the same proposition framework is:

$$\begin{array}{l} I_{12} : I_{12\text{com}}, I_{12\text{dif}} \\ \left.\begin{array}{l} I_{12\text{com}} : \\ P_{12\text{com}} = \{\{p_{12\text{com}}(ij)\}\}_{a\times b} \\ M_{12\text{com}} = \{m_{12\text{com}}(ij)\}_{a\times b} \\ I_{12\text{dif}} : \\ P_{12\text{com}} = \{\{p_{12\text{com}}(ij)\}\}_{a\times b} \\ M_{12\text{com}} = \{m_{12\text{com}}(ij)\}_{a\times b} \end{array}\right\} \end{array} \tag{4.38}$$

2. Comprehensive synthesis of probabilistic type multi-manufacturing information

On the basis of the synthesis of two pieces of manufacturing information, we can comprehensively synthesize multi-manufacturing information in the same proposition framework. The steps are:

   (1) Synthesizing any two pieces of manufacturing information;
   (2) Synthesizing the result of (1) and the third manufacturing information, etc. It is I_{12} synthesizes I_1 and I_2, I_{123} synthesizes I_{12} and I_3 and I_{1234} synthesizes I_{123} and I_4, etc. According to Eq. 4.38, the synthesizing result above is nothing to do with sequence.

3. Comprehensive synthesis of probabilistic type manufacturing information in the different proposition framework
   (1) Comprehensive synthesis of probabilistic type manufacturing information in the two different proposition frameworks

Firstly, a same proposition framework is synthesized by two different proposition frameworks, for example, the two pieces of probabilistic type manufacturing information, which is based on a different proposition framework, is

$$\begin{aligned}
&I_1:\\
&\mathrm{P}=\{\{p_1\},\{p_2\}\},a=2\\
&\mathrm{Mp}=\{m(\{p_1\}),m(\{p_2\})\}\\
&I_2:\\
&\mathrm{Q}=\{\{q_1\},\{q_2\},\{q_3\}\},b=3\\
&\mathrm{Mq}=\{m(\{q_1\}),m(\{q_2\}),m(\{q_3\})\}
\end{aligned}\tag{4.39}$$

In the same proposition framework, the common basic probability value is:

$$\begin{aligned}
&m(\{p_1\}\{q_1\},\{p_1\}\{q_2\},\{p_1\}\{q_3\})=m(p_1)\\
&m(\{p_2\}\{q_1\},\{p_2\}\{q_2\},\{p_2\}\{q_3\})=m(p_2)\\
&m(\{q_1\}\{p_1\},\{q_1\}\{p_2\})=m(q_1)\\
&m(\{q_2\}\{p_1\},\{q_2\}\{p_2\})=m(q_2)\\
&m(\{q_3\}\{p_1\},\{q_3\}\{p_2\})=m(q_3)
\end{aligned}\tag{4.40}$$

The other non-integrity basic probability value such as $m(\{p_1\}\{q_1\})$ and $m(\{p_1\}\{q_1\},\{p_1\}\{q_2\})$ is also defined as zero. The Eq. 4.41 can be proved as following:

$$\begin{aligned}
&m(\{p_1\}\{q_1\},\{p_1\}\{q_2\},\{p_1\}\{q_3\})\\
&=m(\{p_1\})m(\{q_1\})+m(\{p_1\})m(\{q_2\})+m(\{p_1\})m(\{q_3\})\\
&=m(p_1)[m(\{q_1\})+m(\{q_2\})+m(\{q_3\})]=m(p_1)
\end{aligned}\tag{4.41}$$

The proof of other equations is like that above.

   (2) Comprehensive synthesis of probabilistic type multi-manufacturing-information

Because the probabilistic type multi-manufacturing information is in a different proposition framework, its synthesizing process is:

(1) According to the method mentioned above, any two proposition frameworks and their related probabilistic type manufacturing information can be synthesized.
(2) By synthesizing the result of (1) and the third proposition framework and its related probabilistic type manufacturing information, the synthesis of probabilistic type multi-manufacturing information can be completed.

4.2.3 Materialization of Manufacturing Information

In the view of information science, the manufacturing process involves information collection, transmitting, machining and application. Product is the materialization of manufacturing information. In the product lifecycle, materialization is located on the process of machining. In this section, we will discuss the materialization mechanism and preset of materializing manufacturing information.

Materialization of manufacturing information is a special transmission and transformation of original manufacturing information. The purpose of materialization is to produce a product that involves original manufacturing information and expected quality by the transmission/transformation of original manufacturing information in a quick and economical way. The production of materialization is not only controlled by kinds of manufacturing information, but is also influenced by manufacturing information with errors and interference. For instance, in the numerical control machining system, the effect of errors of information transmission link and mechanical errors, as well as various nonlinear factors, the table will shift from command value, and the open-loop system is unable to correct it effectively, thus a conventional CNC machine will still have difficulty achieving high-precision machining even if it makes use of high-performance digital servo-systems.

1. The flow of information materializing
(1) The four main flows

From the point of view of information, materialization is the source manufacturing information, which is mainly non-entity type manufacturing information. It is transformed to entity type manufacturing information which is in entity through the transmission/transformation linking source information with entity type manufacturing information. The flow chart of some common materialization of information is shown in Fig. 4.11.

(2) The information features and requirement in materializing transformation

In manufacturing activities, the main form of manufacturing information involves two categories: non-entity and entity type. The entity type of manufacturing information, that is, the manufacturing information assigned to the entity, includes the ontology information of all entities: the entities with unit

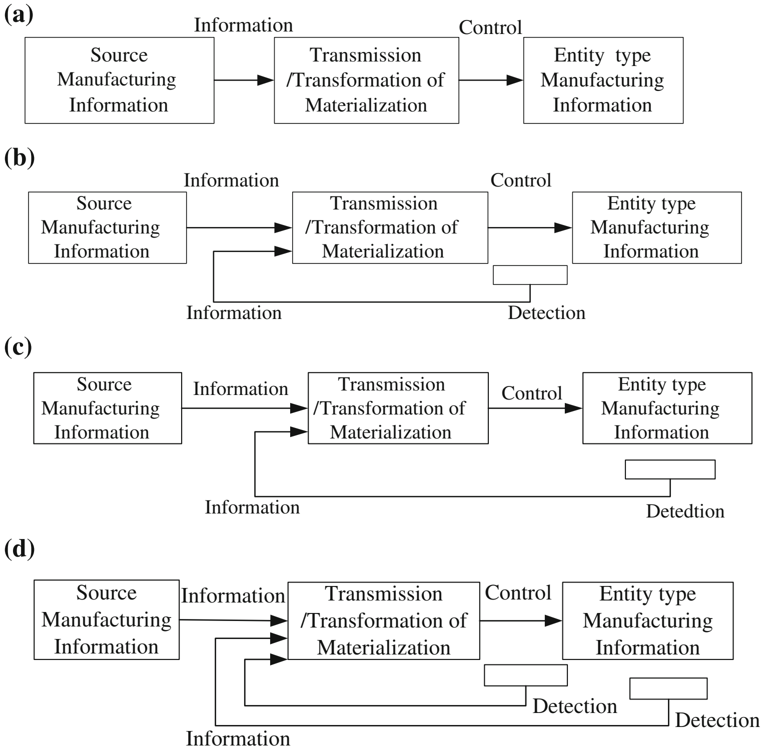


Fig. 4.11 The flow of transmitting/transforming information in materialization. (**a**) Open-loop transformation of materialization. (**b**) Half closed-loop transformation of materialization. (**c**) Closed-loop transformation of materialization. (**d**) Composite loop transformation of materialization

manufacturing information, such as molding cutters, moulds and fixtures, and the entities with unit manufacturing information, such as the RP model, the work after forming, the hardness after machining and assembled components. The non-entity type information includes the manufacturing information, skill information and experience information expressed by symbol.

An information feature in the transformation of materialization is that according to the given order, information i of pre-setting, setting and post-setting are combined with determined manufacturing constrained function f in an appropriate way to become the corresponding manufacturing control c. By using manufacturing equipment E, c will trigger the change in state, process or control of controlled manufacturing entities on the entity B through materialization M, and will generate a variable P set produced by the entity with manufacturing information i, constrained transforming interference n_1 and materializing transforming n_2. From this, we can write the elements set of materializing transformation:

$$\mathrm{W} = \{i, f, c, n_1, n_2, \ \mathrm{E}, \ \mathrm{M}, \ \mathrm{B}, \ \mathrm{P}\}, \text{ and } c = f(i) \tag{4.42}$$

The basic information features of materializing transformation include: the input is source manufacturing information i, which is the instruction of materializing transformation; manufacturing constraint is the corresponding manufacturing control c combining function f and source information i; in manufacturing equipment E, through manufacturing craft M, manufacturing control will trigger the change in controlled state, process or control on entity B; output is variable P set that is produced by the entity with manufacturing information i, constrained transforming interference n_1 and materializing transforming n_2.

At the angle of information, the indispensable information requirements that materializing transformation should meet are:

Firstly, based on the allowable error accepted by the consumer in function and performance information, we should get the variable P set that is produced by the entity with i, n_1 and n_2 quickly and economically.

Secondly, materialization of the original manufacturing information should be good, and the source manufacturing information should match the transmission/transformation of the materialization link. We should then implement full quality management of manufacturing information and full investigation of market demand, and may consider the possible demonstrated scheme and designed concept of demand and implementation. The experimental study, the implementation of virtual manufacturing, establishment of a credible supply chain, making cost accounting and design rational, exercising strict control over cost and ensuring the information of assembling, testing, trial running, packing, shipping, application engineering and after-sales service, etc. are integral.

In addition, the quality of the results of materializing transformation can be detected. Typical materializing transformations are the changes in the rotating speed of the controlled principal axis and changes in the location of the controlled CNC machine table which are all triggered by the cutting processing in the machining center. These qualities of transforming results can all be detected.

(3) Information control in materializing transformation

Corresponding to the flow of materialization above, information control in materializing transformation includes open-loop control, closed-loop control and other different means. Manufacturing information is the dominant energy so it can not trigger entity variance directly by itself, but it must dominate manufacturing constraint with a great deal of energy to generate manufacturing control which can trigger change in the state, process or control of an entity.

The elements set W of materializing transformation is shown in Eq. 4.43. In digital materializing transformation, both i and c are discrete variables,

and $i \in I$, $c \in C$.

The I is a set of manufacturing information; C is a set of manufacturing control, both I and C are limited. The feature of f is: its domain is I, but not any proper subset, and each $i \in I$ is in correspondence with the only $\mathrm{c} \in C$.

In $\langle i, c \rangle \in f$, $\mathrm{dom}\, f = \mathrm{I}$, $\mathrm{ran}\, f \subseteq C$.

Apparently, no two images are the same in I while the mapping is from I to C, therefore, constraint f is a one-to-one mapping, namely incidence. Due to this, the

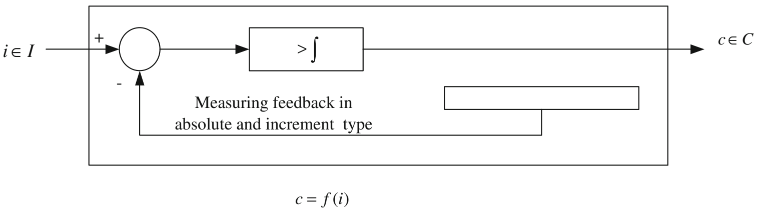


Fig. 4.12 NC displacement closed -loop servo-system $c = f(i)$ in the closed-loop mode of information control

number of different incident functions should be $[n(n) - 1)(n - 2) \cdots (n - m + 1)]$ when I has m elements and C has n elements and $m < n$.

We can use the uniaxial NC displacement closed-loop servo-system as the example of $c = f$ (i), which is a typical closed-loop mode of information control, shown in Fig. 4.12. It is divided into absolute (such as absolute encoder) and increment (such as grating ruler, inductosyn, etc.) measuring feedback type NC closed-loop displacement servo-system. The former's definition of numerical controlled displacement instruction information and set I include all the location instructions. The relation between instructions and displacement range set C is incidence. The latter does not consider the kinds of typical application information package; I just includes four unit instructions, $I = \{$positive unit pulse, zero pulse, negative unit pulse, absolute null position instruction$\}$. There are also three corresponding unit displacements and one absolute null position, C = $\{$positive unit displacement, zero displacement, negative unit displacement, absolute null position$\}$. Evidently, the relation of $I \rightarrow C$ is objective.

(4) Materializing transformation and interference

Though the denotation of manufacturing information i used for materializing is exact or relatively exact, the corresponding manufacturing control c sometimes has the constrained transforming interference n_1, such as a gap in the mechanical transmission chain, windage, the bearings' contested direction flop, guides' straight errors, screws' pitch error, and so on. In addition, inevitable interference n_2 of materializing transformation also exists when we use manufacturing equipment E to achieve materialization through materializing craft M, such as cutter wear, cutting chatter, the deformation of a fixture by force, the deformation of a workpiece by force, the rebound after molding the cover sheet by pressure and the thermal deformation of the machine, all of which constitute inevitable interference in manufacturing transformation. Interference n_1 and n_2 in constrained and materialized transformation will be the output errors on entities; they should not go beyond the given allowable errors.

Suppose the entropy of manufacturing information set I is $H(I)$, entities determined by I produce variable set$P$, the entropy of which is $H(P)$, if there is no interference n_1 and n_2, $H(p)$ is:

$$H(I) = H(P) \tag{4.43}$$

Because of interference n_1 and n_2, Eq. 4.44 is not true. Suppose $H(I, P)$ is the joint entropy of I and P, which is known, the $H(I, P)$ is:

$$H(I,P) = H(I) + H_I(P) = H(P) + H_P(I) \tag{4.44}$$

In this equation, $H_I(P)$ is the conditional entropy of P when I is known; $H_P(I)$ is the conditional entropy of I when P is known.

The definition of transmission rate R of materializing transformation is:

$$R = H(I) - H_P(I) \tag{4.45}$$

$H_\mathrm{P}(I)$ in the equation is referred as to the usability of channel in materializing transformation with interference, which indicates the average fuzzy degree; $H_I(P)$ is the strolling degree, and expresses the error range of P, which is triggered by I at the output terminal.

Aiming at the inevitable interference n_1 and n_2, materializing inaccuracy is expressed as follows.

Materializing inaccuracy of manufacturing information: in materialization of manufacturing information, it is inevitable that $H_I(P) > 0$ exists. The key method is the allowable error of $H_I(P)$ which is set rationally, or trying to decrease or compensate the performance of $H_I(P)$.

According to this, we can deduce that the quality of entities produced is below optimum; it is wasteful to cleanup the errors of variable set P produced by entities through full input of the manufacturing information; improving the quality produced by entities will increase production cost but will reduce waiting cost. Considering the two opposite trends, a domain of economic quality exists; and in the same domain of economic quality, the less dispersion induced by interference that occurs in the output process, the greater the output quality is.

2. Value assignment of materializing information

(1) Preset and reconstruction for presetting manufacturing information

The outstanding characteristic of the manufacturing information materializing is that quite a few parts of the manufacturing information materialized on entities come from preset but are not produced by implementation and value assigned.

Because the manufacturing activities of accomplishing producing entities need large numbers of manufacturing information, it is impossible and unnecessary for a producer to present all the information in real-time and assign it to entities. Usually, when we establish a new manufacturing information package, most of the information is constituted by the various manufacturing information units we have. The manufacturing information units must have the value of recycling and can also be reconstructed. For promoting the rate of recycle of preset manufacturing information, we should define the boundaries of all kinds of manufacturing information units, enrich the content of manufacturing information units and the standardization degree of the interface, and enlarge its resource and update its component units.

The materialization of manufacturing information does not begin with zero manufacturing information, but starts with determined preset manufacturing information. Materialization should make the best of preset manufacturing information that is able to be recycled, and then use it after reconstruction. It should accumulate, update, upgrade the quantity and quality of preset manufacturing information and focus on resolving the problems of reconstruction.

Preset manufacturing information has two forms:

The form of hardware, such as manufacturing equipment, fixtures, cutters, measuring tools, tools and so on. A great deal of set accuracy manufacturing information is already pre-stored in the form of the hardware.

The form of software, such as policies and regulations, market information, technical documentation, product descriptions, management regulations, instructions, manuals, books, journals, photographs, drawings, experts' experience, staff skills, system software, application software, engineering/knowledge database and production organization, are all preset manufacturing information.

At the same time, in order to understand and optimize the processes of materialization, the implementation of manufacturing information materializing requires the establishment of a manufacturing information model. As with the preset of materializing the manufacturing information, a preset of the manufacturing information unit is needed to enhance the efficiency of establishing the manufacturing information model.

(2) Set for materializing manufacturing information

From the point of view of technique, when we complete manufacturing tasks according to market demand, we should preset certain materializing manufacturing information, such as the CAD system, MIS systems, manufacturing databases, machining machine tool, logistic control devices, measuring tools, cutters, butted knife installation, experienced staff, production organization and management system of the workshop. Enterprises cannot start with zero information.

Apart from the mass production tasks, the preset materializing manufacturing information is selected according to the range of products and program during a specific period, not by certain products only. Furthermore, based on advanced manufacturing technology, all preset manufacturing information must have the function of reconfiguration, and all of these functions require the supplementary information to be effective when it is used. Therefore, manufacturing information I_{A} is able to take effect while combining with the materialization manufacturing information I_{R}.

Both preset and real-set materializing manufacturing information needs investment. When the amount of preset materializing manufacturing information does not exceed a certain limit, it might be supposed that the cost of real-set materializing manufacturing information reduces along with investing in preset materializing manufacturing information. If the amount is beyond a certain limit, however, the cost of the real-set materializing manufacturing information will not continue to reduce significantly along with the increasing investment for preset information. The real-set information, which is at least the information about planning, invocation, adjustment, programming and reconfiguration and so on, must be included. Thus, the preset manufacturing information should be considered carefully.

(3) Post-set for materializing manufacturing information

The investment for materializing manufacturing information runs through the whole lifecycle. The output of products is guaranteed by preset manufacturing information I_A and real-set manufacturing information $I_{R,}$ and post-set manufacturing information I_P assures the effective application of products. Its representative form is application engineering of equipment products.

The post-set application engineering information depends not only on the application of engineering equipment manufacturing factories, but also largely on the application conditions. To take full advantage of equipment, it is important for users to do a good job in purchasing new equipment and equipment application projects. Taking the complete set of equipment application engineering as an example, the main contents of post-set manufacturing information I_P are: trial runs of unloaded and fully loaded equipment, qualified workpieces produced according to users' production conditions; reliability test; offline training for consumers' operating workers; the products are disintegrated, packed and shipped after they are authorized by users; in consumers' production workshop, products are installed, debugged, running on trial and tested for reliability to produce qualified workpieces; consumers' operating workers training on the spot; the instructions should be transferred and warranty conditions should be explained; equipment repairs, maintenance and technical transformation after use; regular investigation on usage situation of users' equipment.

4.3 Integration, Sharing and Security of Manufacturing Information

4.3.1 Integration Model for Manufacturing Information

With economic development, society's demands of the manufacturing market are increasingly diversified and individualized, so it is necessary for enterprises, especially discrete manufacturing enterprises, to grasp economic and technical information quickly. The original information system in enterprises is based on a single department or LAN and is therefore confined to a development and application environment in various periods, so that the functions and data of various systems are independent of each other, which results in the "information isolated island". The development in technology of Intranet/Internet/Extranet supplies powerful technical support for integrating system information so that a single system can be merged into a dynamic alliance, from a single department to the whole enterprise and the wider field of virtual enterprises. The study of product lifecycle management has also spread from basic concepts and systems to techniques and implemented methods based on an enterprise's lifecycle holistic resolving scheme. Enterprises will be provided with a supportive environment and functions that support coordinated operation in the whole product lifecycle, as well as standardized implementation techniques and methods. The techniques and applications (including the framework of enterprise basic information, uniform product model and single data source) related to holistic resolving scheme will become the emphasis of product lifecycle management. Therefore, the integration, sharing and even security of manufacturing information discussed in this section are closely linked to the informatization of product lifecycle management.

1. Basic concepts of information integration

(1) Definition of information integration

The expression "information integration" has the meaning of information merging, conforming, fusing and organic combination. Though researchers use different words, the objective is the same. Other common ways this might be expressed are as follows.

Information integration is the idea that organic fusion of related multi-information can be achieved and used optimally. It does not mean the physical accumulation of information or information carriers. It is a dynamic process that organically fuses all the elements in information sources and uses them optimally, which is aimed at the demand for a special field and a special user, in which the object is information, the subject is information resource, the drive is service, the instrument is network, and the method is collaborative business. Thus, it is a process to optimize elements and reconstruct systems.

Information integration also concerns the idea that information is organized and managed according to a certain target or on the basis of special services. The core of integration is that we look upon sources as one big system and adopt technical instruments to adapt information to realize resource sharing. On the basis of a particular subject, correlated information coming from different information sources (whatever its location, data structure or communication requirement is) can be integrated into a whole, and and access provided to users through network and application software. Information integration is a process in which we fuse information resources, technology resources and intelligence resources based on a determined task and use them optimally.

(2) Principle of information integration

The principles of information integration [13] are integration principle (maintaining the integration of resources), continuity principle (expansibility and continuity of resource integration), pertinence principle (ensuring the purpose of the integration is meeting the requirement of special client), hierarchy principle (structure and multi-dimension of integration), science principle (science of integrated object, content and mode), priority principle (using techniques and methods to optimize structure and function), special indication principle, open principle and system principle.

The structure of an integral information integration system involves an application system, interface definition, application support, and data source system [14], as shown in Fig. 4.13.

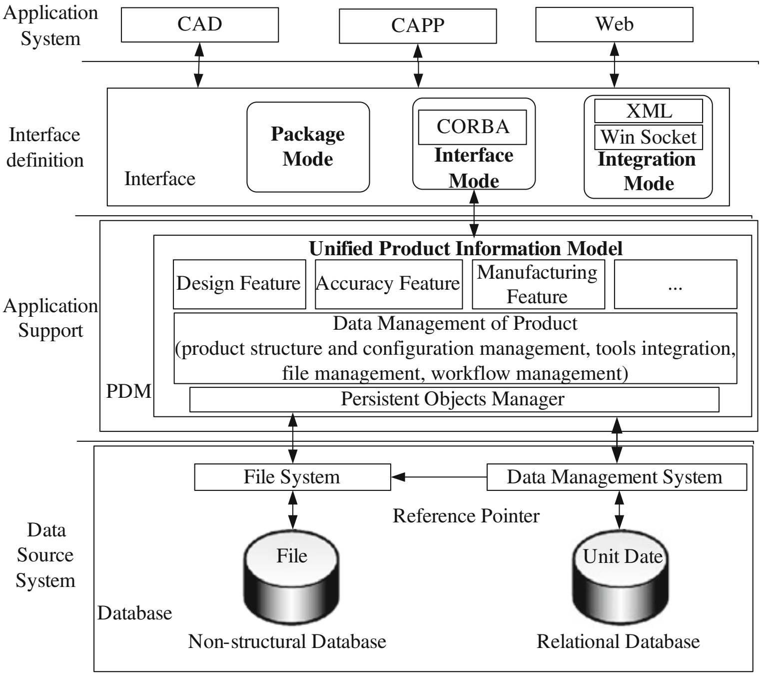


Fig. 4.13 Architecture of information integration system

2. Typical application of information integration—CIMS

CIMS is a typical application in early manufacturing information, and its basic model has some different types, such as point to point, network type, bus type, pipe type and hub type. Figure 4.14 shows the topological structure of models of different types.

Integration optimization is the nuclear technique in CIMS technology and application, and it has developed into process integration whose representative is parallel engineering from the early information integration whose representative is computer integrated manufacture. It also can be divided into three phases: information integration optimization, process integration optimization and inter-enterprise integration optimization. Information integration optimization mostly helps enterprise change and shares information among those automatic isolated islands. The information integration was realized by LAN and database in early times. At present, the important tool that supports system information integration is an integration framework based on distributed object technique, middleware technique and web technique. Process integration optimization refers to data and resource sharing and collaboration business in CIMS application can be realized effectively in real-time by using computer software to integrate supportive tools (for instance, the integration platform); those isolated application processes are then integrated into a compatible CIMS operation system. Inter-enterprise

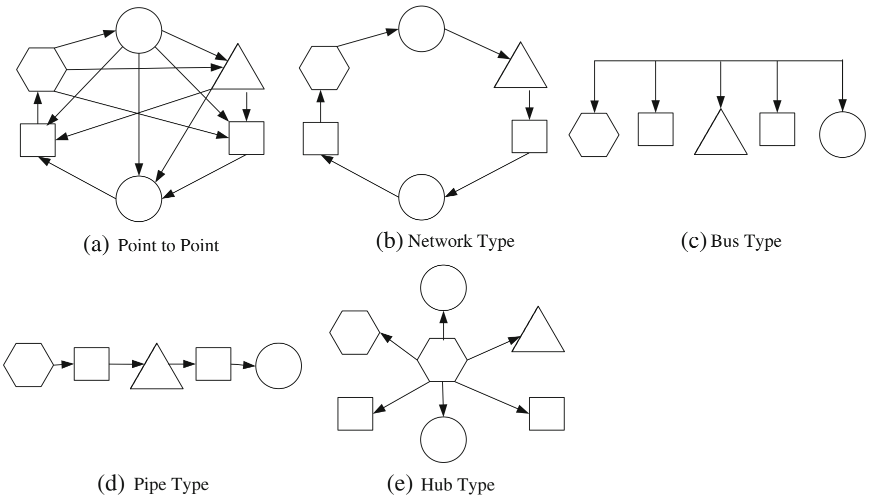


Fig. 4.14 CIMS integration model

integration optimization is the optimal use of enterprises' internal and external resources and realization of smart manufacture in order to adapt to new situations of knowledge economy, global economy and global manufacture. Presently, inter-enterprise integration mainly has seven realizing forms: based on data, based on application interface, based on method, based on business logic, based on data entrance, based on process, and based on service (for example ERP and E-Commerce).

Figure 4.15 shows the integration framework of a CIMS system in the 1990s.

According to the compact degree of integration of CIMS application systems, the integration can be divided into three levels in accordance with current mainstream classification method. The three levels are the application package, interface switching (API) and compact integration. At present, most integration providers mainly use the API technology. Of course, some scholars divide the integration into the five levels: influx, customization, remote procedure call, distributed objects and integration platform, which range from low to high according to the level of integration.

3. Strategy of information integration

CIMS application integration has different classifying methods at different angles. It can be divided into data-oriented integration and process-oriented integration by the object of application integration; by the use of technology and tools in application integration, it is divided into four levels: data integration, systems integration, process integration and inter-process integration (B2B) [15]. Below, we will analyze the integrated technology and methods used in CIMS application integration from the depth of the integration level.

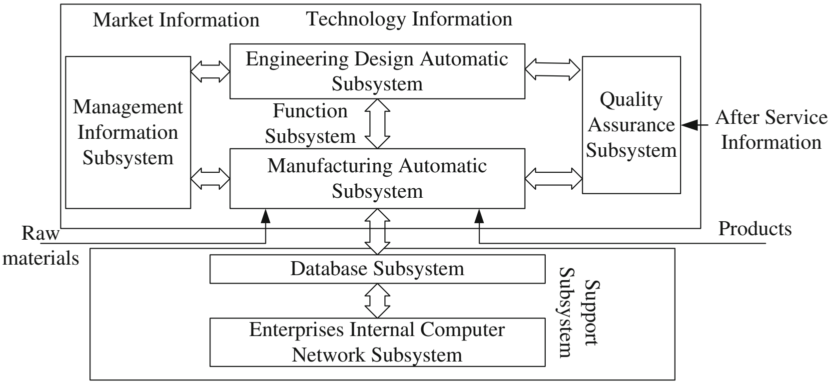


Fig. 4.15 CIMS system of integral application based on enterprise-level

(1) Data/Information-oriented integration

This form mainly realizes data exchanging and sharing in different systems. The important data processing techniques adopted by data integration are data duplication, data and interface integration.

1. Data replication. Data replication is designed to maintain the consistency of data in different databases, but the databases can belong to the same manufacturer or to different manufacturer, even though they can have different models and management modes. The basic requirement for data replication is that it should be able to provide a basic infrastructure to transform and transmit data, so that it can shield the difference between data models in different databases. The characteristic of data replication is that it is simple, low-cost and easy to implement, but it is important to understand the internal business in systems profoundly and fix its application.
2. Data federation. Data federation is used for integrating multiple databases into a unified and viewable virtual database. It is necessary for data to establish a level of middleware to combine various distributed databases and applications. The middle layer will find a mapping between the background real databases and the virtual database. The data federation method has the advantage of expressing the variety of data types as a unified data model, using easy operation language and supporting the exchange of information, without having to change the data sources and applications. It can access every database linked to the enterprises through a well-defined interface, and also provides a good solution for the problems of data-oriented application integration by using a unified interface.
3. Interface integration. The approach of interface integration is that data models in application systems, which need to be shared, are extracted and defined into the whole model of CIMS, so that integration of the application package and customization application will be realized by using a well-defined application interface. The adapters are used for particular realization through integration

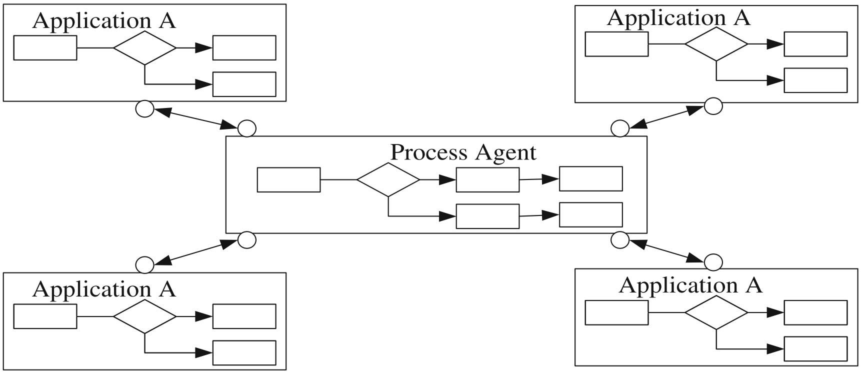


Fig. 4.16 Integration of process agent

agents. They can be middleware based on messages, file systems or other systems. This approach is well-known for aboard application of some application software packets, such as the integration of ERP kits (like SAP, PeopleSoft and Oracle), and currently it is the most popular method in application. However, application integration based on interface lacks a clear process model and framework based on service, which makes its application limited.

(2) Process-oriented integration

Enterprise business process refers to the consumer being the starting point of the process, after which a series of activities is undertaken that can bring value to customers, and the process is completed and generates valuable products for customers. At present, process integration and collaborative business are the developing direction and trends of enterprise application integration. There are many methods and techniques for implementing process integration, and the most popular is to use process agents, as shown in Fig. 4.16.

Compared with the information agent, the agent process can be seen as an expansion of information agent. In addition to disposing of the formatting application session, process logic that is connected to the various application systems is packaged in the process agents. When all process logic is packaged in the process agent, a procedure library is created to give unified management of processes, and the process can be designed, monitored online and adjusted by a visible graphic interface. At the same time, such a visible interface used to design process reduces the complexity of process designing, so that people at different levels can participate in the designing process, which greatly improves the efficiency of process designing and the rationality of the process.

(3) Service-oriented integration

The method is mainly supported by the framework, businesses, distributed objects and other mechanisms. At present its main direction is to provide enterprise application integration business both inside and outside through the Web services mechanism. Integration based on services permits dynamic application integration and has a mass scalability of public business logic; access can be provided by the Internet or distributed server and central server.

Sharing application services need to discover, describe and use these series of sharing services. "Web Services" positions services through names and directory in accordance with the standard of UDDI (Universal Description, Discovery and Integration), service description uses the language norm of WSDL (Web Services Description Language), and these information objects adopt the standard protocol of SOAP (Simple Object Access Protocol). Providing integrated services based on Web Services is the main direction for integration service providers on research.

The emergence of Web services provides an approach that has a whole framework for CIMS integration, which will enable all the application systems to be integrated seamlessly. Through Web services, enterprises can choose components to adapt and assemble themselves to meet the present and future demand for extension according to their business requirements. In this process, it is more valuable that technology hides behind the enterprises and that enterprises obtain their required services online. Even in the near future, the implementation of an enterprise's solution will be as easy as personal application software. Another important standard is that when an enterprise applies an integration system, it is unnecessary for the enterprise to deal with complex standards, and the only standard is XML (Extensible Markup Language). Therefore, users can assemble application systems in a dynamic state, providing the flexibility and convenience of entire CIMS system and requirement for integration. The following equation can be used to explain the structure of Web services:

$$\text{XML} + \text{SOAP} + \text{WSDL} + \text{UDDI} = \text{Web Service}$$

It is worth mentioning that the major technology providers have recently launched tools for building Web services successively, such as Visual Studio.NET in Microsoft, Web Service Toolkit in IBM and SunONE in the SUN. The largest management software provider in the world, SAP, will also provide its software modules by web service, so that consumers can choose parts of modules to use based on individual needs, without having to buy a software packet. In general, models and standards in Web service provide a universal approach to using remote application services on the Internet and pave the way for a new form of integration. This method can be called the "synthesis application", and can achieve complex functions through gathering a number of simple applications and services. Concretely, a new synthesis interface can be achieved by combining process logic with kinds of interfaces used to separate applications and services by user, and ultimately the so-called synthesis application can be created.

When a company already has good information-oriented and process-oriented integration, it will be more controllable and more effective for service-oriented integration projects. By contrast, when there are no existing bases of information and process integration, investment in Web services integration will be difficult to achieve. Therefore, “i before e” (integration before e-business) will be an important rule for enterprises. Any enterprise that would like to enter the inter-enterprise integration business successfully must realize that the basic infrastructure of integration will be a very important prerequisite.

4.3.2 Principle and Mechanism of Sharing Manufacturing Resources

In the manufacturing industry, increasing competition in the global market has pushed enterprises striving for better product design and more effective product development. Collaborative work is also the normal practice in the development of new products, which is a knowledge-intensive process requiring various domain experts distributed at different locations to collaborate closely and share information through mass communications media. Recent developments in Internet technologies have produced advanced communication approaches for the collaborative product development process, and have triggered the advancement of many WWW-based information sharing systems.

Information sharing achieves semantic interoperability among heterogeneous systems, which provides a unified expression, storage and management of heterogeneous information; thus integration of data and transparency of operation will be achieved. However, the information that needs to be integrated in digital manufacture is related to sales, product design, planning, production, supply and organizations and so on. Not only does it have large amounts of data, and the types and structures of data are complex, but also complex semantic relations exist in data.

1. Problems in manufacturing information sharing

In order to achieve information sharing in and among enterprises, certain problems need to be solved.

The problems of distribution and heterogeneity in manufacturing information sharing. The greatest difference between information sharing in manufacture based on network and information integration in enterprise is the distributed heterogeneity in the computer environment (application systems, DBMS, OS, etc.). It will be difficult to meet the requirements for integration mechanism based on the model of mapping information between the DBMS. Currently, the neutral files are usually looked as an integrated media for information integration in a distributed environment.

The multi-medium feature of the data carrier. Owing to the enterprise information involving the data of product design, planning, production resources and organization and so on, it has large amounts of data, complex types and structures of data and complex semantic relations in data, and data carriers are also multi-medium.

The unbalanced management of resources and tasks. In order to improve the informatization of the manufacturing enterprise, it is essential to actualize the rational scheduling management, to do well in auto-control and management of enterprises, and to improve the information exchange within enterprises, because the unbalanced distribution of machining tasks is caused by the unbalanced distribution of advanced manufacturing equipment and between enterprises.

The exact mark of semantics. The more effective search of information resources will be achieved by designing the marks that express meaning more accurately and making the automatic searching engine work better, which will lead to information resources integration sharing.

2. Different-standards-based manufacturing information sharing
(1) XML

XML (eXtensible Markup Language, XML) is a simple SGML (Standard Generalized Markup Language) which focuses on the content of Web pages and the common method used to deal with data in Web directly which also realize the information sharing and interaction in a network. It is a language with independent format and has nothing to do with the platform and application. XML allows a variety of professional fields to develop their own specific tag language, so that data can be separated from the description and the process. As long as application programs are in support of XML, they will be able to seamlessly exchange data among themselves. With such advantages, XML is gradually becoming a standard for supporting data exchange. Therefore, XML is used as a coded language to communicate data in manufacturing enterprises and has immense superiority for solving the issue of information sharing and exchange within enterprises and among enterprises.

The important characteristic of XML is its scalability. This property allows different owners to develop their own markup rules in accordance with the requirements of their systems and provides namespace to define the application scope of markup rules. XML also has a property of structure, and the data storage format is not constrained by the display format. Generally it includes three elements: data, structure and display form. XML separates the content of resources from its display form reasonably, thus the ability of understanding, exchanging and reusing the XML data is a great improvement. In addition, XML has an independent platform. Because an XML document is purely text and independent of the platform and applications, XML can effectively solve the problems of data sharing and interaction between old and new systems, between different application systems or between different data sources. Also, XML is universal; the XML standard does not belong to a commercial company but to the International Organization for Standardization—the W3C (World Wide Web Consortium, W3C), so that users' access application can be parsed, which is the data organizing form based on XML in different platforms.

By understanding the characteristics of XML above, it is not difficult to see that XML is a very good format for Web-based data organization. According to the previous section, through an analysis of the problems solved by transforming the mode of manufacturing information, we know that XML is very suitable to be the middle file format of information transformation to organize data in manufacture in a network, and it is also very adaptive to integrate components for a distributed object integration model.

(2) DBMS

The mechanism based on DBMS (Data Base Management System) is an important technology for information sharing. Because the majority of information systems have adopted various forms of DBMS as their data platform, the mechanism of information sharing based on DBMS is the most widely used in a sharing mechanism. However, it is very difficult to achieve information sharing based on DBMS among distributed systems. Therefore, at present, information integration in a distributed environment mostly chooses a manner of looking at a neutral file as integrated media, which at first identify and extract the relevant symbolic information from the various file formats. Those data and information we have already identified and extracted should then be transformed properly and guided into the database or directly provided to functional subsystems or subsystems of applications.

(3) EDI

In the technology of information exchange in manufacturing products E-commerce, traditional information integration mostly uses EDI (Electronic Data Interchange) as an integration norm. Current EDI standards include the UN/EDIFACT established by the United Nations/International Organization for Standardization and the ANSI X.12 established by the American National Standards Institute. EDI technology was born in the 1970s when the performance of CPU was low, hardware was expensive, and there were no common platforms and file formats for the transmission. In such a limited technical background, EDI used fixed transaction sets and business rules were embedded into transaction sets; in other words, the business rules were hard-coded into the application programs. However, in practice, business rules are affected by not only the different enterprises, but also the changing market. The biggest difficulty in the EDI mode is the conflict between fixed transaction sets and regularly variable actual demands. Connection implemented by EDI his essentially one-to-one, and EDI uses a private network or value-added network as a transmission platform. When two business partners establish their connection, they must customize their own software. EDI standards (such as EDIFACT and X.12) only prescribe the syntax that constructs the data of EDI, the status of which is similar to programming language. EDI users choose an EDI standard and collaborate with each other to draw up transaction sets according to the document required by business. Transaction sets prescribe data field, order of field and length of field, which is the format for exchanging files. As application systems in different enterprises have different business rules and file formats, application systems have to transform the format of files that are application programs and exchange files both before sending files and after receiving files by using a special translating routine. If a new business partner wants to develop new businesses, they have to improve the new document and rewrite the translating routine.

This mode of transferring fixed business sets is the main obstacle hindering further development of EDI. In addition, the difficulties and high cost of implementation also prevent EDI from further development.

4.3.3 Basic Theory of Manufacturing Information Security

1. Concept of manufacturing information security

Information security is a broad and abstract concept, and its task is protecting information property, preventing information from accidental or unauthorized malicious leakage, modification and destruction that make information unreliable or unable to be dealt with and so on. Realizing information security will enable us to maximize the use of manufacturing information, and at the same time, the loss will be reduced to zero or the minimum.

The development of networks, particularly the development of the Internet, has brought a profound revolution to manufacturing and creates an access to network manufacturing with rapid development. At the same time, it also brings information security risks that are difficult to overcome. The many sensitive information and confidential data suffer from various active or passive man-made attacks on the network, such as information disclosure, the theft of information, data alteration and additions or deletions of data and computer virus infection. In addition, the development of the Internet and the growth of broadband services encourage enterprises, government and manufacturing industries to use this public platform to establish their own private networks, which are not restricted by location.

In building the resources platform for digital manufacturing, the whole enterprise is highly dependent on the information. It is very convenient to provide and produce a lot of decision-making data by using this platform, thus ensuring the security of information systems is particularly important. The collapse of information systems may lead to the overall disruption of enterprise production and huge economic losses, which is a deadly threat for an enterprise. Of course, security of data involves not only preventing the loss of data, but also organizing and protecting data integrally and systematically.

When enterprises establish a resources platform for digital manufacturing, they must seriously address problems related to information security. Similar to computer security, manufacturing information security has five main aspects [16]: (1) Confidentiality, which guarantees that only authorized individuals can see the information and non-authorized users are prohibited from seeing data they do not have authority to access. (2) Integrity, which is a concept associated with confidentiality and involves the creation and revision of data. Only authorized users can create or modify (or delete) information. (3) Availability, which ensures these resources are available while the authorized users are using data or systems. (4) Authentication, which ensures that the individual is the person identified by the system. Clearly, this is necessary for transactions online (or access to sensitive or confidential information). (5) Non-repudiation, in which the ability to verify whether a message has been sent or received is much-needed, and the sender can be identified and verified.

However, no matter how much prevention technology has been improved, it seems that some people will always find a way to avoid preventive measures. Therefore, alarm techniques and a method of identifying the location of problems are when preventive measures are disabled. The formula of safety can be expressed as:

$$\text{Protection} = \text{Prevention} + (\text{Detection} \ + \text{Response})$$

In fact, the formula above expresses a well-known operational model of computer security. Each security technology could belong to at least one of three elements in the formula, such as:

$$\text{Protection} \ = \text{Prevention} \ + (\text{Detection} \ + \text{Response})$$

Access Control	Audit Log	Backup
Firewall	Intrusion Detection System	Emergency Response Team
Encryption	Cryptographic Key	Computer Crime Forensic

Generally speaking, the level of security can be expressed as Fig. 4.17.

Of these methods, Access Control is very effective for protecting systems. It has interactive ability between a host (for instance, a procedure in the computer) and an object (for instance, a file or a device), and it has all the security characteristics of preventing non-authorized access to the computer system and network. There are many ways to realize Access Control, and the simplest is Access Control Matrix, or ACL for short. Due to wasted storage space and low efficiency, ACL is not in common use even though it is simple. Access Control must have a determined access model no matter how it is implemented by the computer and network. The access control model has various types, mainly including DAC (Discretionary Access Control), MAC (Mandatory Access Control), and RBAC (Role-Based Access Control).

Every aspect of security should be expressed as a line flow, each phase of the cycle in Fig. 4.18 refers to a human factor. Additionally, each phase of the cycle must have feedback on its former phase, and its effect on all the phases before it. Operation and maintenance is the key phase in the whole security lifecycle, and the feedback from operations is very important. Regardless of whether the program is proved to be safe or not through testing, unexpected problems and difficulties will always appear in an operating environment. If the phase of security assurance (standard, design, implementation and test) do well, then the additional maintenance and difficulties will decrease to minimality, and the analyzer can easily and quickly solve these problems. If the phase of security assurance is neglected or handled improperly, we need to completely re-evaluate the system when there are problems.

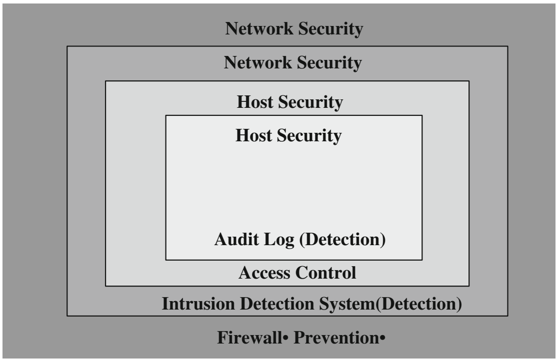


Fig. 4.17 The different layers of security

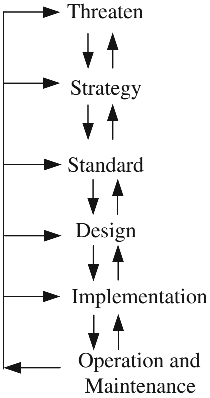


Fig. 4.18 Security lifecycle

2. Security level in digital manufacture

TCSEC (Trusted Computer System Evaluation Criteria) published in 1985 and TNI (Trusted Network Interpretation) for TCSEC published in 1987 by US DoD and NIST, which are called the orange book and red book for short, are the standards of establishing, evaluating and auditing the security criteria of computer systems and network systems. The TCSEC defines four levels: A, B, C and D. Level A indicates that the network system supplies a comprehensive security strategy; level D indicates that the network system supplies the simplest security measures. Each level can be further divided. The different levels are in accordance with requirement of special security characteristics. For the internal computer network systems of network manufacturing enterprises, C2 grade must be achieved, which makes the operation system safe, and ensures that the information processing and transmission system is secure. It emphasizes the normal operation of systems and avoidance of destruction and loss. The collapse of information systems may lead to overall disruption of enterprise production and to huge economic loss. It focuses on ensuring the normal operation of the system and avoids the destruction and loss of stored, processed and transmitted information as a result of collapse and damage in the system. For external information networks, level B1 must at least be achieved. Network systems should provide the relevant security policy model to ensure the security of information in networks. The model includes identifing a user's password, controlling the authority of user access, controlling the authority and mode of data access, auditing security, tracking security, controlling computer viruses, encrypting data and so on. It should be noted that China's equipment, computer and network software sold by foreign manufacturers (mainly the United States) has only C grade in security; we must therefore develop the equipment and software ourselves in accordance with demand and the required security level.

3. Security model for digital manufacturing resources

Security model of digital manufacturing resources includes the following elements: subject and the object with clear definition; description of how subject should access the authorized database of object; reference monitors used to constrain access attempts from subject to object; identification and validation of the trusted subsystems of subject and object; trusted subsystem used to audit the activities of reference monitors. Generally, a system has three basic security mechanisms, which are trusted operation, access control and audit.

The following principles should be satisfied for designing and implementing a universal and efficient framework of access control. They are: (1) it has truly universal properties', (2) it has minimal changes in the system kernel and the smallest influence on the system; (3) it is capable of supporting a variety of security strategies, and these strategies have dynamic change.

Study in the past proposed various MAC models, such the BLP (Bell LaPadula) model, BIBA model, RBAC (Role Based Access Control) model and DTE (Domain and Type Enforcement) model. These models supply control mechanisms of mandatory access with different degrees of tightness according to different security requirements. However, the BLP model protects only the confidentiality of information without taking integrity and privacy into account; BIBA only considers the integrity and neglects other aspects of security. With the growing requirement of security, it is not enough to use a single strategy. Therefore, the security operating system should support models with multiple security strategies and dynamic update and change in multiple security strategies, and provide a support for flexible access control to different applications. The framework of global access control supports multiple security strategies, but the urgent problem that needs to be solved is how to effectively preserve, organize, configure, update and apply the multiple security policies in the framework. We now introduce the GFAC (Global Framework of Access Control proposed by Abrams et al. [17]).

The whole framework of access control is divided by GFAC into two parts (shown in Fig. 4.19): the ADF (Access Control Decision Facility) module and the AEF (Access Control Enforcement Facility) module. The ADF module can preserve, organize and implement the various security policies and meta-policies in the system, but AEF provides ACI (Access Control Information) to the ADF and decides whether to agree to the request for access in accordance with the results of

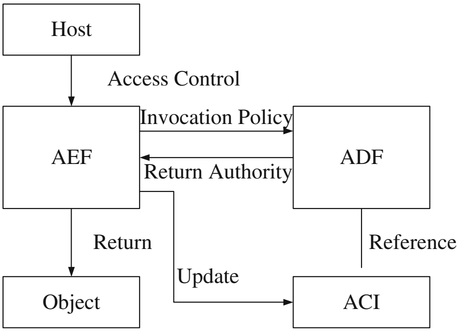


Fig. 4.19 Sketch map of GFAC framework

the decision made by ADF. In the face of the user's requests for access, the working process of the whole framework of GFAC is: when a user requests an access, the request will be pretreated by the AEF and then will be sent to the ADF; ADF will decide whether or not to license the access based on the security attributes and specific security policy of subject and object, and will inform the AEF module of the decision. If the request is refused, AEF will interrupt the user's operation, otherwise the user will be accessed by the authorized object. GFAC will separate the implementation of access control from the access decision, so that the implementation of access control has nothing to do with specific strategies, which allows the system to modify or add a new security strategy without changing the implementation.

The trusted operation in computer information systems, in its initial implementation, asks users to mark their own identity and prove their identity, on the basis of which the computer systems will identify them. The mark and identification of a visitor's identity are the premise of authority, and system will reserve the ability to investigate the responsibility of the user's acts through an auditing mechanism. ID identification can be used only for the subject, but in some situations it is also used for the object. Currently, the identification technology used in computer systems involves three factors: what do you know (the secret password), what do you have (token or key) and who are you (physical characteristics).

At present, the general method used by most commercial systems is only using a password as a basis for verification. This simple method will bring obvious risks to the computer system including cracking passwords by using dictionaries; deceiving the user to leak their login by posing as legitimate computer landing procedures; and collecting passwords that are transmitted in the form of plaintext (such as Telnet, FTP and POP3) or simple coding (such as BASE64 used by HTTP) through the network sniffer on the network. In addition, the management of simple password verification will encounter difficulties when a privileged password is known by more than one person, and the most obvious problem is being unable to confirm who may know the password. When passwords are not changed in time, especially, we cannot ensure that people who have the password for temporary access will forget it "immediately" after implementation of the temporary authorized task.

No password system can guarantee that it will not be invaded. Some systems use an approach that combines passwords with tokens; in this way, the system will vertify whether the user holds the right token (what do you have) or not while it is checking the user's passwords. Token is the software or hardware owned or operated by computer users. As the password is disposable, cracking the password is impossible, and it is worthless to attempt to steal the password for entering and communicating. The token in the form of hardware has a property that makes the holder the only one who has it, so it is specifically granted and recovered to avoid the proliferation of authority caused by management mistakes. Integration of password and token for identity verification will provide adequate security on most occasions.

Access Control is divided into "Discretionary Access Control" and "Mandatory Access Control". DAC is the most common type in the commercial system, and both UNIX and NT operating systems use DAC. In systems based on DAC, the owner of the subject is responsible for setting the access authority. DAC has a side effect, which is that one or more privileged users can change the control authority of the subject. One of the greatest problems in DAC is that the authority of the subject is too big, so it may leak information inadvertently. Furthermore it cannot guard against Trojan attacks. With MAC, the system distributes different security attributes to each object and subject. By comparing the security attributes between subject and the object, the system will decide on the operational feasibility from subject to object. MAC can prevent Trojans and abuse of authority, which has a higher level of security.

The audit is a trusted mechanism. Most operating systems provide an audit subsystem that is able at least to record each document accessed by users. Because there are many other subjects and objects in the operating systems, the audit mechanism is responsible for events such as beginning a program, ending a program, restarting the system, increasing the number of users, changing a user's passwords and installing a new disk drive. Many different records need to be maintained by the operating system, but not all records contain enough information to identify the subject, object and requests for access accurately. To allocate responsibility for the system activities, it is necessary to describe every complete record of decision made by access control. Only through the active audit system are we able to know whether the security strategy in use is being applied correctly or not. Intrusion Detection is based on this simple need. If the systems and networks are not detected, it is impossible to detect intruders or internal incorrect use.

4. Internal control mechanism

The realization of calculation and security is complicated, and regulation control often become unusually ambiguous and heavy in large-scale organizations. However the effectiveness of technology control is that, if a non-technical factor affects the realization and application of technology control, it will undoubtedly have a huge influence on security [18]. Besides, even security control is useless and even dangerous if the technology control is wrongly configured or used improperly. Therefore, it is necessary for the designers, achievers and defenders of security control to properly operate these controls.

The internal control of manufacturing resources includes controlling information resources and controlling the human. In some works, the controller should monitor the activities of the users who are controlled on the network. Sometimes different authorities and passwords should be given to users, and only the authorized users are allowed to enter into a certain subsystem. The system resources need to be protected, and the implementation of unauthorized operations must be refused.

Several aspects mentioned above are not isolated from one another; in fact they are often mixed together. When one control is set, the other control is involved. Some of these controls are completed by the function of a computer operating system, some are provided by the application layer of the information system, and some are set by the management system. Therefore, to design a comprehensive control system is actually a comprehensive, complex project.

There are at least four aspects that should be considered to constitute an internal control system. They are control objects, organizations, working procedures and regulations. First, we must identify: Which are the important and precious resources? Which parts of the information resources are easy to attack? What security measures should we take to protect the system?

It is very important to establish the organization of internal control. It must be clearly defined who is responsible for the security problems of manufacturing resources. Technically, the management operation for manufacturing resources is often decided by allocating authority to the accessing object, but its premise should be decided by the organizational structure and business requirement. In other words, the system operator has determined operational authority, which is managed and constrained by the organizational leadership at the same time. In such a system, the authority of information systems could be guaranteed to be reasonable.

The security technology of a digital manufacturing resource is controlled by people in the final analysis, so it is not possible to solve problems by technology alone. The internal control must be built on a series of working procedures and regulations. The establishment of a manufacturing resource planning system should consider: How should the system personnel divide the work? What are their duties? How can the smooth progress of the division be ensured? For example, when the system administrator manages the authorities of staff, he or she can increase, modify, delete and enquiry the authorities, but all his or her actions should be in accordance with a clear series of steps and regulations.

5. Study and application in security of network manufacturing resources sharing

In satisfying the principles and framework of manufacturing information security, the security technology of digital manufacturing resources has been widely studied and has achieved fruitful results. The School of Information Engineering at Wuhan University of Technology has conducted extensive research work on this aspect, and has many achievements that are mainly reflected in the following areas:

(1) The property right protection of digitalized product

As digitalized manufacturing information should be transmitted and processed in the network, we must study the appropriate theories and methods of copyright protection. Digital water-marking technology provides an effective way to protect the copyright of product and attracts more attention. The literature [19] introduces the basic theory and universal model of digital water-marking and analyzes several typical digital water-marking algorithms. It points out the advantages and disadvantages of existing digital water-marking algorithms and summarizes the evaluation index of the performance of digital water-marking algorithm design. Through the comparison of three digital water-marking algorithms related, respectively, to the wavelet packet, the singular value decomposition (SVD) of image and the spread spectrum communication theory, it proposes the architecture of the protection of property rights of the network manufacturing product and the architecture of manufacturing information security for the first time; it presents the manufacturing-oriented open grid-computing hierarchical model, and establishes the security platform of network manufacturing resources sharing in accordance with the model.

The author also puts forward the digital water-marking algorithm based on SVD and spread spectrum technology, and applies digital water-marking technology and the SVD theory of image in protecting the intellectual property of network manufacturing products, in which the digital image is processed through SVD, and the digital watermark with copyright information is embedded in and extracted from the digital image by adopting the spread spectrum technology. With this method, an image embedded with a digital watermark has the same size as the original and the differences between the embedded digital image and the original cannot be seen by the naked eye. In this way, copyright protection of multimedia data is achieved on condition that the request of visibility and robustness can be ensured. In addition, this algorithm adapts to various forms of meaningful digital watermark embedding. The algorithm was approved in 2003 as a national invention patent of China (Unified Digital Water-marking Methods and Devices Based on SVD and Spread Spectrum Technology, No. CN03125461).

The School of Information Engineering at Wuhan University of Technology has also undertaken many research works on a digital water-marking algorithm for 3D models [20–23]. We also have further study on the 3D digital water-marking method with 3D model intensity projection. First, we choose the best viewpoint of the model by using principal component analysis, and then obtain the depth map of the 3D model in the direction of the best viewpoint and get its Fourier Transform. The watermark embedded in the depth map Fourier Transform is the 3D model embedded with the watermark that is gained by embedding the watermarking information in the Fourier domain of the depth map. An application for national patents for inventions has been lodged for this method (3D Digital Water-marking Methods and Devices Based on 3D Model Depth Projection, Patent Application No. 200710169094.x). Further, we have presented the Digital Copyright Management System Based on Digital Watermark and Mobile Agent, and applied for a national patent and software copyright (Digital Copyright Management System Based on Digital Watermark and Mobile Agent, Patent Application No. 200710169094.4; Digital Copyright Management System V1.0 of Network Multimedia Based on Digital Watermark and Mobile Agent, Software Copyright No. 2007SR19622).

Professor Z.D. Zhou and colleagues studied the digital signature algorithm and put forward a safe, controllable and authorized digital signature method (National Invention Patent, Patent No. CN200510019215.9) and a controllable and authorized digital signature method based on elliptic curve (National Invention Patent, Patent No. CN200510019214.4) in 2005.

(2) Secure transmission of network manufacturing resources

A digital watermark can resolve security issues like copyright protection of a multimedia product's information, but there is much other information in the manufacturing process, such as technics information, management information and other relevant information in the entire lifecycle of the product. In order to make it possible all the manufacturers in the network manufacturing to realize the sharing of resources and to ensure that sensitive data and information will not be blocked, listened to or copied, we must consider how to realize effective transmission in the public network by applying the security technology we have. VPN is a valid and overall solution to protect the security of such information [19].

On the foundation of researches on a widely used VPN scheme—IPSec protocol system, the School of Information Engineering at Wuhan University of Technology designed the embedded high-speed VPN hardware architecture and software systems based on the MPC8250, in accordance with the characteristics of IPsec integrating with the current hardware features that support network processing. A system was designed to process encryption/decryption in IPSec security protocol by DSP, which was approved as a national invention patent (Patent No. CN03125335.0) in 2003. Moreover the system test and data analysis have been carried out to testify to the effectiveness of software system for a realized prototype system.

(3) Research on grid-based security platform of network manufacturing resources sharing

Under the grid environment, information such as the relevant design and manufacturing resources, all kinds of flows and knowledge in the entire lifecycle of the product are integrated to provide a supporting environment for a modern integrated manufacturing system platform, which is the manufacturing grid. Technologies in the manufacturing grid contain manufacturing resources-based systems integration model with interoperability, the standardized wrapped interfaces and protocol of manufacturing resources, knowledge-based data management model and the active systems offering and obtaining knowledge. The manufacturing grid provides effective solutions for the final realization of resources sharing and collaborative operation and the integration oriented to life cycle of product in the network environment.

The security challenges posed by the grid environment can be summarized as three types:

1. The architecture constructed by the abstract interface and solving method converging the kinds of existing services must be extensible;
2. Different virtual organizations have different security mechanisms and strategies, so the different services in them must be able to be transferred and accessed mutually;
3. In the grid environment, definition, management and solving methods to intensify the strategy of trust must all meet the dynamic features of grid services.

These challenges should be overcome by grid security on the basis of the security structures and modules of the original cross-platform and cross-host environment. However, their solutions are not independent of each other, as each type of solution for the security problems need to rely on other types to be resolved. The grid security module has the polymerization of all the security management mechanisms to adapt to the security requirement of diversification. These security mechanisms include key management, registration management, authorization, encryption and decryption, trust strategy management, localization mapping management, and also involve intrusion detection, anti-virus services, assured service data and service discovery. Faced with a variety of security mechanisms, choosing the appropriate security strategy will enable managing the various service requests better in a grid environment. The grid security module should be a flexible, extensible frame structure that is the largest polymer of existing security mechanisms. It allows the use of many kinds of security technologies; therefore, it is very important to use, include and support the existing relevant security standards. In addition, the grid service is built on Web services, so the grid security system should include the expansion of Web services industry standards. Special attention should be paid to the fact that the open grid service system built on Web services is a system concentrating on the service, and its security architecture must be compatible with the security module of Web services.

Through the grid-computing system and researches on the hierarchical model of the manufacturing grid, Professor Q. Liu put forward the dynamic extensible security structure [19], designed a dynamic insertable security module, and established a group communication security structure. All of these reduce the steps of security negotiation and improve the efficiency of interaction between subjects, with full guarantee under the premise of safety, main efficient of security consultation, and make GSI more adaptive, extensible and dynamic. They carry out the application service support based on the manufacturing grid to meet the security sharing of manufacturing resources in a network environment. The establishment of a grid-based network manufacturing resource sharing security platform is thus realized.

Property rights protection of network manufacturing products, manufacturing resource sharing and information security research are related to manufacturing, information and other fields. The knowledge and technology cross many disciplines, so in-depth research on this theory and the development and application of technology will generate a great deal of arduous work.

4.4 Summary

Manufacturing informatics as one of the nuclear theories in digital manufacturing plays an important role in scientific problems such as digital token of manufacturing activities, logical reasoning and quantification calculation and so on. This chapter illustrates the fundamental elements and theory of manufacturing informatics in digital manufacturing from the principles and properties of manufacturing information, measurement and materialization, self-assembling and integration, and discusses the security of manufacturing information, information sharing and integration theoretically, which are important in the digital manufacturing model system and practical application. The relationship between theories in this chapter and the problem of informationization in the product life cycle are also discussed. However, due to the complex characteristics, unconventionality and parallel structure of manufacturing information, there are many problems that remain to be solved.

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Chapter 5
Intelligent Manufacturing in Digital Manufacturing Science

Intelligent manufacturing means simulating the intelligent manufacture activity of human experts through computers by using a highly flexible and integrated way in every section of manufacturing, and then analyzing, estimating, concluding, conceiving and determining the manufacturing problem, with the purpose or replacing or prolonging some part of human brainwork in the manufacturing environment, and collecting, storing, perfecting, sharing, inheriting and developing the human experts' manufacturing intelligence. Its major research contents include intelligent activity, intelligent machine and the methods of combining these two things organically, of which the core is intelligent activity.

Intelligent manufacturing is a crucial part of the basic theory system of digital manufacturing science. It provides the basic theory and method of implementation for intelligent digital maneuver, intelligent digital design, intelligent digital machining, intelligent digital control, intelligent digital process planning, intelligent digital maintenance and diagnosis. Information fusion and knowledge integration are the main portion of the intelligent manufacturing system (IMS) which directly affects the quality and efficiency of system function and product implementation. How to compose decision knowledge and realize the self-study ability and self-organizing ability of the manufacturing system, in a way that digests and concludes the huge amount of information in the manufacturing process is becoming a research hotspot in the intelligent manufacturing field.

This chapter consists of five sections. The first section emphasizes concepts, elements, the architecture of multi sensing information fusion and data mining and its application in digital manufacturing systems. The second section introduces knowledge engineering in the whole life cycle of manufacturing product. Three important specialties of IMS—self-study ability, self-organized ability and self-adaptive ability are mentioned in the third section. The fourth section introduces the multi-agent manufacturing system and the holonic manufacturing system. A summary concludes the chapter.

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5.1 Intelligent Multi Information Sensing and Fusion in the Manufacturing Process

Intelligent machining technology, as the key technology of IMS, aims to settle many problems which cannot be solved by traditional machining techniques by adapting the requirement of modern machining techniques and acclimating the development of IMT and IMS. The objective of intelligent machining technology is to establish the IMS intelligent physics section and provide an actual system which can upward integrate for IMS. Many factors can affect the machining effect directly or indirectly in the process, such as the work piece roughcast surplus not being uniform, the rigidity of material being unequal, the cutter abrased or destroyed, work piece distortion, machine tool heat distortion and so on. Therefore, it is very difficult for traditional processing technology to machine within the best parameters. Intelligent machining can consider the theory, human experience and sorts of effect generally, adjust automatically and contain the best process state, and can accordingly achieve a better economic benefit and a higher process precision. Intelligent monitoring, intelligent decision and intelligent machining are three aspects of intelligent machining. Intelligent decision is based on intelligent monitor, and the realization of intelligent decision depends on intelligent control. Thus, the sensor technology and control technology with characteristics of high precision, high reliability, large information and stronger real-time performance, which can adapt the unknown environment and the dynamic environment, are becoming the key issues of intelligent monitor and control. In the course of monitor and control, the traditional sensor techniques whose single attribute and control method is away from satisfaction. In the middle of the 1980s, the gradually prevalent multi-sensor fusion technology brought a new concept to the monitor of intelligent manufacturing.

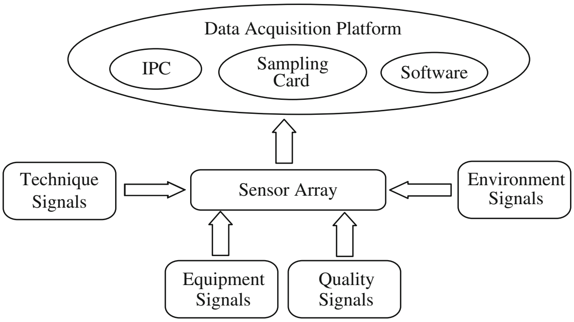
5.1.1 Intelligent Multi Information Sensing

5.1.1.1 Concept of Intelligent Multi Information Sensing

With the development of science and technology, sensor performance is greatly improved and all kinds of multi-sensor system oriented complex applications have emerged. The state of complex things can be acquired through various sensor systems and the integration of existing knowledge. The sensor system is the typical representative of an intelligent sensor system.

The core of digital manufacturing is the discretization and digitization of manufacturing information. The requirement of management, control, monitoring and diagnosis cannot be satisfied by using a single sensor; instead, an intelligent multi-sensor system is needed to provide a variety of data. Intelligent multi information sensing is composed of sensing, controlling, computing, information

Fig. 5.1 Concentrated acquisition mode



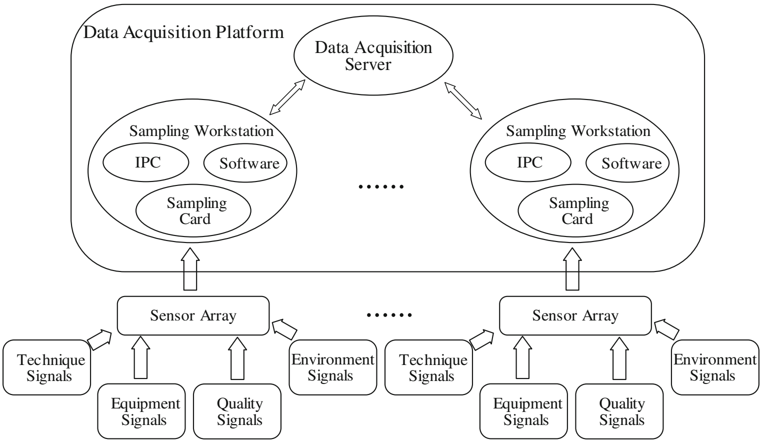


Fig. 5.2 Distributed acquisition and concentrated control mode

processing, network communication, artificial intelligence and many other technologies.

By using sensors and data acquisition systems, raw data about the manufacturing process are obtained. There are, in general, three modes of data acquisition, namely the concentrated acquisition mode, distributed acquisition and concentrated control mode, and distributed/concentrated acquisition and concentrated control mode [1]. They are separately shown in Figs. 5.1, 5.2 and 5.3. The manufacturing process information is complex and transient. The need for information is continuous. Taking into account acquisition requirements, the real-time condition of the manufacturing process, and features of agent and distributed artificial intelligence, an intelligent data acquisition system based on agents is proposed as shown in Fig. 5.4.

Information activities can be abstracted in several stages, such as access to data, extract information, knowledge and decision-making and so on. Intelligent sensing systems generally have a hierarchical structure [2] like the human sensory system having multi-layer as shown in Fig. 5.5.

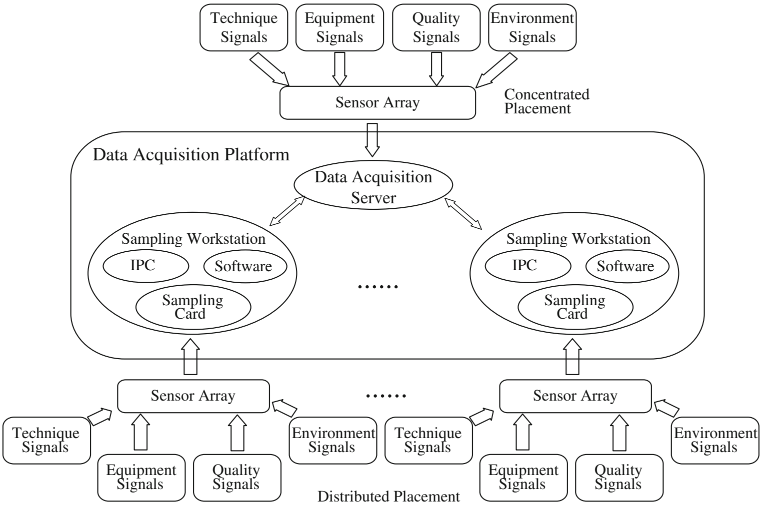


Fig. 5.3 Distributed and concentrated acquisition and concentrated control

5.1.1.2 The Application of Sensor in the Processing

In the digital manufacturing system, the intelligence of manufacturing equipment which is represented by the numerical control machine tool and machining center is an effective method for improving machining efficiency, ensuring the machining precision of the work piece and amending the surface machining quality of the work piece. Sensor is necessary in manufacturing equipment intelligentize. There are three kind of sensors for applying in machining: the sensor applying in a moving process's control, for example, the position sensor, speed sensor, angle speed sensor; and the sensor applying in the machining process's control, for example, the force sensor, power sensor; and the sensor applying in the machining process's monitor and diagnosis, for example, the vibrancy sensor and temperature sensor.

In choosing an appropriate sensor based on the different function of sensor accomplishment in manufacture equipment and its machining process, the key question is to improve the intelligentize level of manufacturing equipment by using a reasonable multi-sensor. Nowadays, the applications of multi sensor in conceiving the manufacturing equipment and machining process are divided into four aspects:

1. Test of machine tool's principal axis
   The principal axes are equipped with a variety of sensors such as temperature, vibrancy, displacement, and distance, which can be used to protect and alarm the principal axis. The purpose is to automatically optimize such parameters as the rotation speed of the principal axis according to different machining status.

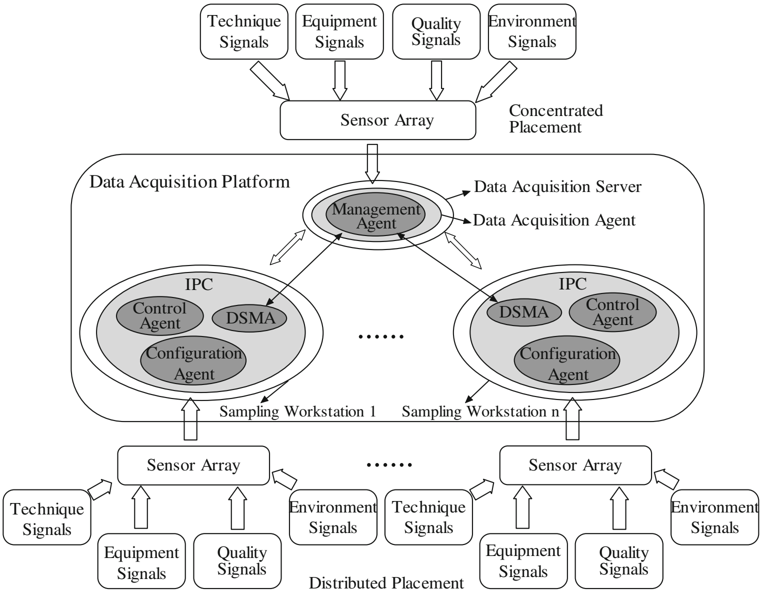


Fig. 5.4 Model framework of AIDAS for manufacturing systems

Fig. 5.5 Hierarchical structure of intelligent sensing system

Upper layer [KNOWLEDGE PROCESSING]
TOTAL CONTROL Concentrated central processing (Digital serial processing)
Middle layer [INFORMATION PROCESSING] INTERMEDIATE CONTROL. TUNING & OPTIMIZATION OF LOWER LEVEL SENSOR SIGNAL INTEGRATION & FUSION
Lower layer [SIGNAL PROCESSING] SENSING & SIGNAL CONDITIONING [INTELLIGENT SENSORS] Distributed parallel processing (Analog)

2. The recognition of tool abrasion and the monitor to be destroyed
   Sensors such as power, cutting, acoustic emission, vibrancy and visual sensor are used in the process of tool monitor; for example, B.BAHR using vibrancy and visual sensor monitor to recognize the abrasion status.
3. The recognition of grinding wheel during grind and cut and the monitor of the course.

The primary factor that influences the final precision of a work piece is the abrasion status of the grinding wheel during the course of grind and cut. National scholars research on the status monitor by adopting multi-sensor information fusion technology during the process of grind and cut. Scholars outside the country carry out a mass of research on the intelligent monitor and optimize in the process of grind and cut, sensors such as acoustic emission, power and force sensor.

4. Intelligent monitor of deep hole bore and cut
   To collect the vibrancy and power signal in the normal machining process and abnormal process, and draw the characteristic information, integrate the data through neural net and then carry out the monitor of processing.

5.1.1.3 Sensor Applications of Tool Condition Monitoring

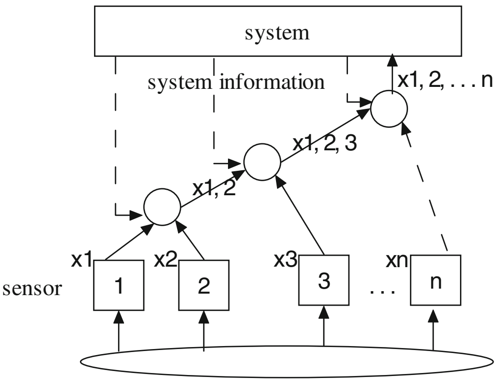
Over the years, many works on tool monitoring technology have been carried out and a significant number of new monitoring methods have been developed. The current detection method is shown in Table 5.1. In the tool condition monitoring system, the sensors act as the information source of the system. The performance of sensors has a direct effect on the success rate of monitoring. At present, there are several detection methods with a wide application field, such as acoustic emission, cutting force, torque, vibration and machine power and so on.

There is much that needs to be researched in knife tool condition monitoring and the main research contents include tool wear and damage monitoring. Strong friction among cutting tools, cutting chips and the workpiece is bound to cause wear on the tool. According to the different parts, tool wear can be divided into crater wear, flank wear and groove wear. Tool breakage and tool wear are also forms of tool failure. When using a knife tool under cutting conditions if it cannot withstand the heat load and cutting stress, damage may occur suddenly, and the knife tool may lose cutting ability early, and this situation is known as tool breakage. In order to reliably monitor the state of tool in the process, the key issue is to choose a reasonable group of sensors. In the study of condition monitoring of the knife tool, sensors that are used widely are acoustic emission sensor and force sensor. Many studies have shown that acoustic emission is sensitive to plastic deformation and micro-activities (stress wave) such as the fissile of the cutting district, and the cutting force spectrum is sensitive to the vibration of tool and workpiece that is caused by flank wear. The advantage of using AE sensor and cutting force sensor is that they can provide relevant information about the micro (stress wave) and macro (vibration) of tool wear. In addition, the acceleration sensor is also a suitable kind of sensor, because it is sensitive to the vibration of the tool and workpiece caused by flank wear. Redundant information for tool condition monitoring can be provided by the sensors mentioned above, and the information between sensors can also complement each other.

Table 5.1 Common tool detection methods

Detection method	Sensor	Operating principle	Scope and feature
Optics image	Fiber, optics sensor, vidicon	Utilization the beam reflection of wear surface, then carry out image processing and recognition	Online, non-real-time, monitor tool wear and fracture, high price
Measure cutting temperature	Thermocouple	Measure outburst increment of cutting temperature among workpiece and tool	For turning, lower sensitive, can be used without cooling liquid
Measure surface roughness	Laser sensor, infrared reflex sensor	Measure change rate of surface roughness	For lathe, milling machine and etc. non-real-time monitor
Ultrasonic	Ultrasonic transducer and receiver	Receive reflection wave	For lathe, milling machine and etc. real-time monitor, influenced by cutting shock
Shock	Accelerometer, shock sensor	Monitor shock signal and its changing of machining process	For lathe, milling machine, drill machine and etc. real-time monitor, the influence of self-excitation, vibration and environment noise need to be solved
Cutting force	Strain and stress sensor, piezoelectric sensor	Monitor ratio and its changing rate of cutting force	For lathe, milling machine, drill machine, etc. real-time monitor
Power	Transformer, current divider, power sensor	Power and change rate of main motor or feed motor	For lathe, milling machine, drill machine, etc. real-time monitor, used to realize self-adapting processing
Acoustic emission	Acoustic emission sensor	Monitor acoustic emission signal and its feature parameter of machining process	For lathe, milling machine, drill machine, etc. real-time monitor, simple to use

Fig. 5.6 General mode of multi-sensor integration



5.1.2 *Intelligent Multi Information Fusion*

Processing is a very complex dynamic system in the digital manufacturing system. The control and diagnosis of product quality needs a large number of state data and information in processing, which includes strength current, torque, position, speed, acceleration, surface roughness, temperature, vibration, spacing, chip, acoustic emission and tool wear, damaged condition and so on. It is difficult to monitor the processing status with accuracy and integrity with a single sensor, so it needs to stress intelligent information processing and multi-sensor fusion.

5.1.2.1 General Principles of Multi-Sensor Data Fusion

1. Basic principles of multi-sensor fusion

The fusion of intelligent multi information is an information process which automatically analyzes the observational information of the multi-sensor using the theory and technology of artificial intelligence, and optimizes synthetically, to complete the necessary tasks of decision-making and estimates.

The network structure of Fig. 5.6 is the general pattern of multi-sensor integration and information integration. Some combined sensors provide information for the system. The first two sensor outputs x1 and x2 integrate the information in the left lower nodes forming a new information which is expressed by X1, 2 the third sensor's output x3 integrates with X1, 2 in the next point that is, X1, 2, 3 and so on. All the sensor system's output integrates into a structure in similar manner of integration. The broken line from the system pane to each node denotes the feasibility of the information exchange of systems in the process of integration. It should be noted that, before the integration of sensor 1, 2 we must match the data of each sensor, namely to unionize the data of each sensor in the space and time coordinate, to make the data belong to the same environmental position in the same time section.

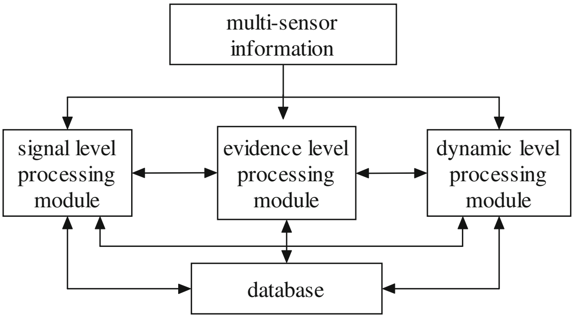


Fig. 5.7 Thomopoulos hierarchy method

2. Configuration of the multi-sensor fusion

The partition of the level of information integration is mostly in the following two methods. The first method is that the integration of information is classified on three levels as low-level (pixels), middle (features level) and senior (decision-making level). Pixel-level integration is a fuse processing to the original information of sensors and information on the various stages of the pretreatment, respectively. Feature-level integration is the middle-level process that analyzes synthetically and processes the characteristics information distilled from the original message of various sensors, and also includes classification, survey and integration of the multi-sensor information. Integration of the decision-making level is the fusion in the highest information level. Different types of sensors have the same observation objective, and each sensor completes pretreatment, feature extraction, identification or judgment at home, to gain the primary conclusion of the observation objective. Then, via correlative treatment and integration of the decision-making level, it obtains a united deduction, so that it can supply the foundation for the decision-making at first hand.

Another method is to classify information fusion into signal-level, evidence-class and dynamic-level, as shown in Fig. 5.7. Signal-level information fusion is a non-analytical approximate simulation of the process for which it is difficult to obtain an analytical mathematical model. At this level, the integration method generally adopts production rules, correlative analysis or trainable artificial neural network technology. Evidence level requires building a statistical model of the measured process; the fusion process of evidence level generally obtains some result according to part reasoning of each sensor firstly, then unites the reasoning, in order to achieve decision-making, identification, hypothesis testing and control and so on. Dynamic-level information fusion can adopt the centralized way or the decentralized way. The so-called centralized way first combines the information of each sensor, then processes the combined information as a whole. In the so-called decentralized way, each sensor first handles their own information, and then fuses the sensor information.

The basic strategy of information fusion is first to fuse the information on the same level, then to obtain a higher level of information, and import the relevant information at the integration level. Generally speaking, information fusion is essentially a

Fig. 5.8 Hierarchical structure of fusion system

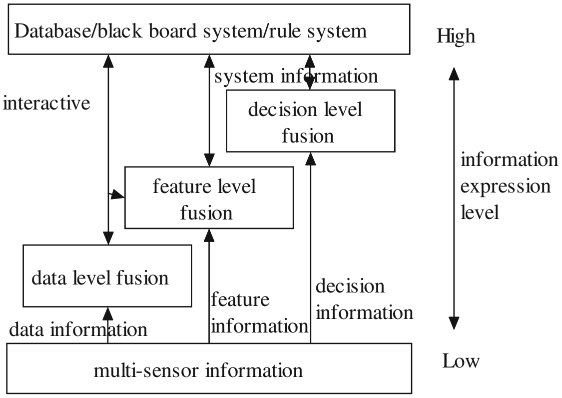
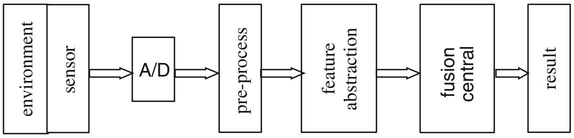


Fig. 5.9 Process of information fusion



multi-information integration from bottom to top level, a process of abstracting information level by level. At the same time in certain circumstances, there is a feedback effect from the high-level information to the low-level information, so that the high-level information participates in the low-level information so that integration; the low-level information also participates in the high-level information integration (mixed-integration mode). It also does not exclude the possibility of putting the high-level information integration. Figure 5.8 is its integration model.

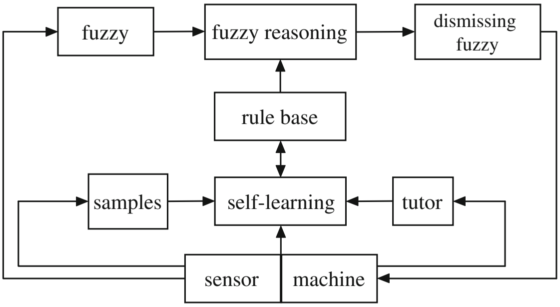
3. Process of the multi-sensor fusion

Figure 5.9 shows the whole process of the integration of information. As most of the tested objects are non-power objects non-power with different characteristics, such as temperature, pressure, sound, color, and so on, they are first converted into electrical signals, then transformed into digital signals which can be handled by the computer via the A/D switch. The digital signals require pretreatment to filter out interference and noise produced by the data collection process, and the useful signal remained still needs feature extraction.

5.1.2.2 The Application of Multi-Sensor Fusion in Tool State Monitoring

As the influence of the dynamic characteristics of machine, tools material and cutting tool conditions. The processing system has strong nonlinearity and uncertainties, and it is difficult to build a mathematical model of the process accurately. Therefore, people focus on the intelligent, multi-sensor monitoring

Fig. 5.10 Principle of fuzzy monitoring system



systems during the process and have adopted methods that include pattern recognition, statistical methods, methods of artificial intelligence and neural network. This section will introduce the use of fuzzy set theory [3] based on neural network tool condition monitoring methods.

1. Based on tool condition monitoring of theory of fuzzy sets

Fuzzy monitoring is based on expert experience and knowledge, building the fuzzy relations between features and states, making the characteristics of information in the process fuzzy reasoning, thus achieving the state identification of the process. A diagram of its principle is shown in Fig. 5.10.

As shown in Fig. 5.10, the fuzzy monitoring system is mainly composed of three parts; that is, fuzzy sets, fuzzy rules and fuzzy reasoning engine. Fuzzy set is to fuzzy the state information and feature information during the process, and it is described in the form of the fuzzy set: fuzzy rules are acquired according to expert knowledge and experience and are used to describe the fuzzy relationship between the characteristics of monitoring and the processing state; fuzzy inference accords with the known relationship to make fuzzy reasoning, in order to obtain the process status of fuzzy information.

2. Based on tool monitoring of neural network

The self-learning ability of neural network and the ability of classification allow it to be applied to fault diagnosis of the problem such as the monitoring and diagnosis of tool wearing in the process, with BP being the most widely used network. Despite many examples of the successful application of BP, it still has limitations in the manufacturing environment. Before the usage of BP network, it generally needs to have samples of all the different failure modes to train the network, and if the network lacks prior knowledge of the failure state, it is very difficult to monitor this fault state. In order to solve the diagnosis problems of these machines, a variety of solutions have been proposed; for example, the ART network without supervision does not exist that problem. Another network form that can be used is RBF network; the hidden nodes of the network use RBF as an incentive function, usually a non-RBF monotone function, thus the hidden units make a meaningful response only when the input into the input space is in a very small designated area [4].

Table 5.2 Comparison of data mining and information fusion

Data processing method	Data mining	Information fusion
Knowledge generation process	Discover unknown from data	Judge the mode instance by using the existing mode as template
Data input	Any data about the object	From multi-sensor information or source data
Reasoning process	Conjecture-conclude: search the relation among data for description object or given rule collection	Deduction: judge and confirm instance which satisfied mode normative by using established mode
Knowledge or model	Unknown: utilization property or prior assumption of data to discover knowledge	Known: utilization existing mode as template to discover or judge similarity mode instance
Knowledge acquirement purpose	A. Discover mode B. Discover new instance that represents for unknown mode	A. Judge instance which satisfied certain mode B. Judge type and state of the known objects from a number of data
Knowledge output	Mode that description relation or action of object or instance	Classify or judge instance by using mode

5.1.3 Data Mining

5.1.3.1 Comparison Between Data Mining and Information Fusion

Both information fusion and data mining are processes of generating knowledge. According to the size of the original data collection, data mining mainly uses artificial intelligence or statistical methods to speculate and search for the potential complexity relationship or the model contained in the data, rather than paying much attention to the data sources. Information fusion stresses the analysis of the information from multiple sensors or data sources, identifying and estimating the objectives or making a comprehensive judgment.

In the logical inference point, data mining and information fusion are two opposite processes. Data mining, which studies and summarizes knowledge from the original data, is a process of induction. Information fusion, which uses already existing knowledge and experience to deal with the data from different areas of the unknown world, is a process of deduction. The comparison between data mining and information fusion in the importation, functions and data processing is illustrated in Table 5.2.

From the comparison above we can conclude that information fusion and data mining as reasoning processes play a complementary role in the establishment of object models (patterns) and using models to screen targets. Because the advantage of data mining is that it uses data collected from the information fusion system to analyze and does not need special experiment processing, it can be very naturally integrated with the information fusion process. By first finding laws and models of the objects from data using data mining technology, then using these laws and patterns as a fusion template to screen objects, the process can be repeated until we get a satisfactory result.

5.1.3.2 Data Mining Methods

Data mining usually includes the following basic processes:

1. Data collection: analyze mining issues, confirm mining tasks, and collect mining-related data in accordance with mining tasks.
2. Data preprocessing: firstly, clean the data to eliminate the noise and inconsistencies in the data; then convert the data to a format fit for data mining.
3. Data mining: data mining here is a key link in knowledge discovery, rather than the whole knowledge discovery process. At this stage, according to the data running, choose the mining method (such as decision trees, neural networks and SVM) and draw mining results.
4. Knowledge evaluation: adopt various interest indicators to evaluate mining results, and find out which knowledge users are interested in it.

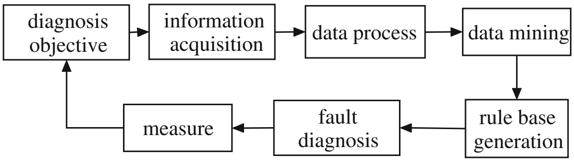
Data mining's task is to find hidden patterns in the data and the models that are found generally fall into two categories: descriptive types (descriptive) and projective types (predictive). Descriptive mining describes the general characteristics of the data in the database. Predictive mining task draws predictions from the current data so as to calculate future trends.

There are many data mining methods. Intelligent data mining methods include the following basic skills: imitation of biotechnology (neural network, genetic algorithms, immune evolutionary algorithm, etc.); statistical analysis methods (immunization control plans, correlation analysis, regression analysis, factor analysis, etc.); set theory methods (such as rough sets, concept trees and AQ11); decision trees methods (ID3, C4.5, etc.); and fuzzy theory methods (fuzzy judgment, fuzzy decision-making, fuzzy clustering etc.) are the top five types.

5.1.3.3 Data Mining Applied to Digital Manufacturing

Data mining in digital manufacturing seeks to mine the hidden and useful information and knowledge from the huge volumes of data, and be able to provide powerful decision supports for online monitoring, fault diagnosis, model identification, control strategies design and projection in manufacture processing. For example, it is used to mine a quality product model from the product manufacturing data recording, then apply it to the process of optimization; to forecast abnormal changes during the equipment running in accordance with the dynamic trend analysis, and then to pre-warn technology staff in time for maintenance, to rule out hidden dangers and prevent the occurrence of major losses; or to provide business decision support for enterprise operators for product orders, sales records and demand trends of requirements and so on.

Fig. 5.11 Total design strategy of fault diagnosis system



1. Fault diagnosis data mining methods modeling

In the course of equipment failures diagnosis, mostly dealing with data collected by sensors, there is a need to monitor the process of the original parameters, including process, switching and vibration capacity; these original non-power signals together with environment noise, which are picked up by sensors, together with the noise introduced by transmission lines, get access to data acquisition systems. Ultimately, the message from the data acquisition system will be more abundant than the original information. In addition to the original process and switching capacity, and vibration signals, there are export data, alarm data and so on. Because of the complexity of the objects' operating conditions and many influencing factors, the same failure often has different outcomes and the same symptom is often the result of many kinds of faults; and because of the variety of forms of the information performance, the demands of information capacity and information processing speed are increasing, all of which have been far beyond the traditional methods of information processing capacity. One of the methods to overcome these difficulties is to use data mining and information fusion for information processing [5], to acquire reliable understanding and interpretation of the tested targets' consistency, and thus to help the fault diagnosis system make the right diagnosis and decision-making.

The failure data is mainly analyzed from two aspects [6]: the first is data analysis of reliable tests, which completes the reliability evaluation of numerical control equipment; the second is based on the failure model to study the mechanism and put forward measures to improve the reliability of the numerical control equipment. With regard to failure mode types division, we usually view a tool, probability and statistics, as a new approach. For failure patterns' identification we adopt a more mature developed theory, association rules, which are used to find the association between variables, and finally to acquire the rules classification needed; that is, to achieve the purpose of classification. Based on these rules, we can confirm faults in the new data and classify them, identify the type of failure, understand the reasons and eliminate them. Mining system design strategy is shown in Fig. 5.11.

2. Data mining method of digital marketing

In the course of product sales, taking advantage of computers, communications, networking and artificial intelligence technology mobilizes enterprise resources for marketing activities: thus fulfilling their products and services demands; this process is known as digital marketing. The basic meaning has two aspects: first, web-based enterprise marketing management activities: that is, knowledge and information resources digitalization; second, the use of quantitative management tools to address the management issues, which is called management computability.

An enterprise database system has a large number of product sales records and customer information. Making full use of these enterprises will give information analysis a comprehensive insight into market trends in the past, present and future and identify the most valuable customer groups in the competitive market, so that business leaders can make timely and accurate decisions.

In order to enhance the analysis capabilities of digital manufacturing enterprises' in market and sales activities, data mining techniques are applied to digital marketing, and database classification methods are used to find the sales regularity of their products and customer base characteristics from the large amount of information of an enterprise's database, with the hope of providing strong technical support for enterprises to make product development, production, sales and service strategy more scientific and more effective.

5.2 Knowledge Engineering in the Whole Life Cycle of Manufacturing Product

Knowledge engineering is an important part of artificial intelligence, which gets the artificial intelligence (including repository, knowledge rule, logical reasoning and so on) and CAX (a general designation of CAD/CAE/CAM/CAPP) system together, to form an integrated system based on the whole life cycle of the products. Introducing knowledge engineering to the phases of the whole life cycle of products through the analysis of the corporation issue can help a manufacturing enterprise to discern, gain, develop, express, decompose, store, deliver and rebirth the knowledge of product exploitation effectively and quickly, so that the knowledge can be processed, accumulated and applied.

5.2.1 Knowledge Representation

Products design, technology processing, assembling the plan and producing and managing systems within the manufacturing system have become highly complicated. The manufacturing system contains and accumulates a great deal of knowledge, which is called "manufacturing knowledge". It is worth observing that the basis of the manufacturing activity is to copy the knowledge or information about the raw materials or semi-finished products to enhance the knowledge content and make it into product. A product is born because of the materialization and integration of the necessary manufacturing knowledge. The quality (content) of the manufacturing knowledge standards sets the application value, and the quantity decides the changing value. Nowadays, the research of manufacturing knowledge is essential. In the beginning, it is necessary to study the class of manufacturing knowledge.

5.2.1.1 The Class of Manufacturing Knowledge

Manufacturing knowledge can be divided into unit knowledge and composed knowledge according to its structure. Unit knowledge means the knowledge cannot be expressed by other manufacturing knowledge (except itself); composed knowledge means the knowledge composed by one unit and expresses the integer character.

Manufacturing knowledge can be divided into form feature, precision feature, assembly feature, examination feature and materials feature knowledge according to the information features of the products. This feature knowledge can be separated into three parts: the first is form feature knowledge; the second is precision feature knowledge which is composed of precision features, assembly features and examining features knowledge (the assembly knowledge/information examining knowledge/information has already been included by the rough degree of the surface and common difference in geometry according to international and national standards); and the last is materials feature knowledge.

Manufacturing knowledge according to the process of the production can be divided into design knowledge, craftwork knowledge, assembly knowledge, examining knowledge, material knowledge and so on. The knowledge includes macroscopic distortion knowledge (for example, punching, cutting, forging and so on) and microcosmic distortion knowledge (for example, hardening, annealing, cold disposal, leaking carbon and so on).

Manufacturing knowledge according to usage can be divided into general knowledge, currency knowledge, specialty knowledge, technique, knack knowledge and so on.

Manufacturing knowledge has close relations with the manufacturing process. It has many aspects and levels, which can roughly be divided into product knowledge and manufacturing processing knowledge. Product knowledge is necessary information expressing the character of products exactly, which includes the geometry shape, size, common difference, grain of materials, all kinds of technical rules and technical requirements; manufacturing processing knowledge includes producing control information (craftwork knowledge) and management knowledge in the manufacturing processing, which brings about some manufacturing process. According to the modeling theory of the whole life cycle of a product, product knowledge can be divided into product design knowledge, product manufacturing knowledge, product maintenance knowledge, product callback knowledge.

5.2.1.2 Knowledge Representation

Knowledge representation is to study the form in which we store the knowledge in the computer in order to deal with it. The representations frequently used in the field of AI almost always come from the abstract models by observation and

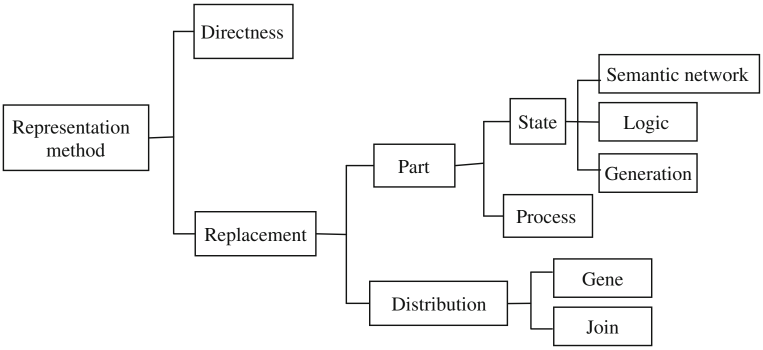


Fig. 5.12 Knowledge representation architecture tree

analysis of the intellectual abilities in microscopic and macroscopic levels by the researcher. According to these theories, we can classify them into three types [7] as follows. The part class: logic, generation system, semantic network, framework, script, process and so on; the distribution class: gene, join mechanism; the directness class: kinds of graphics, images, sounds and artificial environment.

In this way, a knowledge representation architecture tree can be constructed as shown in Fig. 5.12. In this tree, the part representation is fully researched and is a frequently used method in the field of AI. The distribution representation method supplies intellectual abilities.

In the digital manufacturing system, there are many kinds of knowledge representation methods. The common ones are the logic representation method, generation rule representation method, framework representation method and object oriented representation method. Every kind of method has its own range, and is suited for different types of knowledge.

1. Predicate logic representation method

In this kind of knowledge representation method, the predication logic representation method is used widely, especially the first-order predicate. Its knowledge base can be seen as a group convergence of logic formulas, whose alteration is the addition and deletion of logic formulas. Formal logic deduces and performs according to the true facts, in order to obtain new facts.

2. Generated rule representation method

In the objective world, there are various kinds of complicated relationships between objects or knowledge; cause and effect is the most common and simple one. The generation system is a kind of representation method which is fit for representing this relationship. In semantic relation, it a means cause and effect or reasoning relationship of “if A then B”. The generation system is composed by knowledge base, global database and inference engine.

3. Framework representation method

Framework is a complicated data construction which stores all the knowledge of some special thing or object together. It contains the illustration and process information of inner relations defined in the past and the future condition. Depending on their type, we can use the former knowledge to explain the new data. This knowledge form is propitious for dealing with "hope guidance", which means that people in the specific environment look for optimistic outcomes. The slot in the framework makes this deduction possible. Using the concept of the slot, people can add knowledge to the environment constructed by the framework.

4. Semantic network representation method

Semantic network is widely used for its naturalness. The character using the knowledge represented by the semantic network represents a possible world with a marked directed graph. The nodes represent the quality, concept, condition or action, and the marked sizes represent the relationship of the objects.

5. Object oriented representation method

This is a method which has been discussed frequently in recent years. Its basic points are that the objective world is made up by various kinds of objects, that anything is an object, and that complicated objects are composed of several simple ones. All the objects have been classified as different kinds of object class; the operation with the objects in a class is defined as method, and this operation in the object oriented methodology is called "send a message to some object". There is no other relation between the objects except sending messages. All the information located objects and achievements are sealed and packed, which cannot be seen from outside. Object class, according to the sequence of class, subclass, super-class, constitutes a level relationship (or tree structure), called an inherited attribute.

6. Ontology based representation method

This knowledge representation method is one of the hotspots of recent years. This point of view considers whether complex knowledge is made up of the most basic concepts. These concepts are called ontology. Ontology illustrates the basic concepts in detail. The importance of ontology is its shareable and reusable knowledge.

The knowledge in the manufacturing field is accumulated over a long period of project practice, and runs through the links of the whole life cycle of product manufacturing. It includes features of multiplicity, discretion and experience. Each type of knowledge is fit for adopting a different knowledge representation method. For example, expressing knowledge generally has better structural form (e.g., level relation), which is suitable for the frame representation method; estimation knowledge is usually the concluding of the knowledge and experience by experts who work in this field for a long time, so it has experience and elicitation, and it is fit for the generation rule or semantic network representation method; process knowledge reflects in the program achievement, which is fit for the numerical processing method. Therefore, in a practical engineering application, the only way is to combine the multiple knowledge representation method according to the knowledge in the specific field, so that we can find a solid basis for the knowledge base.

5.2.1.3 Spare Parts Knowledge Representation Model

According to the international standard, the feature of spare parts can be divided into three types: geometry model feature representation, geometry attribute (size and common difference) feature representation, and material feature representation. Because the entire feature is the geometry model feature and the attribute feature, it is necessary to use the definition and deduction method. We add the entire feature as an assistant feature to the expression of the spare parts, so that the representation model is convenient to retrieve.

Synthesizing the space element theory and representation type of spares features, using the knowledge representation model built by the four elements of macroscopic feature, geometry model, geometry attribute and materials can represent the spares exactly and completely, to form a complete concept system. The representation space of spares can be defined as follows:

Definition 5.1 The representation space of spares can be defined by an array $<F^*, M^*, C^*, Ma^*>$, where F^* is the set of entire features of spares, which depend on different macroscopic class method and construction method in order to get different macroscopic set; M^* is basic model set, which is also called a primitive set. Primitive is the element that cannot be defined and represented by other elements in the M^* (except itself); C^* is a relation set which represents a universal set of preset relationship; Ma^* is a universal set of attributes, sorts, heat treatment method and resistance and so on.

Using the theory in CIMS for reference, combining the processing method of spares, and classifying the macroscopic feature of spares, the spares can be classified into seven parts: the axis part, box part, support part, tray overlapped gear wheel part, linking spare part, standard part and other special shapes part.

In the CAD system, there are two common formats to represent the spares, which are boundary representation (B-rep) and entity model (CSG) representation. Boundary representation uses dots, lines and surfaces to represent spares; CSG condenses the dot, line and surface of low-level to form geometry objects with certain geometry features (for example, the cylinder, the cubes and so on), and then to represent the spares through a group of Boolean calculations. According to the feature element of CSG in the platform CAD, the primate that is represented by the CSG can be concluded into 23 types of shape, such as tetrahedron, cube, cylinder, cone, sphere, ring, spire shaped, pipeline shaped, extension shaped and other complex shapes.

According to the definition of representation space of spares, any one of the machine parts in certain texture can be represented as $\{F, M, C\}$, where F is feature of F^*, $F^*$is a set of the entire features, M is a subset of M^*, M^* is primitive set in certain texture and C is the topological relationship between the modules. It can also be represented by undirected graph or directed graph. The vertex represents the primitive, the side represents the relationship between primitives, so the geometry features of spares can be represented by $\{F, G, D\}$, where G is the form feature and the graph of topological relationship between the features, D is a geometry attribute set of spares. The spares representation model is $P \triangleq \{F, M, C\} \triangleq \{F, M, G\}$.

5.2.2 *Knowledge Base*

5.2.2.1 Definition of Product Knowledge Base and its Function

Manufacturing activities will generate a lot of knowledge, experience, and the knowledge is a valuable intellectual resource that makes enterprises innovative and sustains development. How to integrate the reasonable knowledge into a knowledge base system to facilitate the organization, management, use and sharing of knowledge for the in-depth development of a manufacturing system is a problem that needs addressing.

The knowledge base system is composed of the instance base, the rules base, the constraints base and the knowledge base. The knowledge base management system is utilized to add, manage and maintain the knowledge base. The instance base is used to store a number of successful instances and new instances generated by the inference engine that is provided by the user. The rules of knowledge reasoning are stored in a rule base, such as the search of instance, similar algorithm, etc. The constraints base is used to store many design constraints, such as the geometric constraints, product performance parameters and other product-related regulations and standards. The knowledge base is used to store expert experience knowledge, experimental data, design criteria and formulas. Knowledge data in the knowledge base can be adopted by the inference engine and obtain knowledge to learn, add or edit through the system.

The product knowledge base on the basis of the relational database is used to manage static and dynamic data that is generated from the process of planning and designing to the product. Historical experience and knowledge in the product knowledge base support the process of product research. Information that is generated in the process of product development can refine into new knowledge and be stored in the enterprise knowledge base in order to continuously enrich the knowledge base. With the accumulation of knowledge related to enterprise products, the product knowledge base provides services for product design in order to achieve rapid product design. The product knowledge base includes the knowledge base, technical knowledge base, manufacturing knowledge base, enterprise basic information base and application system knowledge base.

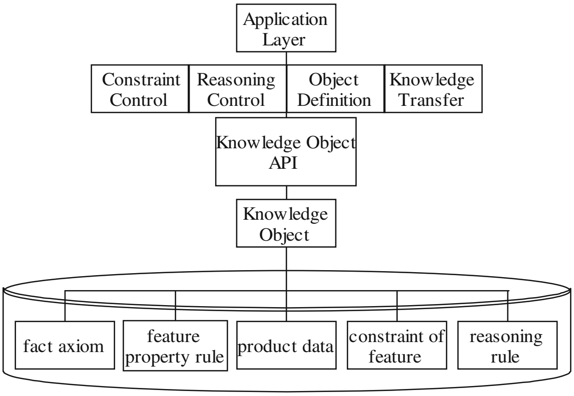


Fig. 5.13 Basic structure of product knowledge base

5.2.2.2 Structure of Product Knowledge Base

Figure 5.13 describes the basic structure of a product knowledge base. A number of resources such as the facts right, feature attribute rule, and product data are defined in the knowledge base, which integrates the structure of the knowledge base into a product model. Resources are integrated into the entity of objects in the knowledge base. Therefore to the outside world, the operation of the knowledge base has become the operation of knowledge objective. As a breakthrough for the environment of resource restriction in different modes the knowledge base model can be used freely in other models of resources, thus avoiding a great deal of duplication of definition.

The concrete steps of product knowledge base construction [8] are: (1) initial knowledge base is empty; (2) wait for the production strategy (this refers to the choice of manufacturing model of corresponding life cycle characteristics); (3) compare the new production strategy with the strategy in the knowledge base; if the rules match, then turn (6), otherwise classify the rule into exception; (4) classify the type of production strategy according to the cluster algorithm when the number of production strategies reaches a certain level; (5) transform the new classification of production strategies to rule and store in the knowledge base, add the corresponding task of strategies into a task table that new rule can mandate, turn (2); (6) add the new task that is solved by using existing rules into the task table, and use the principle of the cluster mission mandate to join a task type, or generate a new classification, turn (2). The knowledge base is now built. Figure 5.14 shows the process of knowledge base update through the learning method.

5.2.3 Knowledge Reasoning

In the product life cycle processes, such as product planning, appearance design, engineering design, and process planning, a wide variety of issues necessitate decision-making through reasoning. The process from market demand to the

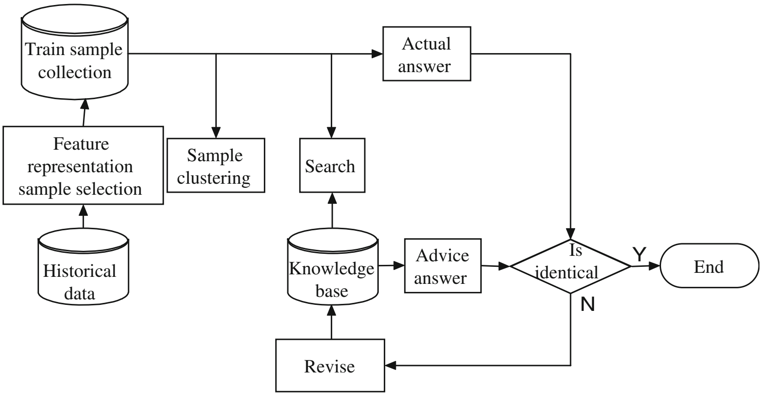


Fig. 5.14 Process of knowledge base update

design and development, production, sale, use, disposal and recycling of a product, have to carry out reasoning and decision-making in accordance with the constraints. The research contents of knowledge reasoning include how to choose knowledge in the knowledge base, carry out reasoning according to the evidence provided by users, and give answers to users or complete specific actions.

5.2.3.1 Knowledge Reasoning Model

1. Precise reasoning
   To express domain knowledge as a necessary causal relation, the premise and conclusion of reasoning is positive or negative, there is no other possibility. For this type of reasoning, a rule is activated; its former parts expression must be true.
2. Imprecise reasoning
   This is also known as likelihood reasoning. It is a reasoning method based on the uncertainty of knowledge to obtain the uncertainty of conclusions. The basic idea starts from the known information, matches the prerequisite then implements conclusions, and constantly concludes new facts.
3. Artificial neural network reasoning
   Neural network knowledge is different from the traditional knowledge expression method. It uses a large number of neurons and its interconnection and the weight of each interconnection to express a certain concept and knowledge diagram. The artificial neural network reasoning approach is a parallel reasoning method; its concrete steps of forward reasoning are as follows:

   (1) Submit the raw data to the node of the input layer.
   (2) Calculate the output of neuron $Y_i = f_i(X_i)$ from the formula $X_i = \sum T_{ij}Y_j + \theta_i$, and the output is equal to the input of hidden layer neuron or output layer neuron.

(3) Calculate the input of hidden layer neuron or output layer neuron from the formula $Y_i = \frac{1}{1+e^{-(\Sigma T_{ij} Y_j + \theta_i)}}$.

(4) Judge the output of the neuron from the threshold function

$$Q_i = \begin{cases} True, & Y_i \geq \theta_i \\ False, & Y_i < \theta_i \end{cases}, \quad \text{where } 0 \leq \theta_i \leq 1.$$

4. Case-based reasoning and rule-based mixing
   Product design and the manufacturing process are complex issues. They belong to a sick structure problem in theory. Experts often use experience and instances to express knowledge and use methods of association, intuition, memory, deduction and induction and others to deal with knowledge. Therefore, case-based reasoning is a very necessary knowledge approach.

If all of the instances in the current cases and instances base fail to match, a simple case-based reasoning will fail. In such circumstances, it is necessary to use other means to carry out the reasoning, and to increase the reasoning time. In order to deal with the problem, we adopt a hybrid reasoning method which composes case-based reasoning with rule-based reasoning. The solution: the knowledge base will be designed as a tree structure, where each sub-knowledge base is a node of the context tree, and each node includes a parameter library. Instances in the system are described in the form of a framework. When reasoning starts, a meta reasoning machine invokes case-based reasoning; the reasoning engine does not match all of the slots of the instance, but only matches some slots of the instance, and the slot has the same name as the parameter name of the root of the context tree.

When the match is successful, turns to other sub-nodes of these shafts to match, then the node-to-node of a match. The instance framework includes not only the slot that is used for matching, but also the slot that records the reasoning path, which guarantees the correctness of the case-based reasoning. In this way, while carrying out forward reasoning along with the context tree on the basis of the case-based reasoning, it probably fails to match the nodes that reach certain levels of the tree, then adopts meta inference and invokes the rule-based reasoning method to continue, which shortens the reasoning time.

5.2.3.2 Knowledge Reasoning in Engineering Design

At present, integration of rule-based reasoning and case-based reasoning, integration of rule-based reasoning and fuzzy inference rules, integration of case-based reasoning and fuzzy inference rules, integration of the instance reasoning of artificial neural network and the fuzzy inference of artificial neural network are widely utilized in KBE systems, such as intelligent CAD, auto parts marking, intelligent mold design and intelligent CAPP.

Fig. 5.15 General process of project design

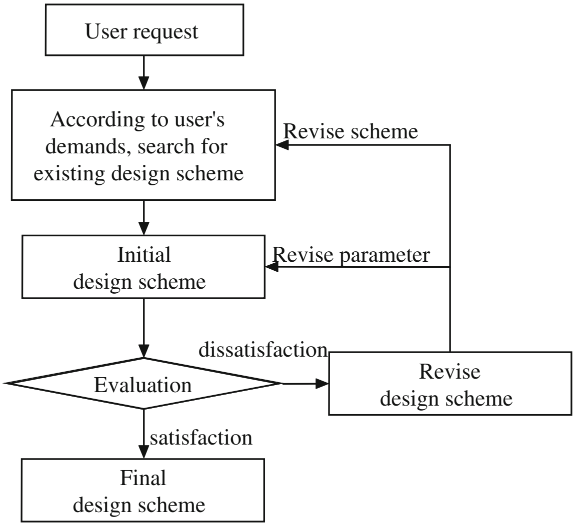


Figure 5.15 shows the general process of problem solving of engineering design. In the engineering design process, the engineers usually do not start with the deductive reasoning (rule-based reasoning) method, but adopt the analogical reasoning (CBR) model to compare the new design problem with past design schemes. They then choose the most similar design scheme and modify the scheme, in order to obtain a new scheme that satisfies the new design requirements. The edit process can be taken as a deductive reasoning process, that is to say, if a situation emerges, then certain parameters are modified. The integration of CBR and PBR follows the repeat process of “elementary design—evaluation—re-engineering”, as shown in Fig. 5.16.

Figure 5.17 shows the reasoning process of the integration of fuzzy reasoning and case-based reasoning. The fuzzy theory is applied to the engineering design, introduces the “matching degree” (the similar degree of two engineering designs), completes the knowledge instance reasoning, then works out the initial solution of the project design. The idea of this reasoning is as follows: The first step is to identify effective instances and create fuzzy sets for each project instance knowledge unit; the second step is to ascertain the subjection function of the knowledge unit, matching the degree between the current design and each project instance; the third step is to determine suitable instance collection by using the project threshold principle, and to optimize the parameter of collection in order to come to the final data and generate the elementary solution [9].

Figure 5.18 shows that the intelligent design system adopts the reasoning strategy mixed with the instance and knowledge of the coupled neural network [10]. The adaptive resonance network of artificial neural network theory (ART1 network) is applied in the intelligent CAD/CAE System. According to the user’s description, through dynamic clustering and index of ART1 and BP neural network,

Fig. 5.16 Integration principle of CBR and PBR

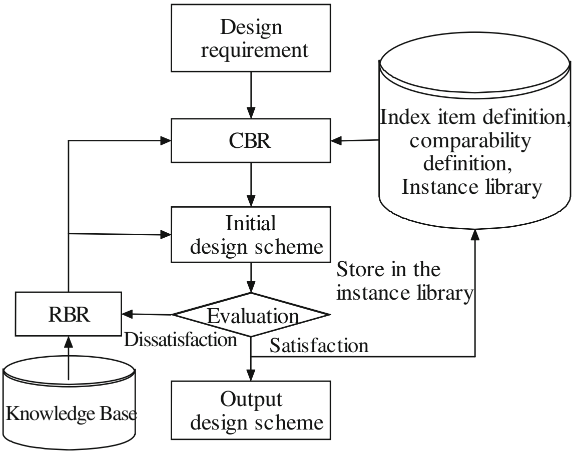
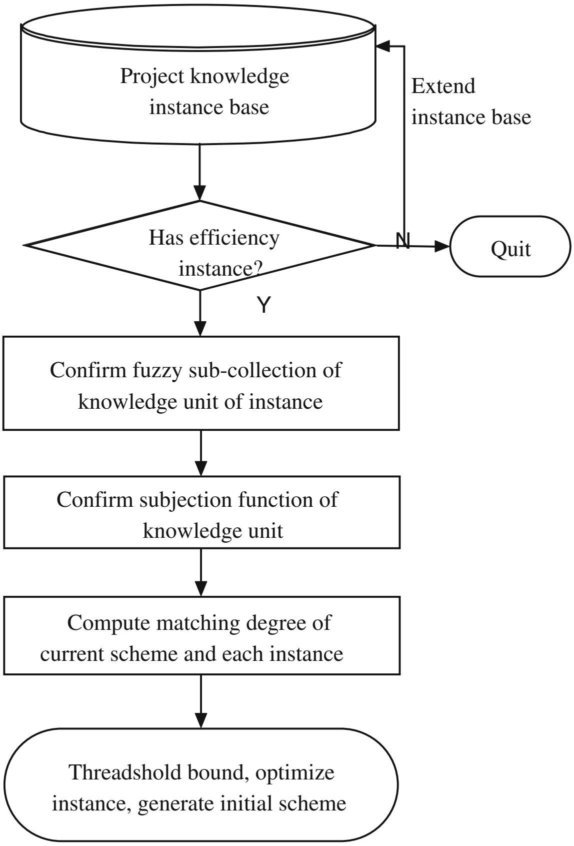


Fig. 5.17 Fuzzy reasoning flow chart



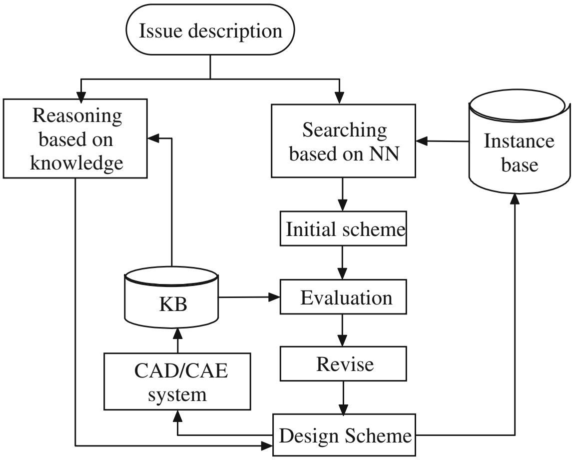


Fig. 5.18 Intelligence design system architecture based on CBR and NN

we extracted similar examples making use of the knowledge-based evaluation mechanism for evaluating the performance of similar examples, and we changed the parameters that did not meet the performance requirements, to achieve a final optimal solution. Clustering was done according to the instance feature description by adopting ART1 and BP neural network and generating an index and retrieval mechanism of each instance, then quickly matching similar instances that satisfied the design request from the instance base. If the CBR system cannot extract the satisfied instance from the base, the system will enable the knowledge-based reasoning mechanism and ultimately provide users with the available design scheme through reasoning judgment on the knowledge of the knowledge base.

5.2.3.3 Intelligent Knowledge-Based Manufacturing System

The architecture of an intelligent knowledge-based manufacturing system (IKBMS) is shown in Fig. 5.19. The system consists of the evaluation module, re-design module, decision-making module, etc.

The main task of analysis of evaluation modules is to evaluate the design or process scheme based on the findings of reasoning and the evaluation knowledge in the knowledge base. By using the relevant knowledge in systems engineering, value engineering, decision theory, operational research and fuzzy math, and adopting corresponding measures to complete a comprehensive assessment, by identifying the value of each evaluation index of scheme, acceptable decision-making for the next stage can be provided. The assessment builds on the expert level, thus it involves a large number of experiences and extensive knowledge, such as index planning and scheme score indicators. Moreover, different objects have different contents of evaluation indicators. Another important task of assessing is to provide important feedback information for the re-design process. It can also help the system to choose the back level of re-design.

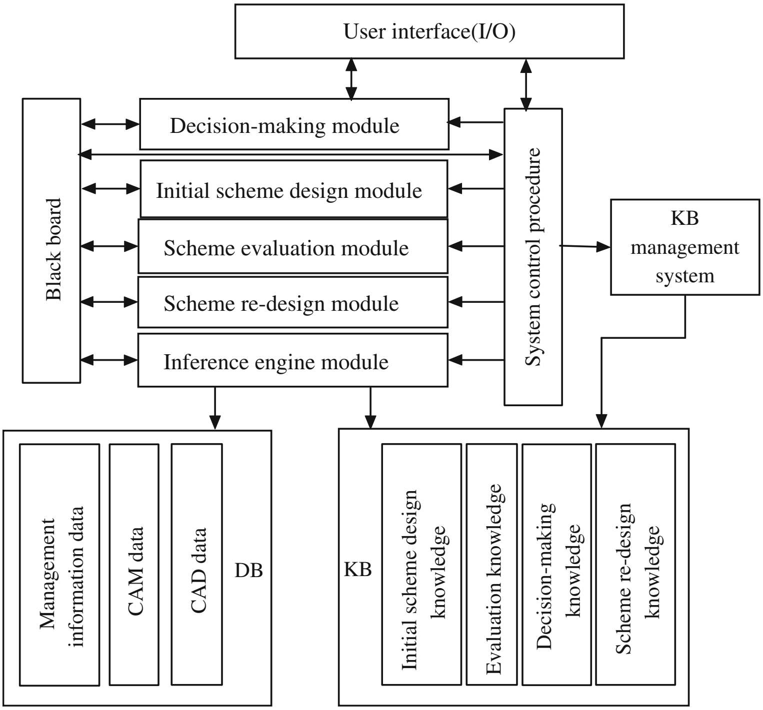


Fig. 5.19 IKBMS architecture

The redesign module is the key stage. Based on the feedback information of the evaluation module and decision-making module, and by using expert knowledge, the task of the system is to modify the original proposal and to submit the new design scheme so that the scheme is close to the acceptable index.

The task of the decision-making module is to check whether the results of the design scheme assessment reach the acceptability indexes. Based on expert knowledge systems, the acceptability index can be automatically generated. The acceptability decision-making has two meanings: first, to check whether the specific design scheme is acceptable, and second, to open a storage area for the feasibility design scheme. Generally, it outputs several schemes after the design of a number of acceptable schemes, and the system can assess the best scheme in accordance with comprehensive assessment indexes.

The IKBMS system is involved in extensive fields, particularly in the aspect of CAFP of the mold intelligent manufacturing area. It includes the processing tool selection, machine tool selection, clamp selection, processing method selection and so on. Different areas have complex degrees of knowledge, so the expression mode in the system is not the same. For example, machining methods and machining tools have certain methods to comply with, so the choice is not dependent on the creative thinking ability of the staff.

Based on existing knowledge and aiming at a specific scope of application, the corresponding decision-making rules can be established, and the logical decision-making methods used to solve them. Therefore, methods related to the machining methods and machining tools can be expressed by generative rule methods.

The knowledge of fixture and plan routine comes from the experience of the craft designer, and the craft knowledge is difficult to express by means of rules, so it adopts a knowledge expression form of artificial neural network to express knowledge. The reasoning mechanism can adopt the integration of case-based reasoning and rule-based mixed mechanism that is described in this section.

5.3 Autonomy, Self-Learning, Adapting of Manufacturing System

The target of IMS is to incorporate artificial intelligence into all aspects of the manufacturing process through the simulation of intelligence experts and by replacing or extending the manufacturing environment in some mental work. In the manufacturing process, the system can automatically monitor their operation, and when an external or internal incentive occurs, it can automatically adjust parameters to achieve optimal self-organization status.

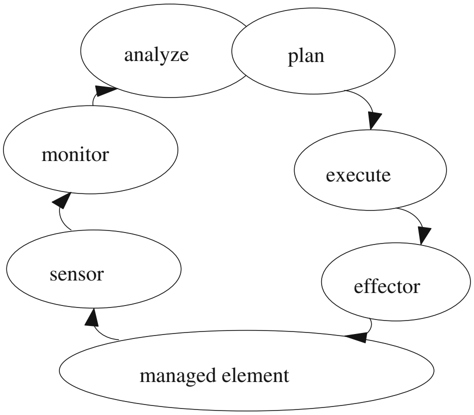
5.3.1 Autonomy of Manufacturing System

5.3.1.1 Self-Autonomy of Manufacturing System

Autonomy is an important character and design goal of IMS. The manufacturing system includes many nonlinear and dynamic processes and the environment frequently changes; thus, autonomy is required in manufacturing system. Pierre Massotte in 1995 described the definition of an autonomous system in one of his papers. He explained that autonomous systems, like the human brain, has to constantly optimize its behavior. The optimization involves a combination of nonlinear and dynamic processes, which implies management and control of ill defined and behavioral complexity. An autonomous system also includes training, learning, and adaptive capabilities by means of artificial intelligence technologies [11]. A salient requirement in high autonomy systems design is the integration of planning, scheduling, diagnosis and control functions. An autonomous manufacturing system should meet the following design requirements [12]: the system must plan and re-plan to realize its goals; the system must be able to execute its plans; it must monitor its environment; it must have cognitive and diagnostic capabilities.

According to these requirements, a framework including the functions required to realize the autonomy of the manufacturing system may be described as shown in Fig. 5.20 [13]. In the figure, the monitor collects measured data and status data of the controlled object/managed element by sensors to monitor controlled action.

Fig. 5.20 Framework of functions to realize the autonomy of manufacturing system



The role of analyzer and planner is to compare data from the monitor with history data, control rules and expert knowledge and then to decide related actions of the controlled object/managed element. The execute part executes the actions by effectors/actuators in the controlled object/managed element.

In a traditional manufacturing model, the manufacturing human experts (or groups) are the only decision-makers (referring to high-level decision-making) in the manufacturing system. The subsystem does not have autonomy, and the various subsystems are connected (or simply integrated) only in accordance with the decision-making of the human manufacture experts. In the IMS, the general decision-making of the human manufacturing experts in the various subsystems is replaced by the intelligence of the computer, since the subsystem is a mainstay of self-decision-making capacity. The integration of the entire manufacturing process is completed through the various subsystems of the decision-making coordination; this is the so-called knowledge integration. Therefore, it can be considered that in IMS manufacturing, the resources (including material flow, energy flow and information flow) in a product's entire manufacturing process are a typical multi-agent for the collaborative process.

The unity of subsystems and their ability to automate decision-making constitutes a certain (artificial) intelligent body of autonomy, and this becomes an essential component unit of IMS. The higher the level of the main decision-making automation, the higher the level of its intelligence, and so the stronger the autonomy. However, the complication of the manufacturing tasks depends on the mutual coordination of each subsystem. This also depends on the whole ability of self-organization or meta decision-making ability of the IMS, that is, on the respective body (or subsystems) of the decision-making organization, coordination, management and ability to integrate. Hence, IMS is essentially a self-distributed manufacturing system and its basic characteristic is the individual's "autonomy" and the whole of the "synergy".

Self-organizing ability is the basic requirement of IMS. IMS can support their respective organizations production units to run under the distribution model, and the entire system consisting of these self-organized production units can run in a proper way, enabling all enterprises to get the best operation of the unit through coordination at all activity levels (company level, the factory level, workshop level). Study of the self-organizing ability of the self-organization unit of IMS will focus on the structure of self-organizing units.

The definition of a self-organizing system is as follows:

Definition 5.2 What cannot be achieved by external control from disorder to order changes, and maintaining a stable and orderly state system is known as a self-organizing system.

According to the principle of information enhancement (that is, the fourth principle of general information) we know:

Theorem 5.1 (1) *Information that has a high amount of information can suck from a low amount of information to increase the energy intensity of their information, so that in both the overall energy increases in an orderly manner;* (2) *As a condition of enhanced information the system has special structural conditions: that is, the system is a nonlinear system, or in a state of nonlinear region.*

Theorem 5.2 *Any self-organizing system enhances the information through resonance, feedback and enlarging (the value) and maintains its stability and orderly effect.*

Therefore, a self-organizing system is a system consisting of a special structure that can enhance information; this system is in a state of nonlinear systems or nonlinear region. We can believe that, in IMS, the low amount of information is the majority of data, a small portion of the information for the knowledge and the highest amount of information constitutes the majority of knowledge data for a small portion of the information. According to Theorem 5.2 we know that in order for IMS to have a self-organizing ability, the IMS unit of self-organization must have an information structure that can strengthen information.

5.3.1.2 The Autonomy Unit Structure of Intelligent Manufacturing Systems

According to the unit system ideology in an intelligence project, the basic unit structure of IMS self-organization is shown in Fig. 5.21 [13].

1. Subsystem interface
   Make one of the necessary subsystems and systems connected for the management, control, use of system. The interface should have the function of changing one non-standard data format of any subsystem into the same kind of language standard format, while the basic system completes the conversion and communication of heterosexual language standard format. Its input is the low energy of various information systems; the output is the result of collaborative

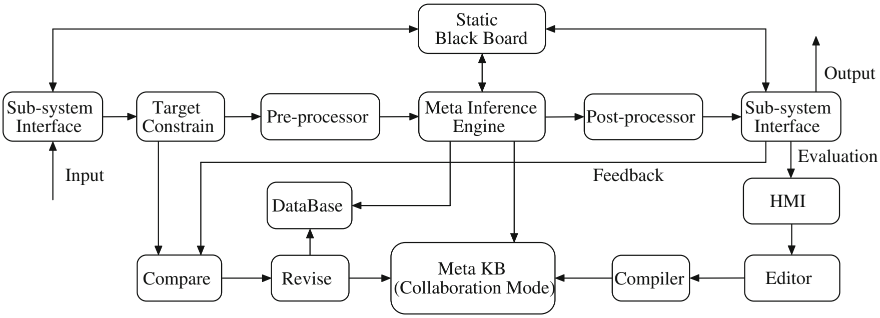


Fig. 5.21 Self-organizing unit structure of intelligence manufacturing system

decision-making that various subsystems are nonlinear and integrated through the basic system.

2. Objectives and constraints modules
   These indicate the task and restrictive conditions that the system should complete. The basic knowledge library is the foundation of the system's management implementation. Yuan knowledge according to its content and nature can be divided into a number of modules.
3. Static blackboard
   In the external memory, a dedicated storage area is built to accommodate the information that should be preserved when the system is running. This is because the whole integration of intelligent software system may not be able to run at the same time in the system, because it would need too much memory.
4. Base database of system
   The database that is shared by the overall integrated intelligent unit (IIU), which distinguishes it from the database of subsystem, which is partial and only used for a subsystem.
5. The characteristics of basic reasoning
   With the characteristic of the dispersion of metadata and diverse forms of expression of basic knowledge, basic reasoning is integrated by a variety of reasoning methods. It can operate and process the complex and diverse knowledge of the reference model, in order to achieve the whole system's control, coordination and use.

5.3.1.3 The Autonomy or Self-Study of Manufacturing System

An intelligent integrated numerical control system (I^2NCS) based on intelligent integrated numerical control technology is shown in Fig. 5.22, which is one key technique in the research of IMS [14]. There are three layers in the architecture.

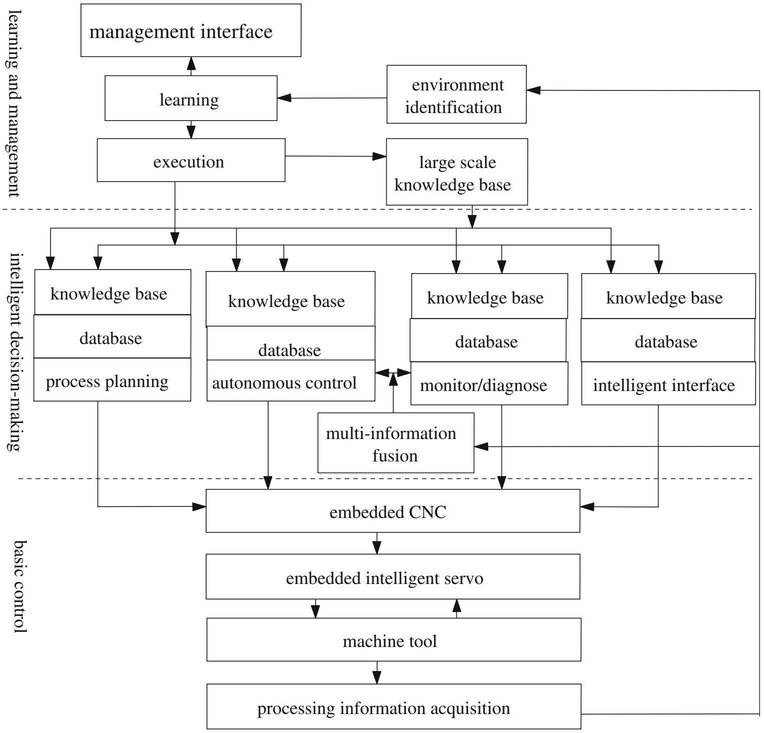


Fig. 5.22 A hierarchical architecture of an autonomous numerical control system

These are the basic control layer, intelligent decision-making layer and learning and organization layer.

1. Basic control layer
   This is responsible for the realization of general numerical control functions. High-speed intelligent control algorithms may be used to improve the system's response speed and increase the system's robustness. Nonlinear intelligent compensation technologies can also be applied to meet the requirement for high precision of machining.
2. Intelligent decision-making layer
   This is mainly used to make relevant decisions, tune the working state and parameters of modules in the basic control layer or in its own, according to the controlled object real-time status and machining specification from users and supported by the knowledge database. It also monitors the system in real-time. There are four modules in the layer. They are process planning, autonomous control, monitoring and diagnosis and intelligent interface. The autonomous control module is the most important. The system autonomic control is realized by it. It senses the system operating condition and status using multi-sensors. Then information extraction and multi-channel information fusion technologies

are applied to conduct multi-information fusion, crossover and integration. According to the processing result and with the support of the knowledge database, the autonomous control module makes decisions by reasoning to tune the operating state and parameters of the basic control layer.

3. Learning and organization layer
   This has the function of self-learning besides relevant reasoning and decision-making. It undertakes the identification and sensing of the whole system operating environment, which includes the operating status of the machining process, basic control layer and intelligent decision-making layer. It then decides to change the knowledge database and knowledge source to modify a specific part or certainty factor of the control rules.

With distributed artificial intelligence widely applied in manufacturing, distributed autonomous manufacturing systems are presented with distributed autonomy. The function and logic structure of the manufacturing system may be based on multi-agent. In the distributed autonomous manufacturing system, coordination and cooperation are important issues. A method for multi-autonomous-agent-based distributed manufacturing system integration has been proposed, which includes the method to construct a distributed manufacturing system in a distributed network environment, the function and logic structure of the autonomous agent, the information exchange among agents and the coordination protocol [20].

5.3.2 Self-Learning of Manufacturing System

Information processing and knowledge synthesis is an important link in IMS. It has a direct effect on the operating system and the quality and efficiency of product accomplishment. How to digest and summarize the various manufacturing processes in the massive data information, and synthesize the knowledge of decision-making and realize the self-learning ability of manufacturing systems is becoming a research hotspot in the field of intelligent manufacturing.

5.3.2.1 Concept and Mechanism of Systematic Study

Simon considered that learning is the changing of a system that adapts to the external environment, making the complete system even better in the future when it has the same or similar tasks. The learning process can be completed by an agent as shown in Fig. 5.23. “Execute module” receives the sensing information of the external environment and the status information of its internal environment. It selects an agent to implement the external action. “Supervisory module” uses the outside world performance evaluation standards and conducts the study and interpretation of the “problem of modules” and has a common role in assisting the “study module “improvement” module” by the decision-making. The agent of the implementation of learning and access to knowledge should show: (1) integrity,

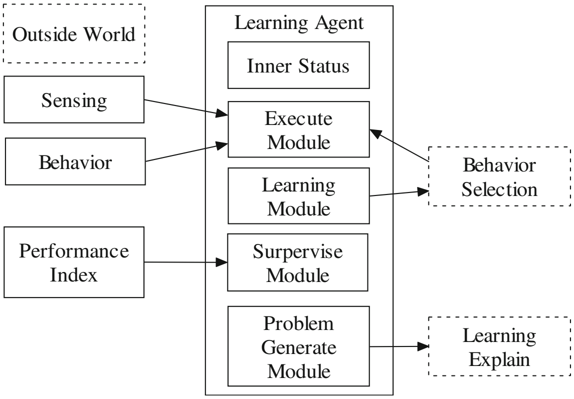


Fig. 5.23 Principle structure of learning agent

the study should collect as much information as possible about the characteristics of its application for a wide range of knowledge, (2) proactive, should be able to learn from the limited examples of special circumstances, making the general rule, and has a predictable capacity, (3) understanding, the learning process and access to knowledge should be easy to understand between people and machines, (4) evolution, in the implementation cycle, behavior and results of study with good performance should continue to accumulate and evolve, and the foolish acts and wrong results should continue to be discarded and degraded.

Research since the 1950s into the learning mechanism has seen the development of the experienced neuron model and decision theory that realize the learning process through step by step modification of the weight value of a network, and includes example learning, induce learning, analog study, learning based on interpretation and so on. Since the 1980s, research into the ANN learning mechanism has revived, several new learning mechanisms, such as competition learning, evolutionary study, reinforcement learning and so on. Refer to paper [15] for more detail about the learning mechanism. The symbols learning mechanism is more suitable for group technology, products, craft design and production scheduling, and in process modeling, diagnosis and monitoring, due to the need to process a large amount of digital information in real-time, thus we inclined to use the neural networks and genetic algorithms. Machine self-learning can be categorized in many different ways. The following description gives several common learning strategies.

1. Rote learning: learning system does not require any form of reasoning or the learning process of knowledge conversion. It can be also divided into learning according to the outside procedures process and learning through receiving information.
2. Learning from instruction: The learning system obtains knowledge from the environment, and converts it to an in-system form and combines the new knowledge with existing knowledge.
3. Analogical learning: The learning system finds existing knowledge and new concepts or similar skills which are obtained through conversion and expansion.

4. Inductive learning: The learning system generates a general description of the concept through the inductive inference on the environment to provide examples of the concept of promotion.

Above all belonging to a single method of learning strategy, their ability to learn is not equal, and they cannot complete all the system tasks of learning independently.

5.3.2.2 Learning's Research and Application in Intelligent Manufacturing

Self-learning is widely used in the field of IMS, such as group technology, product and process design, production scheduling, process modeling and monitoring, process control and diagnostics.

1. Product design

Development of new products inevitably requires repeated amendment, integration, coordination and optimization for shape and size. Therefore, this requires a new generation of systems to modify the design of products with certain changes to structure and size, and an awareness of environmental changes. It automatically modifies the graphics and has flexibility in its design capacity. In order to modify the design model dynamically, the structure of the object shape is applied to the design technology of parameters when compared to stereotypes. It defines binding factors in the form of rules or algebraic equations establishes the drive mechanism of the corresponding reasoning, and makes the solid model and the surface modeling into a unified system. It brings together a model that achieves the best of design automation and the effect of flexible design.

2. Manufacturing process control

Self-learning control is a more comprehensive adaptive control of recognition, judgment, experience and learning function. When the characteristics of the control system cannot be known in advance, or cannot be accurately described using mathematical models, self-learning control can be used continuously in the course of the work. It estimates the characteristics of the system and optimally controls programmers to achieve performance optimization. Adaptivity is a dynamic local optimization process, and self-learning is a process that often reflects the overall approximation.

Learning control involves a wide range of issues. Along with the development of artificial intelligence technology, learning control is also constantly being developed. Involved in the most basic learning theory are: (1) decision-making theory, (2) training and threshold logic controller, (3) reinforcement learning control system, (4) Bayesian learning system with Bayesian estimation, (5) random approximation learning system, (6) random automatic machine model, (7) fuzzy automaton model, (8) theory of optimum number of methods, (9) artificial intelligence learning system and (10) neural network learning system. Early learning control mainly adopts pattern recognition and classification, the probability distribution and density function of the estimates and guesswork and other methods to study the uncertainty of the unknown information. This learning can be a mentor (such as decision-making theory and the training threshold logic) or not a mentor (such as reinforcement learning and random Mai nearly automatic model). In recent years, due to the development of computer technology, optimization theory, neural networks and fuzzy decision-making techniques are largely used in learning control.

5.3.3 Adaptation of Manufacturing System

5.3.3.1 Adaptation of Manufacturing System

Changing markets, societies, consumer desires, technology and environmental concerns are the driving forces that affect manufacturing systems. In order to adapt to changing circumstances, manufacturing systems should have the characteristic of adaptation, which is also the important goal and capability of intelligence. Manufacturing systems are characterized by a changing and diverse product mix over time, prescribed due dates, a huge number of machines, and a large number of routes and disturbances, which have been taken into account in the course of designing and implementing manufacturing control systems.

5.3.3.2 Adaptive and Self-Learning

To be “adaptive” means that the operating environment or system structure changes, and the system has the capacity to access information related to these changes, making the system able to maintain or achieve the desired status or request. A self-learning system is one that is in the work environment that lacks adequate prior information about cases but which learns from past information and experience to improve performance. In essence, adaptive systems and learning systems use memory and experience information. Both methods change or adjust the structure of the controller or parameters through a closed-loop feedback controller which differs in degree, focus and goals, as shown in Table 5.3.

5.3.3.3 Adaptive Control

The significance of adaptive control, or adaptivity, is to change the structure or system parameters in order to maintain the characteristics of a good run in a new environment or new operating conditions. Generally speaking, the uncertainty from of dynamic system has three areas: uncertainty of system structure and parameters, input environmental noise or interference and measurement

Table 5.3 Comparison of self-adapting and self-learning

Self-adapting	Self-learning
Maintain the anticipation through the reaction in response to the changes of the outside world—partial optimization	Achieve the anticipation through integration of structure—global optimization
Emphasis on time	Emphasis on space
Non-memory, cannot predict	Memory y, can predict
Good dynamic performance	Bad dynamic performance
Deal with the new environment and slow time-varying behavior	Deal with uncertainty and nonlinear structure

uncertainty. The adaptive control system can be defined as a special form of nonlinear control system, which can be run automatically in the system to improve the quality of relevant information and to fix the system or structure parameters, making the system meet the required state. The adaptive control system should include the following four parts [15], namely, the basic conditioning control feedback loop; the given system criteria, including the system performance indicators or the optimal criteria; real-time identification, to obtain the necessary information; and real-time adjustment, to change the structure or parameters.

A system block diagram is shown in Fig. 5.24.

Process is a complex process. The process itself and the characteristics of the environment possess many uncertainties, such as how to fix the control laws of the system according to the process, and the environment changes necessary to make the system performance maintain the best condition, which is the basic idea of adaptive control. The control system therefore has two functions.

1. Identify the process or environmental conditions of literacy in an obvious way, accessing the object information of the current state;
2. Comparing, making decisions, and amending on-line control law according to available information.

At present, there are two categories of self-adapting control systems that are widely utilized. One is a control system for self-correction, and the other is a model reference of self-adaptive control systems.

1. Self-tuning control system

The principle of the control system is shown in Fig. 5.25. It is composed of three main components: the process, the identification and the controller. The parameters of the charged process model are unknown or changed, and process and output are disturbed. The reader identifies available online recursive identification methods to enhance real-time performance, such as recursive least squares, parameter of identify process $\hat{\theta}$ or state of online estimate process $\hat{x}$. The controller should use the parameter of identification $\hat{\theta}$ and the estimated (or measured) state $\hat{x}$, in accordance with the provisions of the performance indicators, and integrated

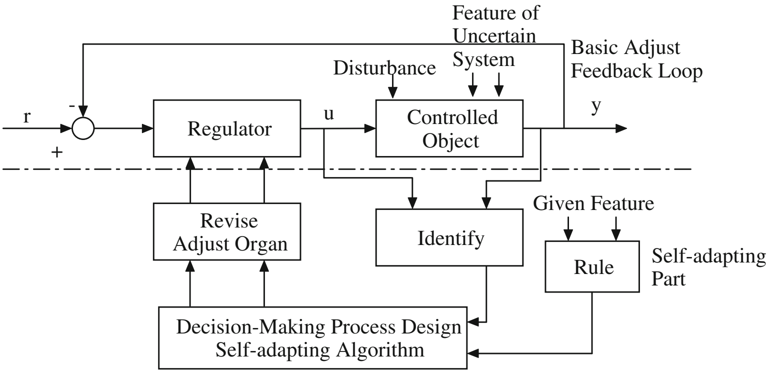
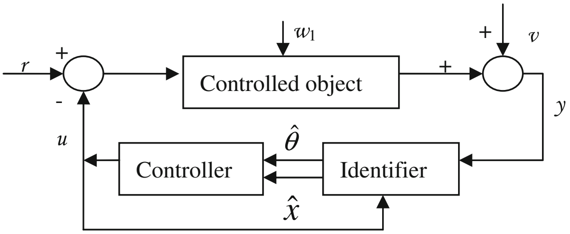


Fig. 5.24 Self-adapting control system structure

Fig. 5.25 Principle of self-corrector adapting adjustment control system



new control law online, so that system performance is close to target or maintains an optimal state.

2. Model reference adaptive control system

The principle diagram of the model reference adaptive control system (MRAS) is shown in Fig. 5.26. A reference model in the structure of the system is one of the basic characteristics of MRAS. The reference model has the anticipated performance indicators and presents the anticipated system output. The basic structure of MRAS is composed of two loops: the internal routing is the feedback loop charged with the adjustable controller and the process, which is similar to a general feedback control system, except for the adjustable control parameters; external routing adjusts the loop adaptively. When the input signal influences the reference model and control system, if the output of the control system and the output of the reference model have inconsistencies, errors e will be output. This means that the actual performance indicator of the system is different when compared with the theory due to the changes of parameters. Output errors e act as the information input for the appropriate agencies in accordance with the principles and methods, modify the parameters of the regulator online (parameters adaptation) or regulate an additional input signal

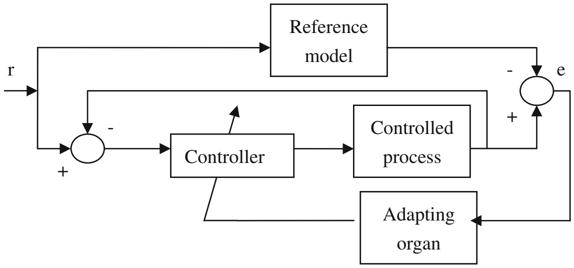


Fig. 5.26 Model reference adapting control system

(signal integrated adaptation), so that the output of the actual reference model system is nearly the same as the output of the reference model.

5.4 Intelligent Manufacturing System

Since the 1990s, people have used modern tools and methods, and the latest research achievements and organic integration of science. A new type of manufacturing technology and systems has developed. This is the intelligent manufacturing technology (IMT) and IMS, which are collectively called intelligent manufacturing (IM).

5.4.1 The Concepts and Features of Intelligent Manufacturing

There is no agreed definition about intelligent manufacturing at the international level. In 1988, Wright and Bourno in the monograph "IM" stated that: "the purpose of IM is to model the skills of manufacturing worker and the expertise through the integration of knowledge engineering, manufacturing software system, robot vision and machine control, so that intelligence robot carry out small-batch production in the absence of artificial intervention".

The general definition is: IMS is a man–machine intelligent system that is composed of smart machines and human experts, which can be a highly flexible and integrated approach using computer simulation intelligence activities of human expert to analyze, reason, judge, think and make decisions in the manufacturing process, thus replacing or extending part of the mental work, at the same time, collecting, storing, improving and sharing the inheritance and development of the intelligence of human experts. IMS transforms people's intelligence activities into the intelligence activities of manufacturing machinery. Figure 5.27 shows the composition of IMS.

The development of IMS is indispensable to artificial intelligence technology (experts technology, artificial neural networks and fuzzy logic), but different from

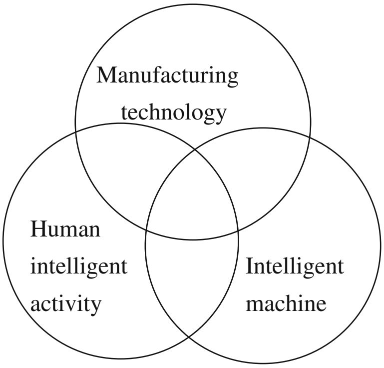


Fig. 5.27 Structure of IMS

artificial intelligence. IMS replaces some of the mental work for research purposes, and requires a system to independently carry out work in a certain range within the surrounding environment. At the same time, IMS is different from CIMS. CIMS emphasizes the integration of materials flow of the internal enterprise and the integration of information flow, but IMS stresses the self-organizing capacity of the entire manufacturing process. IM completes the manufacturing task in situations of uncertainty and cannot forecast. It has the following characteristics: self-organizing capacity; self-discipline ability; self-learning and self-maintenance capabilities, system intelligent integration and so on.

5.4.2 Multi-Agent Manufacturing System

Intelligent manufacturing is an important trend in digital manufacturing systems. In recent years, people have made use of multi-agent system (MAS) of distributed artificial intelligence to research manufacturing systems and accomplish the intelligence of manufacturing systems.

5.4.2.1 Agent and Multi-Agent System

Intelligent agent has been popular in distributed artificial intelligence research since the 1980s, but although it has been widely used, there is still no agreed definition and a proposed agent is usually defined as "based on a scene and have the flexibility and autonomy action capacity to meet the design objectives of computer systems." Scholars have put forward two definitions, "weak definition" and "strong definition": an agent in weak definition refers to computer systems with the basic characteristics of autonomy, social reaction and motivation and is hardware-based or (more often) software-based; an agent in strong definition refers not only to the fundamental characteristics of the weak definition, but also to the fact that the

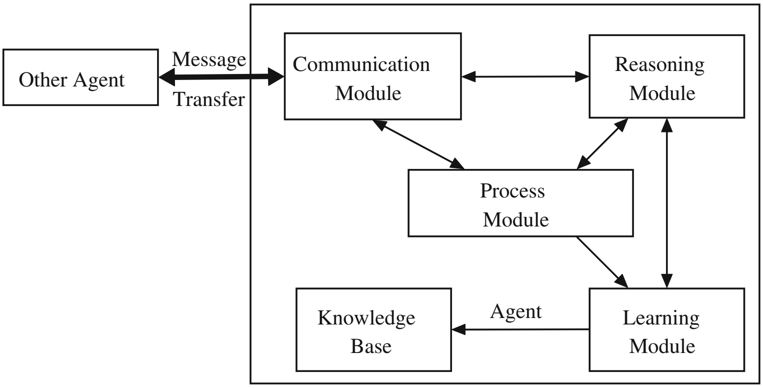


Fig. 5.28 Agent structure

computer system has usually applied to the human spirit of mental concepts, such as knowledge, belief, intention and obligation, even with emotional factors.

The basic attributes of agent is goals, knowledge, logo and others. It is composed of the communication module, business processing module, reasoning modules, learning modules, messaging and other units (as shown in Fig. 5.28).

The agent has the following properties [16]:

1. Autonomy: agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state; they are able to exert control over their own actions and do not have to be triggered by humans. They are goal-oriented and are able to solve problems without input from their owners.
2. Social ability: agents interact with other agents via a kind of agent-communication language.
3. Reactivity: agents perceive their environment (which may be the physical world, a user via a graphical user interface, a collection of other agents, the internet, or perhaps all of these combined), and respond in a timely fashion to changes that occur in it.
4. Pro-activeness: agents do not simply act in response to their environment; they are able to exhibit goal-directed behavior by taking the initiative.

Agent also has other properties, including cooperation (an agent should have the capability of interacting with other agents and possibly humans via an agent-communication language), learning (an agent should have the ability to learn while acting and reacting in its environment), mobility (a mobile agent has the ability to move around a network in a self-directed way) and temporal continuity (the actions of an agent are performed through a continuous running process).

In the manufacturing system, agent has two forms [17]: logic agent, which is a logical entity or a full-featured system unit or the logic abstract of the system, commonly used in information integration. The other is the physical agent, that is,

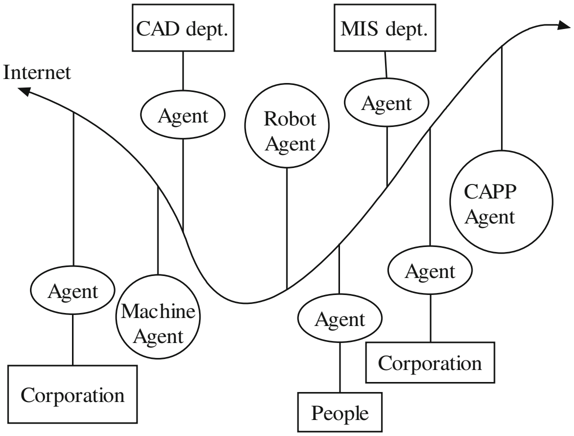


Fig. 5.29 Manufacturing system based on agent

the physical integrity unit or system with complete function, commonly used in the integration of operation unit or material flow. In the research field of the manufacturing system, physical and logical agents co-exist and cooperate with each other. The combination of physical agent, and logic agent is an effective means for the integration of materials flow and information flow of the manufacturing system. Figure 5.29 shows an agent-based manufacturing system. A circular shape represents a physical agent, and an oval shape represents a logic agent.

The determination as to whether an entity is divided into a physical or logical agent is according to the purpose of the study. For example, if the research purpose is task scheduling, a machine tool can be abstracted as a mandate agent which is responsible for accepting or rejecting tasks; if the purpose of the study is the integration of material flow, it may be defined as a physical agent which automatically detects the arrival of the work-piece and processes it by sensors; if the purpose of the study includes both tasks, including scheduling and materials integration, it can be defined as a physical agent, where the internal task of the processing module is responsible for accepting or rejecting tasks, and sensors are responsible for automatically detecting the arrival of the work-piece.

The basic structure of agent in the manufacturing environment is shown in Fig. 5.30. In general it includes [18]: knowledge base and the database (the knowledge base and database that related to entities on behalf of the function); local mission planning (responsible for risk—interests of decision-making and control of functional entity); collaboration management (responsible for external bidding and decision-making) and communication management (responsible for the establishment of external communication links).

The agent in an intelligent manufacturing environment is composed of an agent-based distributed manufacturing environment by communication network, that is, a multi-agent system structure (as shown in Fig. 5.31). Generally speaking, each agent is self-disciplined and independent of other units. In order to complete a task or achieve certain objectives to comply with some kind of agreement to link

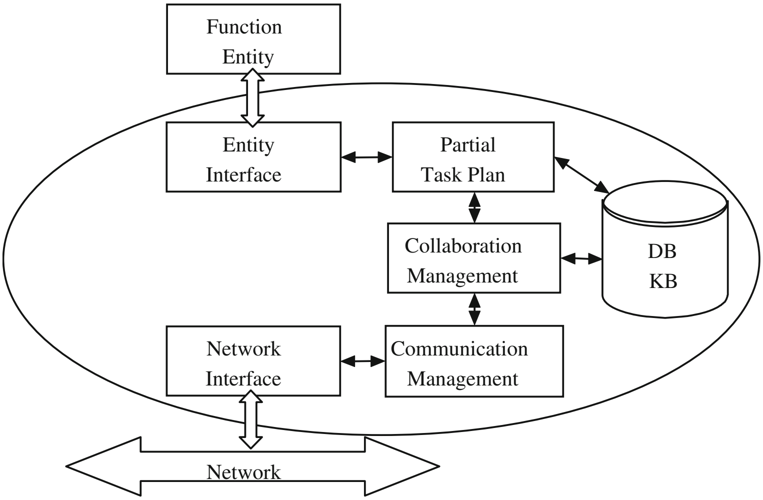
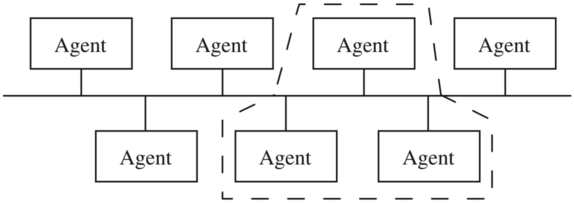


Fig. 5.30 Basic structure of agent in manufacturing environment

Fig. 5.31 Multi-agent system structure



up, they solve questions that are beyond the knowledge or ability of a single agent through interaction and cooperation. Agent can also establish the relationship of "friends of dollars" with a number of agents, composed of relatively close ties, as shown in Fig. 5.31 dotted line.

5.4.2.2 Multi-Agent Manufacturing System Model

The use of agent technology to establish a manufacturing system is a typical multi-agent manufacturing system, shown in Fig. 5.32. MAS is the level of the structure. On one hand, it shows the level features: an agent is composed by other agents or it is a part of the other; on the other hand, it shows an equality characteristic: each agent is a network node, and they are all equal. The manufacturing units are characterized by self-determination through the agents, which improves the function of the system. Through the cooperation and collaboration among agents, the system has the capability of self-organization.

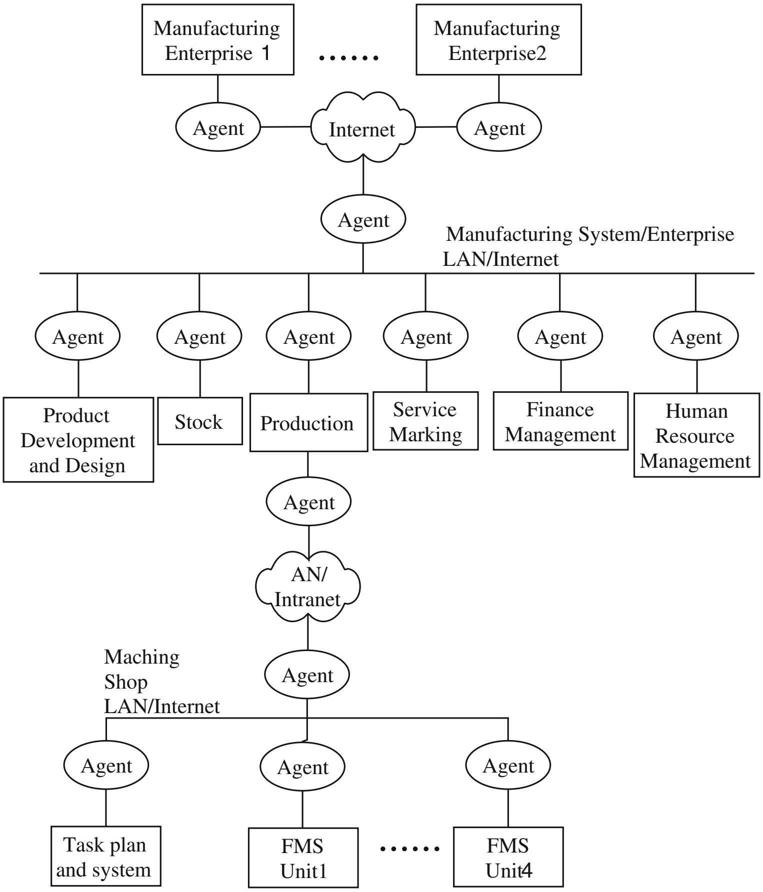


Fig. 5.32 Multi-agent manufacturing system structure

Intelligent manufacturing unit is the organization composed by some agent. The separation of basic agent from the system should follow a few basic principles: every basic agent must be a logical or physical entity; a basic task of system is at least coverage by a basic agent; agent by the interaction with other agent forms a action of support system by combining the local functions of agent.

5.4.3 Holonic Manufacturing System

The holonic manufacturing system (HMS) has been proposed by the IMS program as a solution for a next generation manufacturing system. It is characterized by a distributed control structure, and autonomous yet cooperative basic construction elements known as holons. By imitating living organisms and social systems, HMS is claimed to have the ability to retain robustness within a dynamic manufacturing environment, the adaptability to changing configurations and efficiency in using resources.

5.4.3.1 Conception of Holonic Manufacturing System

In 1967, Koestler in his report entitled “The Ghost in the Machine”, introduced a new word, “holon”. Holon is derived from the Greek holos (which can be interpreted as “all”) plus the suffix on (which can be interpreted as “part”), so holon can be interpreted as “at the same time a whole and a part of the whole.”

Koestler pointed out that “holon” is dependent on the element of autonomy; with independence, it can handle accident events without seeking instructions from a higher level. The ’holon’ power goes to the upper. The former feature guarantees that the holon is a stable form, and it will not be tampered with through disturbance; the later nature indicates that it is an intermediate form, for a greater holon provides a unique function.

Koestler community organizations and biological tissue concept have changed into a series of concepts for the manufacturing industry, provided by ‘holon’ organizations. In order to introduce the concept of holon into the manufacturing system, international cooperation organizations defined HMS and its related concepts as follows [19].

1. Holon: an autonomous and cooperative module that is used to converse, transport, store, and/or process information and physical objects in a manufacturing system. A holon is composed of an information processing part and physical processing components. A holon can be a part of another holon. A holon has the following attributes, namely autonomy: the ability to generate an entity and/or control its plans and/or implementation of strategy; co-operation: the process in which group of entities develop a mutually acceptable plan and implement the plan; flexibility: holons with selection ability change their work targets and the scope of their work based on changes in the environment.
2. Holon architecture (Holarchy): the holonic system means that holons can work together to achieve a purpose or goal. Holarchy defines the basic rules of collaboration between holons, thus limiting their autonomy.
3. Holonic manufacturing systems (HMS): the holon architecture means it integrates with all manufacturing activities, including contract signing, design, production, entering the market and achieving agile manufacturing enterprises.

In HMS, a holon can be formed by other holons, with self-advocacy and integration trends. “Self-advocate” refers to the dynamic description of the holon, which also describes the behaviour of the holon when making decisions. Integration trend means the dynamic performance of the holon, and mutual coordination and consultation behavior between holons when holon individuals experience conflict regarding goals. The two relatively independent attributes

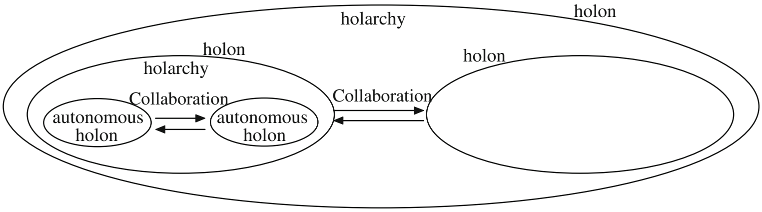


Fig. 5.33 Holon and holonic system

show the self-government and cooperative relations of holon. For example, each production unit (such as machine tool) can be regarded as a holon. These production units work together with other units—from planning and scheduling to the production and manufacture of products.

The holonic system is the organizational structure defined by holons through their function or mandate. Fig. 5.33 shows that the characteristic of combination and integration [20].

Compared with the multi-agent manufacturing system, HMS focuses on coordination on the basis of a multi-agent manufacturing system, which cooperates to realize global optimization. The stratification structure facilitates the construction of a more complex system; from the application perspective, the multi-agent manufacturing system is more suitable to regional decentralization, with a local relatively loose structure between the manufacturing systems (such as virtual enterprises and manufacturing network systems), and HMS is better adapted to the relative concentration.

5.4.3.2 Holonic Manufacturing System Reference Model

Product-resource-order-staff-architecture (PROSA) is a HMS reference model [21] proposed by Belgium's Professor Hendrik Van Brussel. In his view, the manufacturing system involves three relatively independent aspects, resources, products and related craft technology, and aspects related to user requirement, delivery time and supply. Therefore, the HMS should have three kinds of corresponding basic structure modules, namely resources holon, product holon and order holon.

1. Resource holon
   This includes the physical part (that is, productive resources) and information processing part (for control of productive resources), which provides the production and processing capacity to other holons. The resource holon also preserves methods resources allocation, as well as the knowledge and process for the organization, for use and control over productive resources to drive production. Holon resources are abstract production facilities, such as factories, workshops, machine tools, transport cars, knives, trays, raw materials, operation workers, materials storage, energy and so on. Resource holon also denotes

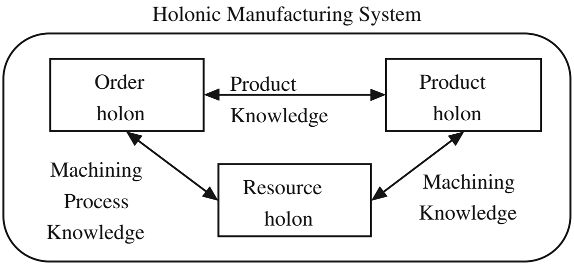


Fig. 5.34 HMS structure and its relation

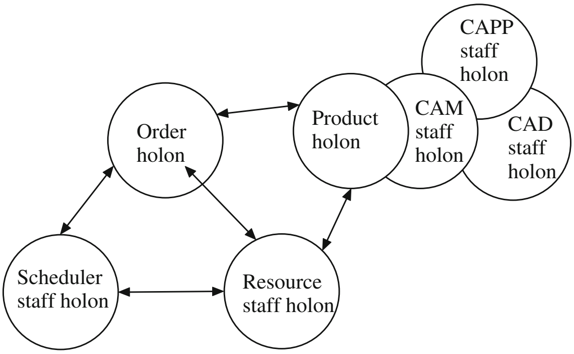
the state of current resources (its status in order to complete the activities and the activities that have not yet been completed). The activities of resources can change with the dynamic changes of the environment, such as new orders arrival, other resources damage or mission delay.

2. Product holon
   This preserves the technology and product knowledge to ensure the quality of products. Product holon includes the latest information in the whole product life cycle, as well as user requirement, design, process planning, material form, quality assurance processes and so on. Therefore, it is the preservation of the "product model" rather than the "product state model." Products holon acts as the information server to other holons in the HMS system.
3. Order holon
   This represents mission in the manufacturing system, responsible for the accurate and timely processing of distribution orders, and manages physical products, the product state model and all the relevant logic information processing. Order holon can express user order holon orders, inventory orders, prototype production orders and maintenance and repair orders and so on. Order holon can be seen as a control of entities; it is responsible for managing orders and for the processing system. In this process, order holon, other order holons and resource holons should consult with one another.

The relationship of the three basic holons and their exchange of knowledge is shown in Fig. 5.34. Machining operation knowledge exchanges between order holon and resource holon, processing knowledge exchanges between product holon and order holon and production knowledge exchanges between product holon and order holon.

1. Processing knowledge: includes the information and methods in the process of accomplishing specific processing. It is about the information of resources ability that is, to say, resources are able to complete the processing, and related processing parameters, processing quality and so on.
2. Production knowledge: the information and methods that are used to produce a specific product. Production knowledge includes working procedure, the data structure for the expression of product result and assessment methods of production plans which operate on specific resources.

Fig. 5.35 Assistant holon



3. Processing operation knowledge: the information and methods of processing progress in some resources, it includes the knowledge of processing requirement, knowledge of the appointment resources, knowledge of monitoring the implementation process, knowledge of interruption processing and knowledge of the starting processing request.

4. Auxiliary holon
Auxiliary holon assists the three basic holons to complete production tasks. It provides sufficient information to the basic holon, so that the basic holon can correctly solve the problem. The basic holon has decision-making power, while the auxiliary holon can be seen as an outside expert providing recommendations. The conception of the auxiliary holon allows the system to have a central processing unit. It is very useful for resolving issues which are difficult to solve using a distributed method. Auxiliary holon allows the smooth transit of the existing hierarchical structure to the holonic structure. However, the ultimate decision-making power still exists in the basic holon, so it is not introduced to the rigid hierarchical structure of the system.

In fact, the proposed auxiliary holon enhances the function of the basic holon, thereby eliminating mutual influence of robustness and agility in the process of system optimization. Due to the distributed architecture of the system, HMS has the characteristic of robustness and agility and is easy to expand and recompose. In adding the auxiliary holon, basic holon is subject to auxiliary holon as far as possible, as shown in Fig. 5.35.

5.5 Summary

Intelligent manufacturing is a basic discipline of digital manufacturing science, making use of artificial intelligence tools and computational intelligence methods (such as expert system, neural network, fuzzy logic and genetic algorithm), solving intelligent digital scheduling, intelligent digital design, intelligent digital processing, intelligent digital control, intelligent digital process planning, intelligent digital maintenance and diagnosis and other related problems in the process of digital manufacturing. Intelligent manufacturing is based on digital manufacturing, and the digital manufacturing system will enable the intelligent digital manufacturing system to achieve a new level of artificial intelligence.

In the beginning of this chapter there is an introduction to multi-sensor data fusion and data mining concepts, principles, architecture and their application in the digital manufacturing system. Secondly, the concept of knowledge engineering in the whole product life cycle of manufacturing a product is introduced. The main content includes knowledge expression, the construction of knowledge base, knowledge reasoning and other critical theory; in addition, three important attributions of the IMS—self-organization ability, self-learning ability and self-adaptive ability—are studied. Finally, through introducing the multi-agent manufacturing system and holonic manufacturing system, readers gain a more comprehensive understanding of the basic content of IMS.

Manufacturing intelligence is the inevitable result of the development of modern manufacturing technology, computer science and artificial intelligence; it is also the product of these three technologies.

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Chapter 6
Science of Bionic Manufacturing in Digital Manufacturing Science

Since the 20th century, with the continuous development of science and technology, manufacturing technology and life science have made a great breakthrough, which is leading the trends in technology. The combination of life science and modern advanced manufacturing technique will bring about a new revolution in manufacturing science. Nowadays, similarity between manufacturing industry informatization and life sciences engineering-oriented implementation is becoming more and more obvious and prominent. Life subjects and manufacturing disciplines should learn from each other; as the saying goes, "A Stone from Other Hills may Serve to Polish the Jade of This One" [1]. In this way, bionic manufacturing science has come to the fore. Bionic machinery and bio-manufacturing are the main elements of bionic manufacturing, whose important feature is nonlinearity, and which use digitalization, discretization, and knowledge to achieve results. Bionic manufacturing is an important branch of digital manufacturing which reflects features of digitalization and informatization in digital manufacturing. It becomes an important part of the basic scientific theoretical system in digital manufacturing. The study of the theory and technology in bionic manufacturing plays an important role in developing digital manufacturing science.

Bionic manufacturing will be introduced briefly in this chapter. According to the subject structure, issues in bionic manufacturing will be discussed from bionic machinery and biotechnology, including background, concepts, subject features, scientific issues, current status and trends.

6.1 Overview of Bionic Manufacturing

6.1.1 Background

With great changes in the size, complexity and dynamics of manufacturing systems in recent years, many new manufacturing systems structures have emerged,

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and many advanced manufacturing technologies have also come into being. As we know, biological evolution has been developing for thousands—perhaps billions—of years, but manufacturing has essentially developed during the past several hundred years. Biological genetic characteristics, such as self-organization, self-growth, self-generation and many biological intelligence characteristics are better than many man-made products, and are worth understanding and developing. Biological skills grow with the struggle against nature, and most of the mechanisms have not been recognized. Understanding these mechanisms and using them in an appropriate manner will undoubtedly promote the development of manufacturing and bring about a revolution in the manufacturing industry. The development of life sciences and biotechnology also creates a new paradigm for the manufacturing industry. Life sciences and biotechnology allow the manufacturing industry to create all kinds of replica organs and tissues with biological functions, which can help prolong the life of people and organisms, restore some organ function, or replace certain organs and tissues which have lost function (such as bone, skin, muscle, nerves, limbs, nose and heart) [2].

It has taken a long time for the combination of manufacturing science and life science to broaden, deepen, and gradually form a new subject—biological machinery and bio-manufacturing. The concept of biological manufacturing (bio-manufacturing, BM) was proposed at the end of the 20th century by Dr. John Bollinger, chairman of the American Committee on Visionary Challenges. The Committee on Visionary Manufacturing Challenges established by the National Research Council's Board on Manufacturing and Engineering Design in 1998 has compiled ≪Visionary Manufacturing Challenges for 2020≫. The book lists the ten most important strategic technology domains in the manufacturing industry in the 21st century, and clearly puts forward "biological manufacturing technology" as the fourth strategic technology domain. It contains: (1) the bionic structure application in engineering designing, (2) form and assemble parts by biological process, (3) "designing" protein, enzyme and tissue voxel, biological-catalyst, (4) biological assembly of new food (5) biological devices with memory function and so on. Dr. Bollinger emphasizes that nano-technology and biotechnology can lead to changes in manufacturing processes in the 21st century, and these two types of technology are involved in precision control and assembly at molecular and atomic level [3].

Bionic machinery and bio-manufacturing as an important branch of bionics is one of the new concepts of recent years. Bionic machinery creates and improves the concepts, principles and structure of manufacturing engineering science by researching biological mechanisms and biological institutions to set the foundation for the production of new products. Bio-manufacturing includes biological functional manufacturing (gene copying, biological removal or biological growth) and biology manufacturing or organisms manufacturing. Bio-manufacturing integrates life science, materials science and biotechnology into manufacturing technology and makes a significant contribution to human health, environmental protection and sustainable development.

6.1.1.1 Progress and New Challenges in Manufacturing Science

Information technology has developed rapidly for half a century and supports manufacturing technology in meeting the challenges of manufacturing science. Many advanced manufacturing techniques have emerged, such as flexible manufacturing systems (FMS), the computer integrated manufacturing system (CIMS), concurrent engineering (CE), lean production (LP), intelligent manufacturing system (IMS) and virtual manufacturing system (VMS). The global network technology revolution and network environment caused by this revolution have had unprecedented all-round effects on human life. Virtual enterprises, remote manufacturing and other technologies have also flourished. The development of manufacturing technologies has two sides: on one hand, it has created dazzling material civilization; on the other hand, it has encountered new challenges with its development.

If using tools is an essential characteristic of people, the history of human evolution is also the evolutionary history of manufacturing technology to a considerable degree. Nevertheless, no matter how much modern manufacturing techniques have developed, they are still overshadowed by nature. Therefore, studying the growth of natural biology, and simulating nature to perform human activities is an advanced form of manufacturing industry. The introduction of life sciences takes manufacturing out of the physical or chemical model and gives it life. Manufacturing will also penetrate the processes of human life, thus greatly enriching the understanding of manufacturing science [4, 5].

The combination of bionics and manufacturing is not accidental, and appears after the relevant disciplines have reached a certain level. Specific manifestations are as follows:

Firstly, the development of life sciences has made new demands of manufacturing science. In the 20th century, mankind could design a new bio-genetic blueprint in accordance with their own wishes, then create a new life so as to build a site. All these are based on life science. New technologies, such as cloning technology, human stem cell culture, cracking the genetic code, the large-scale human genome sequencing plan and transgenic technology that have all emerged. From cloned sheep and cloned cattle to cloned rat, and a series of animals successfully cloned by embryonic cell cloning, cloning technology has made one breakthrough after another. It has not only stepped into the practical stage [6], but also created new scientific topics in manufacturing science.

Secondly, the rapid development of materials science creates the material basis for manufacturing science. New materials are important parts of modern high-tech and also the material basis for the development and application of high-tech practices. All high-tech manufacturing and the development of high-tech industries must be based on new materials and is closely dependent on the research and development and production of new materials. At present, materials is developing into a field of high-performance, high-function, bionics, intelligence, lightweight, composite, low-dimensional, limit and integrated. All kinds of new materials that are being developed have high-intensity, high toughness, high-temperature resistance, low-temperature resistance, wear resistance, corrosion resistance and fatigue resistance.

As manufacturing materials, bionic materials with appropriate strength and flexibility have certain fatigue resistance, wear resistance and corrosion resistance, and some have good compatibility with human tissue. It is possible to repair and recycle human tissues and organs (such as teeth, bones, blood vessels, skin, ligaments, nose, throat and heart valves) in order to maintain their original function and ensure human health and longevity. Moreover, the bionic materials are based on biological protein, which will gradually replace ore-based metal materials and oil-based engineering plastics, nylon and other organic polymer materials. This practice will not only solve the problem of lack of resources and energy, but also cause no harm to the environment, thus creating a new era in Materials Science and Manufacturing Technology [7].

6.1.1.2 The Similarity of the Manufacturing Process and the Life Course

With the progressive development of manufacturing technologies and biological sciences, people have become increasingly good at seeking similarities in the manufacturing process and biological phenomena, and such similarity provides an important basis for the integration of the two disciplines, which is shown as follows:

(1) Ordering based on the self-organizing mechanism

Each individual, whether animal or plant, must continuously intake material, energy and information (negative entropy) from outside, excrete high entropy waste, maintain a higher level of information than the surrounding environment to survive and improve its degree of order and breaking of symmetry to achieve its growth. In order to enhance the information content of raw materials or roughcast, and to convert them into products, a modern manufacturing system must also continuously intake material, energy and information from outside, and excrete waste of a high degree of disorder. The biological variety and the ingenuity and complexity of modern products reflect the trend of high degree ordering. Present studies on the theory of dissipative structures reveal that an open system which is unbalanced can continuously improve its own order degree by the exchange of materials, energy and information with the outside and by absorbing negative entropy from outside. This phenomenon is called “self-organizing”. Both the manufacturing process and life process enhance their order degree by self-organization, and both make dissipative structure theory a part of their basic theory.

(2) Individual copy based on the information model

Organisms can adapt to the environment to sustain vitality and develop and improve themselves by using the functions of self-identification and self-development, self-recovery and evolution. These functions are achieved by transferring two kinds of information: one is a type of DNA information, which is genetic information, carried by inheritance and evolution from generation to generation; the other is a type of BN information, which is obtained by an individual through learning. The harmony and unification between these two types of biological

Table 6.1 Comparison of the life process and the manufacturing process

Life process	Manufacturing process
Genetic code (DNA)	Product model (STEP)
Genes	Characteristics
Individual copies: DNA–RNA–protein synthesis—individual life	Production: product model—process—regulations—material processing—production
Messenger RNA (mRNA)	Processing model or NC model
Ribosomal RNA (rRNA)	Production equipment
Transfer RNA (tRNA)	Raw materials
Adenosine triphosphate (ATP)	Energy
Various enzymes	Various production tools and information processing tools

information helps organisms to adapt to complex and dynamic environments. Biological cell division, ontogeny and population reproduction involves a series of complex process, such as the replication, transcription and interpretation of genetic information. These processes reproduce new individuals in accordance with the model of biological information. This is very similar to mankind's manufacturing by CNC machining parts or by product model machining parts, as shown in Table 6.1 [8].

(3) Formation of a high degree of adaptability through the evolutionary process

From bacteria to humans, living organisms on the earth have experienced a long evolutionary process. The driving force of evolution and competitive survival is called "natural selection and survival of the fittest". The joint role of genetics and variation is the mechanism of evolution: attempts at new changes occur in the latter, while the former accumulates those changes that are proven to be conducive to survival. The purpose of evolution is to enhance its ability to adapt to the environment. Biological evolution is competitive and collaborative, just like the phenomenon of "symbiosis" and "gregariousness", which are elements promoting biological evolution.

Human history of manufacturing activities is not as long as the history of biological evolution, but its development from early crafts to modern large-scale industries has been steady. Market competition plays an important role in the development of the manufacturing industry. The purpose of competition is to improve the ability of industry and enterprise to adapt to the market. Inheritance and innovation are the main mechanisms of the manufacturing industry and product development. Industries or enterprises not only compete but also combine with each other, through which means they develop and evolve continuously. In fact, the theory of biological evolution and adaptability has long extended beyond the field of biology and has become a general law or philosophy of evolution and development of things.

In addition, manufacturing activities are also an indispensable part of senior life phenomenon and an extension of the biological phenomenon. Nature has created human beings and given them high order degree, and humans convert part of their own order degree to various products they manufacture. Humans have created splendid material civilization to improve their living environment. This shows that the similarity between the human manufacturing activities and the natural life phenomenon has deep origins and is not accidental.

6.1.2 Overview of Bionics and Bionic Machinery

6.1.2.1 Overview of Bionics

The word "bionic" was coined by Jack E. Steele in 1958, possibly originating from the Greek word "*βἵον*", pronounced "bion", meaning "unit of life" and the suffix -ic, meaning "like" or "in the manner of", hence "like life". He defined it as the "science of the artificial systems whose functionality is based on the natural ones". The first bionics discussion session was held in the United States that year, marking the birth of Bionics [6].

Through research, study, imitation, copying and recycling the structure, functions, working principles and control institutions of a biological system, bionics can give new machinery, equipment, building structures and processes some biological features and functionality, thus greatly improving humans' ability to adapt and transform nature and promote the progress and development of human society. Bionics is a synthetic frontier science, which has distinctive innovation and applicability.

Modern bionics has appeared in many fields. Its development depends on the interchange of multiple subjects such as life science, physics, chemistry, medicine, mathematics, materials science, mechanics, dynamics, control theory, aviation, aerospace and maritime engineering. Conversely, bionics can also advance these subjects.

6.1.2.2 Overview of Bionic Machinery

Study into imitating organisms researches the relationship between behavior, structure, institution, function of organisms and its geometry, physics, chemistry, materials, and so on. This has resulted in the creation of bionics-mechanism and mechanics, bionic manufacturing, bionic functional surface, bionics-contact mechanics, bionics-tribology, and more. Through the imitation of the form, structure, and control theory of organisms, bionic machinery has been designed and manufactured with more centralized functions and higher efficiency machinery with biological characteristics.

The main imitation targets of bionic machinery include the structure, principles, functions, control mechanisms, energy conversion and process of information transmission in biological systems, as well as biological growth [4].

At present, bionic mechanics is largely considered as a new concept and method for solving a series of problems in modern manufacturing through the study of the structure, working principles, functions and control mechanisms of biological systems. It establishes scientific theories and models based on the nature and laws of biological activities acquired through researching the structure, energy, conversion and process of information of biological systems, then transforming existing engineering technology systems or creating new ones.

6.1.3 Overview of Biological Manufacturing

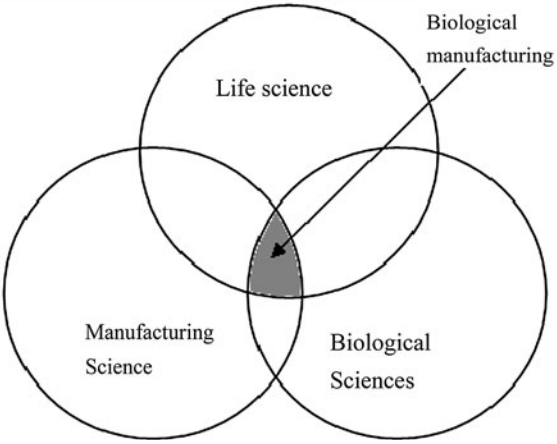
Biological manufacturing is a process that imitates the growth patterns of nature. The theoretical study of biological manufacturing technology and the implementation of the project is called biological manufacturing engineering.

6.1.3.1 Fusion of Disciplines

In ancient times, humans have mastered the brewing technology to produce alcohol, which is the earliest use of natural biological processes for biomass production. Biological processes are physical, chemical, information and other integrated processes. These processes produce energy, food, medicine, materials manufactured by using the design of proteins, enzymes, biological catalysts, etc.; biological devices with computing and memory functions, including biological memory and logic devices (having the advantages of identifying a stimulation in the environment, studying and adapting to changes); processing, forming and assembling by bacterial erosion.

Humans continually explore the mysteries of life and try to repair human organs or create living organs which could replace human tissues. Since the 20th century, the development of technology has brought an in-depth understanding of biological mechanisms and the structure of micro-organisms, and this pursuit has extended from fantasy to reality, then into science. The in vitro construction of tissues and organs with biological function for repairing diseased tissues and organs has become a remarkable scientific frontier. It has presented new challenges to the traditional manufacturing industry. The concept of biological manufacturing engineering has been raised and developed as a result of this demand and development. While this concept was initiated in the 1970s, it is only in the last few years, with the rapid development of life sciences and manufacturing, that increasingly widespread application of the prototyping technology in the field of life sciences has taken place. In Fig. 6.1 biological manufacturing engineering is presented as an intersection of life science, manufacturing science and biological science [9].

Fig. 6.1 Schematic drawing of the definition of manufacturing engineering



6.1.3.2 The Basis and Definition of Biological Manufacturing Engineering

Biological manufacturing engineering integrates the latest progress in the research and development of rapid prototyping technology, bio-materials science, molecular biology and cell biology, and is the new development of manufacturing science and life science.

The development of rapid prototyping technology based on the principle of discrete or accumulation and the application in the biomedical field is the foundation manufacturing science of biological manufacturing engineering. Since the 1990s, the micro-droplets spray deposition based on the rapid prototyping of new technology makes converting the electronic model of complex human tissues and organs into a functional gradient physical model possible. These processes can also achieve the preparation of materials and the forming of materials. The new rapid prototyping technology includes the low-temperature deposition manufacturing process, the layered plastic in situ techniques and technology such as cell print.

The research and application of new biological materials are also an important material foundation of biological manufacturing engineering. In the 1990s, third generation biological materials came into being. Unlike the first generation bio-inert material and the second generation bio-absorbable material and biological activity materials, the third generation biological material integrated the performance of biological activity material and bio-absorbable material. Components making specific reactions to cells are introduced to the bio-absorbable polymer by molecular modification, and cell adhesion, proliferation, differentiation and extracellular carbomer production is controlled. These structures and performance are designed and synthesized according to human tissues and organs of physiology, biochemistry, biophysics and forming, which have created the conditions of the biological manufacturing project [10].

The new development of cellular and molecular biology and developmental biology is the basis for biological manufacturing engineering. After World War II, cellular and molecular biologists studied cell structure and the basic life activities in depth. Stem cell research has made enormous progress and was classified as one of the world's top ten scientific and technological progresses of the 20th century by U.S. Time magazine in 1999. At present, stem cell research includes embryonic stem cells and adult stem cells. The strong variety in potential stem cells provides a rich source of cells for biological manufacturing engineering research [9].

Biological manufacturing engineering can be defined as follows: it is the general name given to the combination of manufacturing science and life science, through controlled assembly to the complete manufacture of organs, tissues and bionic products at the level of micro-droplets [11].

Material and energy metabolism is the most basic of life processes, and energy conversion and transmission in the assembly process is also conservation. The general assembly is a non-equilibrium, non-linear and non-reversible process, which follows the entropy increment principle. Modern biological technology research, especially the development of molecular biology, making nucleic acids, proteins, polysaccharides, biofilm, and other macromolecules, has been very in depth. As the human genome project and post-genome research was carried out, people began to understand the mysteries of life from the simple life of the machinery to the molecular and atomic level.

The machinery view of life says that "all life phenomena can be explained with physical and chemical vocabulary, and life is full of physical and chemical products". From such a simple, clear and straightforward concept, biological manufacturing's philosophy is formed that any complex life phenomena are able to be reconstructed through physical, chemical theories and methods under artificial conditions; tissues and organs can be artificially manufactured. The manufacture of organisms is not the creation of life, since there is no issue concerning the origin of life, however, active units and life units are utilized to "assemble" tissues, organs and bionics products with practical functions.

The definition of manufacturing engineering will continue to develop because it is a cross-disciplinary research area which is still evolving. No matter how technology changes, the goal of manufacturing tissues, organs and bionic products by binding manufacturing science and life science remains unchanged.

6.1.3.3 The Architecture of Biological Manufacturing Engineering

As a cross-disciplinary research area, bio-manufacturing engineering has many related technologies, as shown in Fig. 6.2. Biological manufacturing engineering has integrated these technologies. As shown in Fig. 6.3, the bio-manufacturing engineering system uses different scales of assembly technology to get biological material, tissue and organ "parts" and tissue engineering scaffolds, and then acquires live tissues and organs by cell/tissue culture.

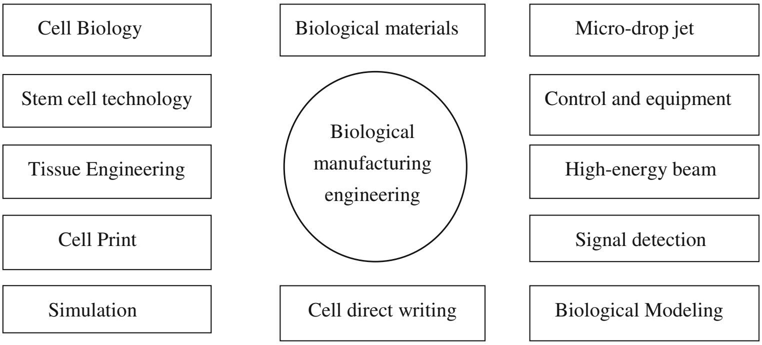


Fig. 6.2 Related technologies of biological manufacturing engineering

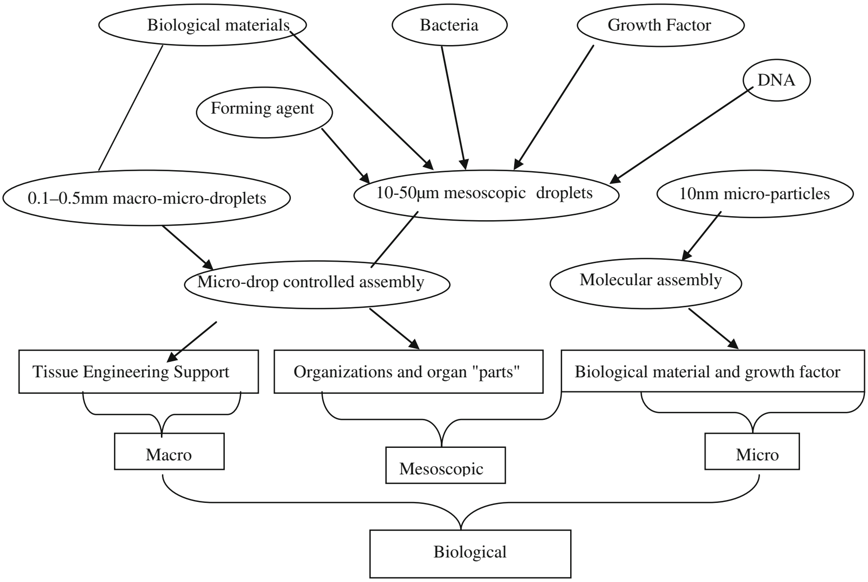


Fig. 6.3 System frame of biological manufacturing engineering

6.1.3.4 The Impact of Biological Manufacturing Engineering Science on Manufacturing Science

From the perspective of product forming, bio-manufacturing engineering is a principle and method of forming between traditional forming processing and biological forming, and is a forming pattern that advances the direction of the development of biological forming. The objects of the traditional forming process are metals, non-metals and other non-life characteristic materials. Tissues and organs form through cell proliferation, differentiation and self-assembly in the growth forming. In biological manufacturing engineering, micro-droplets which contain the unit cell (a characteristic of life) replace the non-living materials in the traditional forming processing, and manufacture organisms by controlled assembly of the unit rather than self-assembly. Information is mainly used to control the process parameters, such as campaign tools, feed movement, pressure and temperature in the traditional forming process. In bio-manufacturing engineering, the process of life manufacturing is controlled by forming equipments, extracellular matrix materials, growth factors and cell genes at the same time. Organisms manufactured through bio-manufacturing engineering are not only controlled by the process of information, which is similar to traditional forming, but also by the information of the forming materials (including cells). Therefore, biological manufacturing is a powerful integration of physical processes and information processes.

Philosophically, it is very important to assemble cells into organisms by using biological manufacturing engineering technology and equipment. It shows the intrinsic and original relation between manufacturing science and life science. The huge gap between manufacturing and growth is being filled by bio-manufacturing engineering. The important task of bio-manufacturing engineering is to eliminate the human cognitive boundary between manufacturing and growth, explore the biological mechanisms and manufacturing principles of cell-assembling, explore new technologies, and to create new forming technology and equipment and the product evaluation system.

6.2 Bionic Machinery

6.2.1 Basic Principles of Bionic Machinery

6.2.1.1 Bionic Structure

Based on the principles of mechanical engineering, bionic structure takes research of different statuses (dynamic and static) and different structure levels (macro and micro) to create a bionic simulation of material, structure, system and improve the efficiency of engineering structure [12].

6.2.1.2 Bionic-Information

Sensory organs like eyes, ears, tongue, nose and skin are the receivers and pre-processors of all kinds of information from outside. Their wonderful function and fine structure provide the inspiration for people to improve the input and transmission equipment of information technology systems and to design new detection, tracking and computing systems [13].

6.2.1.3 Bionic in Control

Automatic control systems exist in the human and animal body to ensure the normal operation of metabolism, adaptation of the environment inside and outside, and harmonization of the whole organism. These accurate and reliable automatic control systems existing in organisms have compact structure and perfect functions. The current man-made control system is not fully comparable in many ways. Human and animal automatic control systems seem to be references of the development of automatic control technology [14].

6.2.2 Major Progress in Bionic Machinery

Currently, the United States has achieved remarkable progress in the development of bionic materials, bionic manufacturing technology and fluid drag reduction bionic technology. U.S. DARPA (Defense Advanced Research Projects Agency) has spent 24 million dollars on six laboratories to hold the controlled biological systems program. The U.S. National Aeronautics and Space Administration proposed the development of smart materials and biological systems based on the biological organism principle of self-healing injury in 2002. In 2001, the U.S. Rand Corporation Institute for National Defense reported the development trend of bio-technology, nanotechnology, materials and information technology to 2015 to the National Intelligence Council. They considered that the increase in multidisciplinary technology had promoted the development of bionic technology. Madison University constructed nano-mechanism and nano-circuits with live bacteria. They chose 5 nm long, 0.8 nm wide *Bacillus mycoide*, added an electric field to the microbes to induce polarization and “pasted” them in the electrode. The group studied the conductive bridges which made the polarization. This research will possibly lead to a reconfiguration of the nano-circuit.

Bath University, Pisa University, the Greek Research and Technology Foundation and Tubingen University have conducted co-operative research on bionic campaign structure under EU funding. The research concerned the movement and sensor systems of lower animals (parasites, worms and insects) and set out to design a micro-machine which can run in the human body. The University of Southampton and the University of Reading in England carried out research on the spinal muscles of animals to build a large displacement and high spring damping system.

The National Institute for Advanced Interdisciplinary Research (NAIR) in Japan was established in January 1993. Its purpose to strengthen interdisciplinary research work. Bionic design is one of three basic projects, and the function of the self-repair of motor vehicles will be among their research priorities in the next five to ten years.

Germany focuses on electronics, nano-technology, materials, sensors, self-cleaning technology and other aspects of bionic research. Russia and South Korea have had effective results in bionic technology and established priority development in this area. Russia has classified the research on organisms structure, materials and acts. Their goal is to integrate the structure of organisms, material and acts mechanism and to produce a powerful tool for resolving issues in science and technology.

The research of the material, shape, and function of bionic material on the crafted surface has been very thorough. To achieve the goal of lightweight absorbency, the Minnesota Mining and Manufacturing Company produce multi-generation nano-particles absorbent film which is in use of film sputtering technology on the surface of hollow glass ball. Subsequently, the Institute of the U.S. Navy used the biological self-assembly of lipid-chemical plating of nickel to produce an absorbent material which has a good wave-absorbing effect for ship-based missile stealth.

The F-16XL aircraft developed by the U.S. Space Administration (NASA) and the Air Force (USAF) used a biological surface respiratory principle on the surface of its wings to control the surface resistance of the aircraft. Artificial dolphin skin on the surfaces of submarines and torpedos made by the U.S. Navy reduces turbulence by 50% or more and the speed is markedly improved. This bionic design can achieve a higher level comprehensive effect of resistance reduction and wave absorption when it combines with new technology in biological manufacturing. In 2010, the U.S. developed a coating system which can adapt to the background and to threats automatically. It is predicted that by 2020 biological reduction resistance and stealth intelligence will diversify the threat perception to the craft from the chemical and biological environment.

In China, several universities and research institutes such as Jilin University, Beijing University of Aeronautics and Astronautics, Harbin Institute of Technology, Tsinghua University, Zejiang University, Shanghai Jiao Tong University and Wuhan Institute of Virology, Chinese Academy of Sciences (CAD) have researched bionic machinery from 1970s and made several important developments. Jilin University first proposed the concept of semi-walking internationally and developed a semi-walking wheel and a variety of bionic walking wheels, walking wheel vehicles and air-cushion of walking mechanicals. Moreover, they undertook systemic bionic research on desorption and resistance reduction in ground machines and developed ground bionic machines and relevant key parts. Beijing University of Aeronautics and Astronautics and Harbin Institute of Technology have made important progress in the development of a bio-robot. Tsinghua University, Shanghai Jiao Tong University and Harbin University of Science and Technology have focused on testing a humanoid robot and insect-imitation micro-machines. Zhejiang University has made important progress in area of the medical bio-robot. Nanjing University of Aeronautics and Astronautics has developed a gecko-imitation climbing machine. Beijing University of Aeronautics and Astronautics first fabricated micro gear with microbes, and proposed a cell-cycle theory and bacilli cell metallization process and theory based on "biological removing processing". Wuhan Institute of Virology, CAD utilized magnetic-trending bacteria to manufacture nano-magnetic bodies, which are used for smart pills navigator manufacturing and bio-chip magnetic probes manufacturing.

In addition, tremendous progress has made in the development and use of animal and plant resources.

6.2.3 Development Trends of Bionic Machinery

6.2.3.1 The Biological Surface Bionic Engineering

Key features of biological surface bionic engineering are the study of the biological surface characteristics and the relationship between functions; typical biological surface technology integration (a multi-layer, cross-scale, multi-disciplinary integration of information technology, digital, intelligent research and the development network); and biomimetic surface treatment technology, such as invisible biological surfaces, imitation, noise reduction, stability and so on. Effects such as oligodynamic effects, weakening the impact of inertia, the moment effect and the role of gas storage should be the focus of ground-breaking research and development, in accordance with sustainable development and green, energy-saving design. Under special conditions, these technologies might include the technology of bionic anti-adhesion of mechanical surface, the technology of trans-scale bionic non-smooth surface processing, the technology of couple of geometric bionic patterns-coordination of bionic quantitative characteristics, the surface technology of compound bionic functions, the super bionic hydrophilic surface technology and even the bionic non-smooth drag reduction technology relative to the mechanical surface in fluid, etc.

6.2.3.2 Biological Structure and Function

Insects have specific functions such as attachment, jumping, connectivity, folding, lubrication, sensing, fixation, positioning, and self-cleaning filters, and studies focus on the special structures and mechanisms of insects and their diversity of function. Micro-mechanical structure and function are the basis of bionic design. Hairiness is an additional system that significantly increases external contact in animals. It has strong attachment and exposure to resist fault-tolerant. Different insect or bird wings have different chain lock features, such as crawling structures, micro-structure of thorns and brush structure. These surface structures have unique features and ingenious design, and form the key research direction of bionic machinery.

6.2.3.3 Integration of the Structure and Function System of Machinery Bionic

Research of bionic integration is based on the integration of “geometry—the surface morphology—structure—organ—the system features”. On the one hand, it contains a whole bionic machinery technology, and on the other, it involves multi-functional bionic mechanical technology, including bionic structure bionic, sports bionic, control bionic, bionic vision, energy bionic and so on. Animals are rich in structure which is integrated with movement. Bionic mechanical structures and bionic movement are also able to be integrated. This integration enables controlled bionics, bionic vision, sense of smell bionic, bionic navigation and other bionic

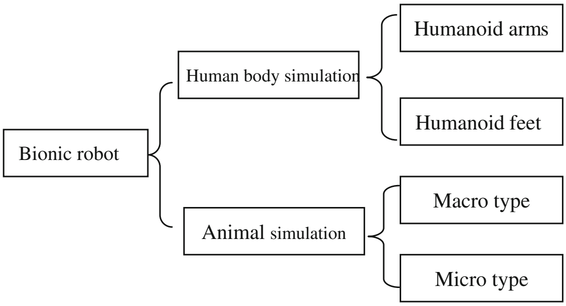


Fig. 6.4 Bionic robot classification

technology. Examples of this kind of integration are the lunar landing vehicle, soft walk vehicles and so on.

6.2.4 Application of Bionic Machinery: Bio-Robot and MAV

6.2.4.1 Bionic Robot

1. The basic concept of the bionic robot and its classification

It is well known that the active organism has diverse forms and smart moves. The most flexible among these are human dexterous hands and human feet which make it possible to walk upright, but there are still some functions of inhuman biology that man cannot achieve. A bionic robot is a robot system which imitates the external shape or function of an organism. There are many types of bionic robot which are classified according to their characteristic of imitation (shown in Fig. 6.4).

The main research of the humanoid-arm is the combination of a joint type robot operating arm with a multi-fingered dexterous hand and arm, dexterous hand with 7 degrees of freedom or multi-degree of freedom. The main research of humanoid biped is the mechanism of the Biped Walking Robot. The main research of the Acer inhuman bionic robot is on the multi-legged walking robot (4, 6 and 8 feet), snake-like robots and underwater fish-like robots, and these bionic robots are larger. The main research of the micro-inhuman bionic robot is on all kinds of insect-like robots, such as a crawling robot that imitates the geometrid pest, the micro-robot dog, micro-cricket robot, micro-cockroach robot, micro-locust robot and so on. The main characteristics of bionic robots are that most of them have redundant degree of freedom or ultra-redundant degree of freedom, and some are different from conventional articulated robots in their driving mode-bionic robots use ropes or artificial muscle to drive them [14].

2. The research status of bionic robot

The dexterous actions of bionic robots are a great help in production and scientific research activities, and robot scientists have therefore been researching the bionic robot since the mid-1980s. Since 1983, the U.S. Robotics Research

Corporation hypothesized the formation of a combination humanoid arm. They developed the K-1607 series with 7 degrees of freedom single humanoid-arm robot and the K/B-2017 dual-arm robot. One of the arms of K/B-2017 has been used in space station experiments. In 1986, the U.S. Engineering Design Centre, University of Utah successfully developed the famous UTAH/MIT dexterous hand. The hand has four fingers, the thumb has two joints, and the other three fingers each have three joints, rope-driven and tension sensors. In 1990, Bell Labs completed hardware and software systems in control of the dexterous hand and carried out experiments on the simulation of holding, folding, grasping and various other actions performed by the human hand. In 1992, the Japan Machinery Laboratory, Jakasago Research & Development Center started work on a polydactyl humanoid-arm. The system was composed of a main arm and a sensor control system. Their dexterous hand has four fingers and every finger has three joints; the hand has 14 degrees of freedom. With the development of multi-fingered dexterous hands, more and more attention has been paid to the development of a humanoid-arm with dexterous hands and its system. U.S. CED, Sarcos Research Company, Bell Laboratories and the Department of Energy undertook joint development of the hands of a humanoid-arm and introduced a new type of smart remote control operating system (DTS). The dexterous arm (DA) is a hydraulic arm with 10 degrees of freedom (including 3-DOF hand). In 1995, the University of Bologna designed a humanoid-arm system with three-fingered dexterous hands based on the PUMA robot.

The humanoid walking robot is a frontier topic in robot technology and is one of the most challenging technical problems. The P2 and P9 humanoid walking robot made by Honda Company and Osaka University represent the highest level of humanoid walking robots in the world today. With a height of 1.8 m, weight of 210 kg and 30 degrees of freedom, the P2 robot simulates the structure of the human body completely. In November 2000, the Honda company introduced a new generation of humanoid robot, ASIMO (Fig. 6.5). It is 1.3 m high and weighs 52 kg, with a walking speed of 0–6 km/h. It is the most advanced humanoid walking robot today.

There are two groups in the United States MIT Leg lab engaged in research of a humanoid walking robot. Their completed projects include a planar robot weighing 22 kg. Britain's shadow program has achieved great results in recent years. Plastic and rubber are used to manufacture materials which can simulate human muscles. This program uses the muscle-driven approach to manufacture a biped walking robot with 22 leg muscles. The position and functions of the leg muscles fully simulate the human body.

Study on imitating a non-human bio-robot has been a very active field over the past 20 years. Many foreign research institutions and companies have undertaken research and development area; the TITAN-VIII quadruped walking robot researched by Keisuke Arikawa can walk on uneven ground in a stable manner, can pass obstacles on the ground in a non-contact way and can move in any direction. At the same time, versatile legs are used to perform tasks. Rolls-Royce made use of a snake-like robot for the construction and maintenance of pressure water reactors in the British nuclear submarine. Its joints were connected with Hooke universal joints, and the maximum bending of each section is 3 degrees.

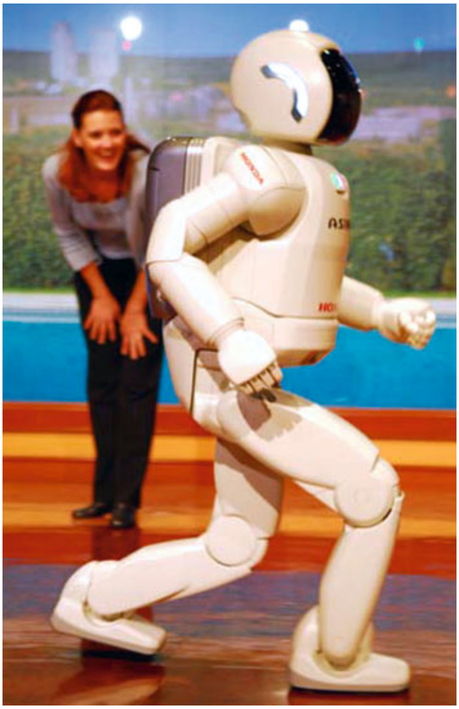


Fig. 6.5 Japanese humanoid walking robot ASIMO

In the U.S., NASA is studying a snake-like robot to use for space exploration. It is a highly flexible, high redundancy snake-like robot consisting of simple and low degree of freedom components. Takaharu Ldagki developed a pipeline inspection robot piezoelectric step in the test of the robot's movement. Its diameter is 5.5 mm, length 20 mm, weight 1 g. It can walk in an 8 mm diameter pipe. Pet dog AIBOERS-110 developed by the Japanese in 1999 has 18 joints and each of them is driven by a servo motor to maintain compliant motion. CWRU's bionic robot research laboratory studied a robot based on the crickets' sports function. It had six legs in all, post two legs are longer and had two joints. Movements of the legs were driven by compressed air. The robot can walk and jump to a certain extent and is able to adapt to rough areas and obstacles [15].

Scientific research institutes and universities in China have studied the bionic robot. They have developed a 6000 m underwater autonomous robot which has three fingers, a nine degrees of freedom dexterous hand and can achieve a simple grasping operation. They have also developed a humanoid-arm with high flexibility and a humanoid biped walking robot. The humanoid-arm has such characteristics as a large working space, no singular gesture joint, compact structure and so on. Through software control, it can avoid obstacles, evade the limits of joints and optimize dynamic performance and so on. The biped walking robot has a form of joint with 12 degrees of freedom. It has walking function as flatland forward, back, side walk, steering, upper and lower steps and so on. The United States and

Japan are at the forefront of research into the bionic robot, and Canada, the United Kingdom, Sweden, Norway, Australia and other countries are also carrying out technical studies in this area.

3. Development direction of bionic robot research
(1) The special bionic robot

There are a variety of organisms in nature. According to their particular features, developing more types of bionic robots which can adapt to specific natural environments is a future direction for the further development of the bionic robot. For example, a machinery earthworm which can wiggle in a pipeline is a pipeline robot based on bionic design principles.

(2) The miniaturization of the bionic robot

The key to the miniaturization of the bionic robot is the achievement of the miniaturization of the electromechanical system by integrating the driver, transmission, sensors, controllers, and power into a piece of silicon and making a micro-electro-mechanical system. At present, parts of micro-bionic robots made of micro-electromechanical systems have been put into practical application instead of laboratory research.

(3) Copying the bionic robot

The similarity of the appearance of the bionic robot and the organism it imitates is a hot topic in bionic robot research. In military reconnaissance and espionage missions, a robot that is exactly the same shape as the organism will be more subtle and safer in completing the mission.

(4) The bio-robot

The bio-robot, which has the manual control of living organisms, is the product of highly developed and integrated biology, informatics, monitoring and control technologies, and micro-electromechanical systems. Countries around the world have for a long time studied the use of animals for combat, such as trainings dogs to burrow into an enemy's chief position and destroy it, or using dolphins to investigate submarines. Now more countries are engaged in studies that install tiny sensors on small animals to enter places that are inaccessible by humans. In 1995, a team led by Professor Shimoyama of Tokyo University studied the control technology of cockroaches by removing the cockroach's wings and bread for exploration on its head and inserted electrodes, a microprocessor and infrared sensors, and then generated electrical stimulation through a remote control signal to guide the cockroach in a specific direction. In 2002, by implanting micro-controllers in mice, the State University of New York successfully realized artificial guidance in mice such as turning, going forward, climbing trees, jumping and other movements. Institute of Bio-inspired Structure and Surface Engineering Institute at the Nanjing University of Aeronautics in China is developing a gecko robot by developing gecko artificial control technology. They implanted micro-electrodes into geckos and controlled their movement through electrical stimulation of the nerves.

6.2.4.2 The Micro Air Vehicle

(1) The basic concept of MAV

The micro air vehicle (MAV) is a new type of aircraft developed in the 1990s. Because of its great application prospects in both military and civil aviation, it has attracted widespread interest from the very beginning. The MAV has not been strictly defined. Generally considered, the main yardstick should be about 15 cm, may be even smaller in the future, reaching the order of millimeters. The flight Reynolds number Re of this aircraft is very low; its air viscous effects are significant and its lift-drag ratio is significantly decreased. Aerodynamics show that some characteristics are markedly different from the high Re number. Conventional aircraft design methods can not meet the requirements. It is difficult to ensure stable flight in an actual operation environment; therefore, it is necessary to develop new technologies and establish new development methods.

Many flying animals in nature and micro-flying aircraft are on a similar geometric scale and generally have very good flight performance. Taking the dragonfly as an example, its wings are about 8 cm long and the area is about 0.0015 m^2, the total mass is about 1 g and its flight Re number is about the order of 103. According to the fixed-wing unsteady aerodynamic theory, its lift coefficient is only around 0.9, and hovering flight hours required for aerodynamic coefficients should be around 2.4–3. This shows that there are other mechanisms and methods for high lift in dragonfly flight.

(2) The enlightenment MAV obtained from bionics

Currently, the main known method for birds and insects to have high lift are as follows: wings flutter, Weis-Fogh flutter, the deflection and torsion of a wing's spanwise and tangential direction, cracking wing tip or zigzag trailing edge and so on. Weis-Fogh flutter is a motion of wing closure/opening. In the open course of two wings, the front forms a strong separation vortex which makes a great lift. The results show that its biggest lift coefficient can reach 5, far more than the lift coefficient value obtained from the stable theory. Bionics provides a great exploration of space and application prospect for people. People have started to pay more attention to biological motion biomimetic mechanics research and have gained many useful inspirations.

MAV is small in its scale, quality and moment of inertia and its anti-wind ability is poor. Thus, one of the main practical issues facing MAV is anti-jamming and the ability to adapt to a complex flight environment. In principle, the use of stability augmentation and control technology can achieve the requirements of anti-interference and stabilized flight. However, MAV, because of its very small size, has very low aerodynamic efficiency; if it uses rudder deflection to provide anti-interference ability as in an aircraft, the effect will be very limited. Many birds or insects which have a similar scale as the MAV can fly stably or hover in strong winds and complex environments. The main reason is that their wings as well as their body can change into adaptive deformation by conditions on the outside. This ability is difficult for people to acquire.

Many flying animals in nature have fast speed and high mobility which is unmatched by humans. The greatest speed for most people is about 3–4 times the length of the body per second and a supersonic aircraft whose Mach number is 3 can reach a speed about 30 times the length of the fuselage per second, but a common pigeon often flies with a speed of 80 km/h which equals 75 times the length of the pigeon per second. The European starling can reach a speed of 120 times its length per second and some swifts can reach a speed of 140 times the body length per second. The roll rate of high mobile combat aircraft is about 720 degrees per second and the roll rate of a barn swallow can exceed 5,000 degrees per second. The maximum radial track allowed for general aircraft is 4–5 g, and the maximum radial track allowed for aircraft is 8–10 g, but many birds often reach 10–14 g when they are flying (here "g" is the value of acceleration of gravity). These outstanding performances of organisms relate to their full use of the unsteady aerodynamic effect and adaptive deformation capacity in their flight, plus the fact that they always maintain the most favorable position and flight status [16].

(3) The development direction of MAV

Before simulating the high stability and high mobility flight capacity of birds and insects with the use of bionics methods, we must be able to develop an intelligent autonomous control theory and method which apply to the high reliability, strong adaptability and high stability, and strong anti-interference capability of MAV in order to improve the anti-interference capability and system robustness to maintain an optimal state under different flight conditions. Of course, this method demands higher standards of aerodynamics, structure, and control especially in the size and weight of control system components.

Weight loss is the key issue in developing high-performance bionic intelligence MAV. The materials and structure of many flying organisms in nature have superior performance because of their ultra-lightness, high-intensity and adaptive deformation. The wings of some insects like dragonflies are composed of a light mass of reticular veins and thin film materials. There is a lack of understanding of the composition of such ultra-light biological materials and their physical–chemical and mechanical properties, and there is no available method in addressing the problems of new-style structure in using this kind of material and the integrated optimization design in materials and structure. Further in-depth meticulous observation of the materials and structures of many flying organisms in nature and their superior adaptive performance is urgently needed.

The total energy/power quality in micro-aircraft is about 50 percent, which is a large proportion. Therefore, the prominent problem is how to further reduce this. Many birds have excellent long-distance flying abilities; some migratory birds can keep flying for 1,000–2,000 km without eating. This phenomenon is not yet well understood, but at least it is possible to determine that their energy consumption should remain at a very low level. There are many issues in this area which are worthy of further study.

The study of the bionic mechanics of biological motion has provided many useful inspirations and ways to solve the key technical problems of the research in MAV, and has played an important role in the practical development of MAV. The subject of bionic bio-mechanical movement has many areas which are worthy of in-depth study and exploration, and great attention should be paid to its development.

6.3 Biological Manufacturing

6.3.1 Research Direction of Biological Manufacturing

6.3.1.1 Research on Biology

To make the "live" micro-drop modules of living cells into a controlled assembling target inevitably involves many basic issues related to living cells: the discovery of key genes in cell differentiation; the external environment settings in cell differentiation; the needs of cells/material micro-droplets units controlled assembly for cell culture; the pretreatment of cells before assembly; the formation, function and control of extracellular matrixes; and the characteristics maintenance and environmental control of cells and clusters of cells.

6.3.1.2 Research on Biological Modeling

Modern manufacturing is closely related to information technology, and bio-manufacturing is more closely related to the process of information. Bio-manufacturing involves many optimal design and modeling issues: the theory and methodology of human organ modeling; the processing of biological modeling, research of data transmission, and the corresponding software development; the data compression, processing and reconstruction of anatomy of human tissues and organs; the software modules of functional gradient design (including the components gradient and pore structure gradient); non-homogeneous materials modeling software modules; the data structure and data channels in growth forming and bio-manufacturing; system optimization based on the theory of fractal geometry modeling, materials modeling and functional modeling; and bio-manufacturing and growth forming process simulation based on the cellular method of composite material.

6.3.1.3 Research on Material Science

All kinds of biological materials are the target of processing in bio-manufacturing. On one hand, we should synthesize and modify to obtain the required performance of the biological materials, and on the other hand, we should also study the biological properties of the materials forming processes. This mainly includes artificial bone, artificial cartilage, sustained-release antibiotics artificial bone, artificial bone with a half-joint surface of cartilage; the synthesis, forming properties and surface chemical properties improvement of biological materials by cartilage cells configuration in vivo and liver cells configuration in vivo; the relations between composition, micro-structure, forming of biological materials and biological properties; the impact of rapid prototyping technology on the biological and mechanical properties of materials; the impacts and mechanisms of implants, live pore structure and mesoporous structure, distribution and porosity on biological properties; the bionic synthesis of cartilage cells and the extracellular matrix of liver cells, and the compatibility of materials/cells and materials/growth factors; biodegradable materials, the main growth factors from the BMP, and the controlled release of active protection.

6.3.1.4 Research on Micro-Droplet Jetting and Deposition

Rapid prototyping has the characteristics of layered manufacturing, point by point accumulation and digital model direct-drive. This mainly includes: taking into account the requirements of functional gradient structure accurate and maintenance of accurate biological characteristics of the material requirements of the development of micro-drop control module assembly processes selecting different spray enabling technologies according to the different scales and viscosity of material droplets, such as: screw extruder, low-temperature spray, piezoelectric nozzle or magnetostrictive nozzle direct writing and laser guided direct writing; developing different precision processing technologies based on the various process equipment, and to study different molding process parameters to optimize the research and development of precision nozzles.

6.3.1.5 The Cell Assembly Enabling Technology

In the cell assembly process, under the control of a digital computer model, micro-drop modules are accumulated and assembled through various enabling technologies. The technologies used (capture, transport, location, assembly, etc.) on the micro-drop modules can be roughly categorized into two fields: micro-droplet jetting technology and high-energy beam technology. Both are cell assembly enabling technologies. Micro-droplet jet-usually adopts extrusion jetting technology (for a higher viscosity of non-Newton fluid) and jet-printing technology (for a lower viscosity of Newton fluid). The high-energy beam technology uses the particle properties of a specific wavelength laser, and uses optical pressure to capture single cells suspended in the culture medium; hollow fiber-optic micro-displacement and the accumulation of a single-cell table is used to create a three-dimensional (3D) structure.

6.3.1.6 The Technology and Equipment of Cell Assembly

Cell assembly is the core of biological manufacturing engineering. Cells need to be manipulated directly or controlled indirectly by a computer, which assembles living “parts” according to the design. Now people can develop a proliferation of various cells in vitro, but it is an extremely challenging task to assemble many kinds of cells to form a certain structure according to the specific structures and functions required to achieve its physiological functions. Specific research on the assembly process and related equipment is an important part of the study of biological manufacturing engineering.

6.3.2 Features and Functions of Biological Manufacturing

Biological manufacturing is a major branch of manufacturing science, and there are many common points between biological manufacturing and traditional manufacturing. As a complex technology, bio-manufacturing includes manufacturing science, life science, computer technology and material technology, all of which have their own characteristics.

6.3.2.1 Building Complex Platform of Biological Manufacturing

An important aspect of biological manufacturing, unlike general parts manufacturing, is to build a special platform. The input to this platform is the manufacturing information which is generated from biological modeling and data processing, and the output is tissues or organs which have complex 3D structures and corresponding functions. The platform is built differently to accommodate different needs. To build a bio-manufacturing platform, the priority task is to establish a human organ digital model. This is based on CT layer data and a vector CAD environment, and effectively describe the relationships and composition of internal organs, and also meet the demands of manufacturers [17].

6.3.2.2 The Specialization of “Parts” of Biological Manufacturing

The products the mechanical manufacturing industry are assembled in parts. Every part is a single entity made of one material and has a single function as well as other mechanical characteristics such as shape, surface quality and mechanical properties. The various tissues and organs which compose the whole organism can also be regarded as assembly of “spare parts”. However, these “parts” are active; they not only have complicated structures and compositions, but they also have specific physiological functions. Therefore, biological manufacturing engineering not only ensures the mechanical characteristics of products; it emphasizes product biocompatibility and biological activity to ensure the effectiveness and safety of the clinical application.

The “parts” of biological manufacturing engineering have the following characteristics: (1) physical characteristics: materials and components in a microstructure of “parts” form a gradient distribution within the three–dimensional space in accordance with the design requirements, and form the physical properties of the gradient distribution; (2) chemical characteristics: a combination of many materials and different materials with different components, surface characteristics and chemical properties; (3) biological characteristics: possesses a certain biological function and organization and provides the conditions for further growth of the cells; (4) time characteristics: the cell/tissue will express different genes following completion of the forming process and will change as time passes; (5) individual manufacture: different users correspond to a single production, and not only will external dimensions of the individual change, but the individual cells will also change; thus, implantation of the body will not cause immune rejection [9].

6.3.2.3 The Personalized and Timely of the Biological Manufacturing Process

Because the "parts" of biological manufacture are the organs and tissues of body, it is clear that bio-manufacturing is a personalized production; each "part" may have similarities, but it must meet external dimensions of the individual, and therefore, mass production in bio-manufacturing cannot be achieved. However, the "biological parts" required are often uncertain and unpredictable, and because this requirement is also urgent and must be produced within a certain time, the basic requirement of creating artificial human organs is fast generation, which requires the development of a bio-manufacturing system to be highly flexible.

This shows that, in order to make more complex products that meet the characteristics of the demand, bio-manufacturing engineering devices will need to make design, material preparation and the forming process into a highly flexible manufacturing system. The ideal biological manufacturing engineering system should have the following features: (1) can create and directly operate different scale micro-droplets units and connect them to achieve continuous material and a non-continuous gradient; (2) can construct micro-droplets units with complex shapes and internal micro-structures according to design requirements; (3) will not disrupt the biological characteristics of materials or contain/produce toxic substances during the manufacturing process; (4) can complete the "parts" of modeling and data processing through computer images of 3D medical scanning reconstruction, and achieve the process of automatic control; (5) possesses high degree of flexibility. Based on rapid prototyping technology, the discrete accumulation of the basic principles of a good bio-manufacturing system can meet the above requirements [18].

6.3.3 The Implementation Technology of Biological Manufacturing

6.3.3.1 Constructing the Biological Manufacturing Platform

When researching biological manufacturing, the construction of the manufacturing platform in is an important problem which should be considered first. The input terminal of constructing platform in biological manufacturing manufactures information through biologic modeling and data processing layer. The input terminal of constructing platform possesses implantation materials with complex 3-dimensional structure, stent even organs. The specific content of the platform is different according to different needs. In order to construct a bio-manufacturing platform, the current priority tasks are to build a digital model of human organs based on CT/MRI Layer Data, which can effectively describe the topological and constitutes of the internal organs to meet the demands of manufacturers, vector-based CAD environment, and to achieve a certain physiological functions of the vascular function of biological manufacturing.

The cell sizes in biological manufacturing range from 0.1 to 100 μm; the structural sizes range from 10 μm to several hundred microns; the processing and forming size ranges from the micro level to the macro level. The essence of biological manufacturing is discrete or accumulative forming material, but the cells, clusters of cells or composite materials unit are special materials. The establishment of the bio-manufacturing platform must first consider the characteristics of the manufactured object.

With regard to the manufacture of artificial bone with articular cartilage, the construction of the platform’s main tasks include: the development of the corresponding equipment, to further improve and develop rapid prototyping and freeze-drying process. According to a 3D reconstruction of the data of medical CT images, using the support of artificial cartilage biological active materials’ manufacturing platform, to manipulate the support of artificial cartilage with the gradient of structure and function is a challenging task.

In the process of the biological manufacturing of body functions, especially the lives of some soft tissue that possesses bioactivities, a vascular network manufacturing platform should be established which not only embodies the characteristics of biological manufacturing but also is the correct way to solve the problem of the manufacture of artificial soft-tissue organs, such as the liver or kidney.

6.3.3.2 The Principle and Implementation of Micro-Droplets Assembly

Researching the principles and implementation methods of micro-droplets assembly, especially those which transform the research from layer data bound by the digital product model to physical structure channel, has a great impact on manufacturing science. At present, it is a concept put forward throughout the world, but it has never been the subject of deep research. Micro-droplets assembly is the primary form of biological manufacturing. Micro-droplets assembly is a discrete or accumulative of engaging in technology on macro-scale. Material discretion is a process of the material unitization. When reaching to $0.1 \sim 0.5$ mm orders, the stacking unit is known as a micro-droplets assembly. The unit-scale changes of the micro-droplets assembly will change physical, chemical or biological characteristics, which should be given attention. According to the biodegradability and biocompatibility of the micro-droplets, there are three levels, namely, the incompatible, the compatible with no degradation, and the compatible with degradation.

The forming process is affected by the four main controlling factors (the impact): materials, energy, information and errors. There are many kinds of energies taking part in the forming process. The study of energy dissipation and non-linearity in the growth forming will further essentially explain the forming process and can provide a theoretical basis for real-time personalized manufacture. The physical nature of the micro-droplets assembly should be analyzed by linking the two key physical processes in digital channels. These are obtaining and assembling the material micro-droplets-drip. The material micro-droplets-drip is obtained through the enabling system and the material system of the digital channel. The enabling system is usually composed of a controlled injection system or high-energy beam system. Under the pressure form from electricity, magnet, gas, liquid, etc., the former injects the melting materials through the spray nozzles, thus according to the request of the data, forming the micro-droplets that correspond to the data pulse. The latter adopts the high-energy, high-density and easy-to-focus-precisely high-energy beam to transform (solidification, cross-links, gas-separation, sinter) the materials to micro-droplets.

The assembly of the material micro-droplets-drip is the precise location of the material micro-droplets-drip and the connection of the units. The assembly is completed by the movement system driven directly by data. The precision of the physical structure formed through the data channel depends on the scale and location precision of the material micro-droplets-drip; and the characteristics of the physical structure is associated with the characteristics of the material micro-droplets-drip and the connecting characteristics among the units.

6.3.3.3 Material Formability

According to the specific targets of biological manufacturing, facing the artificial organs, tissues or functions, designing and synthesis of materials that have the characteristics such as degradation rate, mechanical strength, biological compatibility and manufacturing technology are the main characteristics of biological manufacturing. These highlight the importance of the formability of researching materials and the choice of preparing materials. At the same time, it is necessary to pay attention to the mobilization of the human self-recovery function when tissues and organs are growing, and to consider reunification with the preparation and choice. The processing and modification are also very important.

After analyzing data from anatomy and materials science, we found that through micro-and macro-scale structures the material for real bionic optimal design and preparation can be obtained by joining living cells and growth factors, implanting them directly into implantation materials forming a biological activity device, or planting cells into biological materials that can directly make biological manufacturing. In addition to meet the general requirements of the biocompatibility and biological activity, the cells or material/cell unit, complex assembly of manufacturing technology, also meets the special requirements of manufacturing processes, such as discreteness of material assembly, especially for cells in extra cellular matrix composite where accumulation of cells are able to be assembled in discrete, assembly, maintaining cell activity in material selection and preparation and so on. These issues are problems that are different from specific conventional study. Only when the material problems are solved can, the biological products be obtained through biotechnology.

6.3.3.4 The Accumulation and Assembly of Cells

Biological manufacturing research is still at the basic, cell level stage. One important innovation is that material-cell complex particles are accumulated to make a 3D microstructure using a computer-controlled laser beam under the control of computers and applying biomaterial forming and living microbes to space-controlled production. The function of the laser beam is to bind microscopic particles, such as cells, using the axial propulsion of hollow optical fibers. According to reports, research overseas refers to preparing 3D accumulation for its application. We hold that on the one hand, the accumulation and assembly of cells relate to life science and manufacturing science, and on the other hand, it should make full use of new achievements of micron-nano manufacturing.

The accumulation and assembly of cells are completed in two ways: (1) Design and produce a bionic scaffold which has human organization and composition and implant it in human bodies. An optimized scaffold provides the best conditions for cell growth and for the construction or organization of in vivo tissue; (2) Invest in an extracellular matrix as an important material for scaffold structure which is suitable for the growth of cells, implant it in living cells, and implant the cells in bodies; existing or implanted blood vessels can help the cells to live and breed.

6.3.4 Some Frontier Issues of Biological Manufacturing Engineering

6.3.4.1 Basic Issues of Tissue-Like Precursor

(1) The spatial arrangement law of a tissue-like precursor cell and its structural optimization

The adaptive spatial arrangement of massive variant cells is the base condition for constructing complex artificial organs, in which a 3D structure is built to form a suitable micro-environment for cell proliferation and growth. Locating the special cell—There are two core issues. One is to locate the special cell-bionic extracellular matrix material units by using anatomical significance. The other is to do the spatial arrangement and structural optimization which needs manufacture, further cultivate, developing, training artificial-like precursor to convert it to the tissue and organ.

(2) The matrix bionic material of tissue-like precursor

Many metabolic functions of the cells and tissues are regulated by the extracellular matrixes (ECMs), which mainly include collagen, elastic fibers, non-collagen glucoprotein, proteoglycans and enzymes associated with Matrix metabolism, etc., so it is necessary to carefully design and select the extracellular matrix bionic materials, and to make their composition and functions as close as possible to natural tissue extracellular matrixes. Moreover, in the cells arrangement process, the extracellular matrix bionic materials play the most important role in the cure of morphology, maintaining the arrangement order and precision and stability in formation. The extracellular matrix bionic materials determine the cell 3D arrangement process, so it is a top priority to select and optimize their composition.

(3) The 3D open material and energy exchange system

The tissue is regarded as a complex open system composed of cells and its extracellular matrixes, a material and energy exchanges system with nutrition and metabolic exchange. The most important feature of the tissue-like precursor lies in imitating natural tissue structure in the composition and morphology. It is a dynamic, orderly, material and energy exchange open system. The biochemical functions of tissue rely on interaction through the cells or between the cells and the ECMs, and have a correlation with the arrangement structure of cells; this is one research emphasis.

(4) The hierarchical structure of tissue-like precursor

Because of the restriction of the proliferation distance of ions or molecules in the micro-environment, we must design and construct a nutrition and metabolism channel, as with the structure, to achieve large-size cells in an extracellular matrix material 3D open system. This is also a requirement of the vascularization of artificial structure tissue in the spatial structure. To design and manufacture the whole structure and access according to a digital model of organ anatomy, it is necessary to form a macro three-level structure. At the micro level, cells must be allowed to posses a balanced space for movement and contact. Cells should be in the 3D support frame (namely, the primary structure) which is similar to truly natural tissue, rather than in an adherent status. This requires the support structure which can guarantee the micro-environment mentioned above. And this structure is twice smaller than cell's structure. The secondary reticular structure lies between the primary structure (micro) and the three-level structure (macro), which has great significance in strengthening the three-level structure and establishing the primary structure. The design and manufacture of a hierarchical structure with the combination of macro- and micro-structure is the key for manufacturing a stable tissue-like precursor by imitating normal tissue. In this hierarchical structure, the three-level structure resolved millimeter and micron problem of the main structure based on millimeter and micrometer, and the primary structure promises to construct the micro-system and the terminal circulatory system by self-assembly and self-growth. The significance of the neither research is great, that is the induction mechanisms on the tissue growth by the primary structure, gene expression of cell by growth factor in the micro-environment and the relationship of the interaction between cell-extracellular matrix bionic Kom cell and cell.

(5) The expression of specific gene and its regulatory mechanism in the development of tissue-like precursor

The artificial construction of a complex organ involves cell 3D arrangement, which involves another important issue, that is, how to control and guarantee the expression of different types of tissue genes of the tissue-like precursor at different times. These are all core issues related to ensuring the functional and harmonious development of tissues. The reconstruction of tissues and organs involves self-assembly in an appropriate 3D environment and the mutual recognition and transmission of signals through different types of cells. This is a dynamic and orderly process of gene expression and regulation.

6.3.4.2 Computer-Aided Cell Three-Dimensional Controlled Assembly Technical Principle

(1) The combination of the cell controlled assembly and its self-assembly

The combination of the cell controlled assembly and its self-assembly is the best way to construct artificial tissues and organs, using 3D controlled assembly technology to construct the macro or microscopic structures. However, this structure creates the conditions and environment by weak self-assembly, so it is necessary to construct fine micro-structure by self-assembly.

(2) The cell 3D controlled assembly of a complex organ functional unit

The functional unit of a complex organ includes cardiac tissue, hepatic lobule, membrane gland, and kidney, and common problems are as follows.

To achieve the fixed point arrangement of one or more types of cells and growth factors and to form the modeling technology of the 3D structure by non-homogeneous materials; the cell 3D arrangement process that is, just three-level structure appropriate process formed upside, including: the blend between the extracellular matrix bionic materials and cells, the protection of cell extrusion, extracellular matrix bionic materials unit preservation, forming accuracy and stability; the basis of the above forming process is the physical and chemical cross-linking and mixed cross-linking of collagen-like material, to study the various mechanisms and their impact on cells and the three-level structure; to study the function of identification in vitro and the biological evaluation methods of the tissue-like precursor. Although the life sciences and the medical profession have a perfect detection system, artificial organs designed and constructed to have the metabolic function of humans still have particularities that need to be studied; bioreactor technology is used for culturing tissue-like precursors, and the bioreactor should consider the good training function of a tissue-like precursor when designing the special bioreactor by organizing parameters which can provide a real-time training effect.

(3) The material selection and formation of the cell 3D controlled assembly

The chosen extracellular matrix bionic materials should be similar to ECMs in chemical composition, flexibility, hydrophilic nutrition and metabolism diffusivity, etc. The major features are: that it is water-soluble, so that cells can survive in its liquid environment; there is a demand of sufficient diffusivity for the hydrophilic matrix; there is high moisture content; there is good biocompatibility and biodegradability; there is a certain extent of formability.

(4) The engineering-oriented platform of the cell 3D controlled assembly

Whatever the forming process this requires the corresponding equipment, and a common set of circumstances for forming the physical, chemical, biological environment, anatomical data of automatic analysis and processing and 3D scanning and disinfection system. The notable feature of the cell forming controlled platform is that it not only handles the active biological materials, but also the living cells.

Natural tissues grow in an environment of complex mechanics, acoustic, electric, magnetic and various rays, and an engineering-oriented platform should provide these exogenous signals and physical loading conditions, and should detect and record the various responses of organizations, such as the former of tissue precursor, in real time.

The integration of engineering-oriented platform and cell separation–passivation equipment and its process, and the integration of engineering-oriented platform, cell culture and bioreactor are needed. The importance of the laser-directed writing platform used for capturing, transporting and depositing one cell in the assembly process becomes more and more obvious, and should be included in the research program.

The research of open platform should be suitable for the formation of different materials and the construction of different types of tissue-like precursors.

6.3.4.3 The Design and Manufacturing of a Prosthesis and Tissue Engineering Scaffold

(1) The bio-manufacturing enabling technologies of a prosthesis and tissue engineering scaffold

The research of micro-droplets assembly experimental platform: research into an experimental platform with data processing capacity, used for multiple biological material micro-droplets 3D controlled assembly, has great significance in obtaining a fine complex scaffold. Compound digital jetting of a multi-nozzle can guarantee various materials with different physical, chemical and biological properties. Life materials are sprayed through the nozzle, and in a measure, real-time, non-drip way, accumulate precisely into the configuration according to the computer commanded planning path. The forming process of the various scaffolds is created by the combination of the rapid prototyping technology and traditional fibrous connection, solution casting-particle leaching, phase separation method, gas foaming and freeze-drying method. The platform is also very important for building the vascular scaffold. The large number of applications of the prosthesis model of tissues and organs in medicine and in complex surgery drive the research into low cost, high efficiency, easy operation and moderate accuracy forming equipment, which is also associated with the platform technology.

The research of material jetting technology: material micro-injection technology is the key technology of the micro-droplets assembly 3D accumulation forming. The difficulties associated with material micro-injection technology are much greater than those of ink-injection technology, and many new technologies are emerging. Research into different jetting and controlling technologies and equipment according to different materials and precision has great significance.

(2) The optimization design and surface modification of the scaffold functional gradient structure

The optimization design of the scaffold functional gradient structure: the material composition functional gradient structure directly affects function, such as the degradation rate, the induced tissue regeneration rate and the drug effectiveness. It has matching functions, such as the match between the degradation rate of implants and the regeneration rate of tissue, the match between the degradation rate of implants and the demanding drug effectiveness, etc. The mechanical performance requirements should be used to optimize the design of the compositional gradient and the pore structural gradient, to analyze the scaffold assembly structure and its pore size, and to study its composition. This not only has great impact on the spatial distribution of cells and the relation among cells, but also provides the signals of cell proliferation and differentiation.

The surface modification of the scaffold: the gap between the scaffold requirement exhaustiveness and the scaffold reality limitation often influences the application of many scaffold methods. For instance, the contradiction between formability and hydrophilicity has influenced the applications of many polymer scaffold materials. Undertaking surface modification on the scaffold materials is an important measure in enhancing the performance of polymer scaffold materials. Surface gradient modification also makes small molecules with an identification function attach firmly to the surface of the scaffold and implant according to certain rules, thus promoting bio-compatibility and bio-activity.

6.3.4.4 The Construction and Cycling Characteristics of the Tissue and Organ Canal Systems

(1) The mathematical description and bionic design of canal systems

From the viewpoint of manufacturing science, the complex tissue and organ canal systems mainly include the vascular network, the salivary gland, the lacrimal gland and some parts of the nervous system. The study of the system topology includes the types, density, shape, pore diameter, trend, conductivity and other distribution laws; the study of the geometric description of the statistical law and its characteristics according to the laws of size distribution; the study of the structures and parameters of the canals and 3D canals which meet the requirements of the micro-manufacturing process (lithography, precision micro-droplets assembly, precision replica technology, etc.). The study of artificial blood vessels should hold a priority position in all the above study.

(2) The principle and method of canal system manufacturing

The micro-canal can be manufactured by micro-lithography; by strengthening the study of precision replica technology and the multi-layered materials of a complex canal system, the fine biological activity of the pipe inner wall is ensured, which is beneficial to the formation of an anti-thrombosis function; The mechanical properties of the exine and middle must ensure the operation of the canals and their strength in use. The precision micro-droplets assembly process has great potential in micro-canal manufacturing, which should be strengthened by study.

(3) The metabolic function and micro fluid dynamics in canal systems and in the hierarchical structure

Microfluid is the basic carrier: to guarantee the metabolic function, and create the basic survival conditions for cells; to study the dynamic characteristics between microfluid and transport molecules and to study the laws of interaction between microfluid and biological cells; to study the laws of microfluid pressure, flow rate, molecular infiltration and finite element analysis in the micro-canal system, to study the transportation efficiency and controllability of the metabolism impacted by the microfluid; to study the promoting effects of the growth achieved by the microcirculation parameters; to study the laws of proliferation, range, characteristics of the ions and molecules and to study their relationship with the development of cells at the molecular level structure.

6.4 The Development of Bio-Manufacturing and Bionic Machinery

6.4.1 The Development Trend of Bionic Machinery

The basic technical studies about bionic machinery will be discussed below. The basic technologies include mechanical assembly, mechanical parts and machine surface. Bionic machinery is developed from a single bionic structure or function to a complex one. The integration of bionic shape, bionic structure and bionic function will strengthen the process. Mechanical bionic technology will span the multilevel structure and function of macroscopic, microscopic and even nanometric. Bionic machinery has developed from traditional bionic machinery to modern bionic machinery which integrates informationization, digitalization, intellectualization and networking. Bionic machinery's design ideas and technology further reflect biological research production. New-style bionic machinery will be developed. Energy-saving and efficiency-improving bionic technology for large-scale machinery will be developed. Precision bionic technology for microcosmic machinery will be developed. Bionic research that can realize noise reduction, stealth and adaptive will be developed. Machines which can land and walk on the outer planets will be developed. Bionic machinery is developed from a conceptual design and a model design to practical implementation. Environment-friendly and green bionic machinery will be developed.

6.4.2 The Development Trend of Bio-Manufacturing

6.4.2.1 A High Degree Integration of Manufacturing Science and Life Science

The existing over-refined and specialized subject pattern will change. Along with further human exploration, the importance of subjects and technology's integration will be shown. Society and nature form a complex system with many interwoven factors. In this complex system, the limits of growth and manufacturing will not be so obvious. On the one hand, modern manufacturing techniques use life sciences to make the manufacturing of human organs and tissues easier. On the other hand, with the continuous development of medicine and the in-depth study of biological engineering, the application of biotechnology in traditional manufacturing will also encourage the update of manufacturing technology.

6.4.2.2 The Development of New-Style Material

As the basic processing objects of bio-manufacturing technology, biological material must have similar composition, properties and function to the extracellular matrix material, and must have formability properties that are suited to manufacturing techniques. In order to meet the need of manufacturing figuration and the biology, biochemistry, biophysics characteristics of human tissues and organs, the design synthesis and optimization of properties of biological material are necessary links in biological manufacturing engineering development.

According to bio-manufacturing science and technology's need, we find the main research directions of biological material are as follows: filtrate and, optimize the existing biological material and change the properties of existing biological material to synthesize new biological material which is seamlessly compatible with cells and tissues. Thorough research in material's tissues compatibility, blood compatibility, physiological property and mechanical property and biological anti-aging property to acquire biological material that has a similar function to the human extra cellular matrix. For the realization of smooth transition in the contact of material and cells, lives surface, further research is need on material surface's modification technology and other biological treatment method. In accordance with the requirements of figuration techniques, it is necessary to research the relationship between the composition and properties of a material's structure to enhance the biological material's formability.

6.4.2.3 The Development of Technics and Method

Manufacturing technology and human civilization promote each other's development. Processing objects develop from natural material to various artificial rebuilt and synthesized materials, and to today's live unit which is built by special material that can be operated. The means that to make a cell, a representative life unit, as a processing object is an important foundation of bio-manufacturing.

Since the 1990s, many new bio-manufacturing techniques have come into being. These techniques are used for the figuration of biological material and material which contains life substances. These techniques are as follows: low-temperature deposition manufacturing (LDM) techniques, layered in situ cross-linking (LISC) techniques, cell printing techniques, bio-plotter techniques, cell-assembling techniques, and so on. Developing and improving these techniques and exploiting new bio-manufacturing techniques to produce organ precursor analogies are the important directions of bio-manufacturing engineering in the future field of manufacturing. In particular, it is of great significance that man can develop the new techniques and interrelated equipment which can capture, transport and accurately locate cells. This kind of bio-manufacturing technology realizes the "physical structure" which is composed and copied by cells.

6.5 Summary

As a subject which combines manufacturing science and life science, bionic manufacturing science represents one of the main development trends of manufacturing science in 21st century. This is an introductory study into researching bionic manufacturing science. It involves numerous related technologies of basic subjects. This chapter firstly analyzes the production background of bionic manufacturing science. It points out that the manufacturing industry will face increasingly severe challenges because of the advancement of science and technology. Learning from biology becomes one of the solutions to this problem. With the development of related subjects, bionic manufacturing science has emerged.

Bionic machinery and bio-manufacturing are the two main components of bionic manufacturing science. In the section on bionic machinery, the principles, research status and scientific problems of bionic manufacturing science are introduced. The application of bionic machinery in making bionic robots and micro air vehicles are also introduced as examples. The section on bio-manufacturing introduces the theoretical basis and main research contents of the bionic manufacturing system and also describes the implementation technology of bio-manufacturing and the science problems faced in the development in the bionic manufacturing science. The chapter lastly forecasts the development trend of bionic manufacturing, and points out that it is of great significance to bionic manufacturing science to develop new-style material, new techniques and new methods in future research.

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Chapter 7
Management of Technology in Digital Manufacturing Science

The basic process of digital manufacturing is the design, simulation and manufacture of product in digital environment. That is, when receiving an order, firstly complete the conceptual design and overall design. Then finish the computer simulation or rapid prototyping process. Until the technics planning engineering, CAM and CAQ process are completed, and the product eventually comes into being. The process above is not just a simple manufacturing process, but a complex system which relates to numerous links. So, traditional manufacturing enterprises must establish a new organization and management model to adapt to the digital manufacturing process. In a digital enterprise, a perfect competitive system of markets should be established to enhance the enterprise's competitive power. Under this competitive system, according to the continuously changing market information and customers' order and going from the overall-situation and long-term benefits, the enterprise can evaluate its production and management state, forecast its future operation status, decide the research and development strategy and production plan by the decision model. To achieve these functions, management of technology becomes one of the basic theories of digital manufacturing science.

In this chapter, Sect. 7.1 introduces the basic content of the MOT. Section 7.2 puts forward Research and Development (R&D) management in the digital manufacturing enterprises, and introduces the manner of its implementation. Section 7.3 describes the methods of technological strategies management and technological venture. Sections 7.4 and 7.5 analyzes the relations between digital manufacturing and external environmental factors and puts forward the corresponding countermeasures. Section 7.4 discusses the digital manufacturing process and human engineering of production mode. Section 7.5 discusses the digital manufacturing mode based on cultural differences and thinking mode.

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7.1 Management of Technology (MOT)

7.1.1 Concept and Development Process of MOT

The word of technology comes from Greek, which means the talent of creation and ability. Technology can be explained as experience, skill and feat gained through practice. It can be seen as a means to an end. That is, all effective acts and methods can be regarded as technologies. With the development of modern science and technology, and with the deepening of technology and economic integration, technology development shows three distinct features: 1) whether from the units or from the overall scale, the investment of technology research and development has shown an increasing trend; 2) the cycle from a technical invention to the commercial application becomes more and more short; and 3) the contribution of technology in modern economic growth has been increased. In short, technology is currently the main source of competitive advantage and the key factor that decides the success or failure of modern business competition. Moreover, the investment and complexity of technology development has increased.

However, according to the research we find out that technology innovation is not the unique or necessary condition to promote economic development. For example, in Japan, a country having strong technology innovation capability, the amount of its patents in 2002 was on the top in the world, but its international competitiveness level was only the 30th in the world [1]. In China, the average conversion rate of scientific and technological achievements was only about 10 and 80% of the new technology cannot be transformed into productivity. The contribution rate of technology progress to the economy was only 30%. Why the technology innovation does not consequentially serve the economic growth? Some researchers think that it is because of the existence of a gap which is called 'The Valley of Death', between technology innovation and economic development. It means that a lot of achievements in scientific research can not move toward the market and are buried in the process from basic research to commercialization [2]. Therefore, how to impel technology innovation break through 'The Valley of Death' via effective management, becomes a problem that is concerned by the researchers worldwide. MOT emerges in such an environment as an area of research in which effective technology operation and management are realized. Its purpose is to improve the input–output ratio of technology innovation, and maximize the value of technology innovations.

MOT began sprouting from late 1960s to 1970s, when management entered a stage of system management. The main changes are: system analysis and system engineering are widely applied; enterprise's plan tends to be long-term planning and strategy plays a more important role; universal participation occurs in the world. Schumpeter thinks that economic development, in essence, is to constantly introduce the technology-based innovation in the market. Innovation is the transfer of a new production function or a new combination of production factors into the enterprise. The purpose of innovation is to gain entrepreneur's profit. In the 1980s, management entered a stage of strategic management. Technological innovation began to shift from the economics field to management study. So, MOT was officially born. People realized the transfer from R&D management to R&D and technological innovation management. Strategic MOT has been widely used in large enterprises, especially high-tech enterprises.

The definition of MOT can be divided into three categories according to the different perspectives and emphasis points [3].

The first category delegates the definition in the report named "Management of Technology: hidden advantage", which was issued by the National Research Council of United States in 1987. The report gave the definition of MOT as: "The content of MOT which relates to the scientific, engineering and management theory, is to program and complete the organization's strategic and operational objectives through the plan, development and implementation of the technological capability." This definition stressed the schematization of technology development.

The second category definition mainly focuses on technological invention and innovation. For example, Bezier pointed out that: "MOT means the timely creation and improvement of the company's products and production capacity. MOT can be divided into two kinds of successful management: to encourage invention and to encourage innovation." Enterprises' success depends not only on their own MOT changes, but also depends on the achievement of technological potential and the processing of environment. Therefore, MOT often includes commercial culture, strategies, organization structure, management attitudes, human resource policy and other issues.

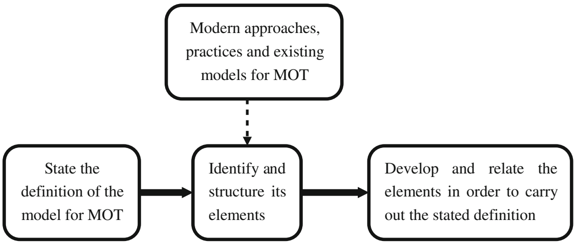
The third category defines that MOT is part of the strategic management. Business and technological integration is very necessary in the present environment of brutal competition, rapid changes in social value, and the fast development of new technologies. Beide Wei pointed out that: "MOT reality is the practice of company's integration of business strategy and technological strategy. The integration needs the meticulous coordination among research, production, market, finance, human resource and other departments."

From the three definitions above, we can see that MOT is a series of management processes about technological innovation and technological strategy. MOT includes the planning, organization, coordination and control of knowledge and technology. The core mission of MOT is to enhance the core competency of enterprise through research, exploitation and management innovation. Thus, it can enable enterprise survive and develop in the fierce competitive environment [4].

7.1.2 *Model of MOT*

If an enterprise does not want to be eliminated by market, it must own the competitive advantages. These advantages mainly come from the price, quality, output, service and other factors ever before, but these factors are difficult to last for longtime, because competitors can catch up and surpass very quickly in these areas. More

Fig. 7.1 General process to design the model



sustainable advantage will be the technical advantage. In order to obtain the technical advantages, enterprises must broaden or correct the understanding of the management, and then the establishment of a technological management model can contribute to the achievement of management change.

To model such a process, we followed three basic steps. Firstly, we established a set of general guidelines grouped under several concepts called Principles. Their function is to provide the minimum level of guidance for any one in the organization to make right decisions. Secondly, we identified the main elements participating in the process. Their functions and relationships were established. Finally, these elements were arranged into a coherent structure. The general process is shown in Fig. 7.1.

MOT focuses on resources, infrastructure, models, systems and practices at three levels within the organization: individuals, functional areas and corporate. Issues related to MOT are diverse. They include strategy, innovation, research, development, engineering, operations, product development, linking technology to finance and marketing, managing risk for technology projects, levering core competencies, information technology for expediting work flow and decision making, dealing with new and disruptive technologies, strategic alliances, outsourcing, acquisitions, knowledge management, government policies, environmental and ethical implications of technological choices, linking customers, suppliers and even competitors, and market intelligence among others.

A Model for MOT that would help people to implement this discipline requires a few elements containing all possible issues. The elements of the Model we are introducing were defined from concepts on MOT that already developed from the study on the extensive literatures related to the subject.

Strategy. A broad formula for how the company will find competitive advantages from technology, what its goals should be and what policies would be needed to achieve those goals. It must include market needs, core competencies and technologies, growing areas and required infrastructure. Therefore, it is a top management responsibility but the organization must widely participate in both formulation and implementation.

Leadership. Ability to achieve results by seeing and communicating specific forms to develop competitive advantages from technology in different areas of the company. It includes implementation of the technological strategy of the company and the establishment of a culture of technology focused on value generation, new business opportunities and social responsibility.

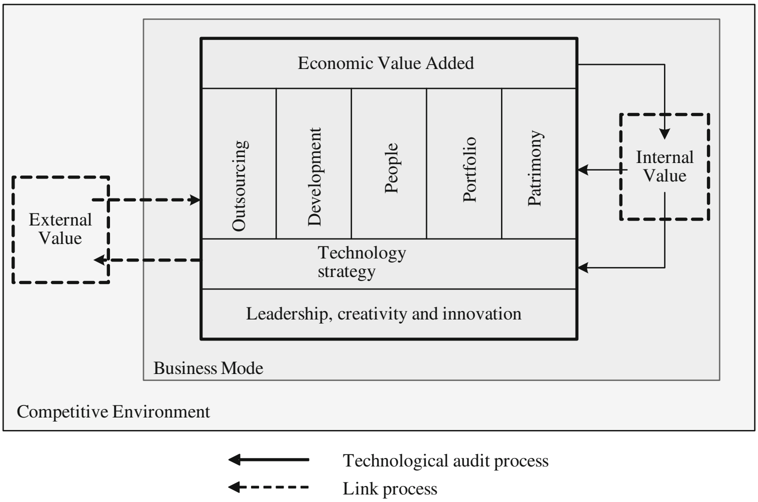


Fig. 7.2 Model for management of technology

Innovation. Basic means to satisfy specific needs and create new markets for existing products. Providing the necessary resources and eliminating barriers to innovative ideas and the people who create them is a top management responsibility.

Outsourcing. Creating value for the company by building strong alliances with customers, suppliers and strategic partners. These alliances may include fields, products and services where the company has high competencies to perform.

Portfolio. Set of projects that have successfully gone through a process of proposal, evaluation and approval and are used as means to develop competitive advantages, grow and diversify products using both known and new technologies.

Patrimony. Experience, processes, machinery, devises, patents, knowledge, technologies, human resource, infrastructure, reports, test results and other resources used by the company.

Human Resources. People with the competencies and knowledge that create solutions for customers. They are hard-to- replace people who provide work of high value.

Results. New business, products, processes or knowledge implanted and bringing economic value added to the corporation.

Audits. Activities to certify that the company maintains or improves its technological position in the competitive environment where it operates.

To communicate and practice MOT a simple but powerful representation of the complete concept was needed. The Model shown in Fig. 7.2 is a solution to this need [5]. The Model produced has great flexibility whose architecture makes sure that it is applicable to most business.

In the Model, three blocks can be distinguished: the competitive environment, the company's business Model and the company's MOT. These blocks coexist at the same time and space. Leadership, creativity and innovation are the platforms

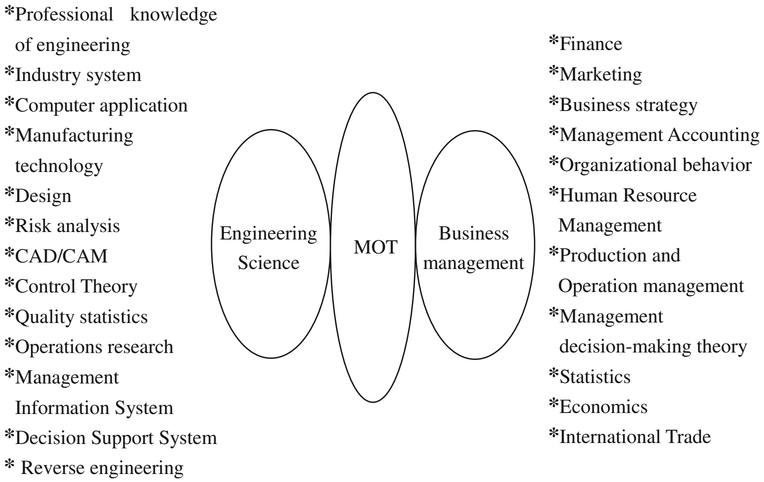


Fig. 7.3 Theories and subjects involved in MOT

for MOT. The core of the company: people, patrimony, external sources, development and project portfolio, are at the center of this block diagram supported by technological strategy and directed to economic value added.

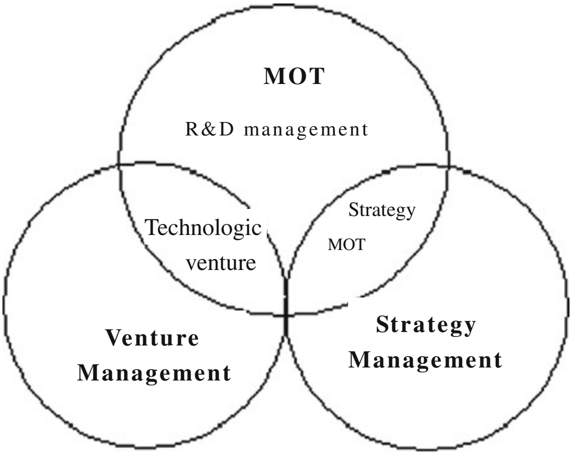
The functionality of the Model is indicated by loops. The main loop goes from technological strategy to EVA through the core of the company and closes from EVA back to technological strategy through an audit process. The other loops bring value into the core of the Company from other areas of the business and from external sources.

MOT is a powerful concept that helps companies to become more competitive. It expands the conventional approach to management to make technology the main source of lasting competitive advantages. The development of MOT within a company requires a lot of practice. This Model facilitates both practice and assimilation of the concept. The experts and infrastructure of a company have limited its innovation and R&D capabilities. By using the Model, a company may add external resources and virtually have unlimited capabilities to generate competitive advantages.

7.1.3 The Connotation of MOT

MOT is a new subject that emerges when technology economics transforms to business management. To some extent, technology economics and business management reflect a relation between the theory and commercial application which is similar to the relation between management and economics. The commercial application of economics forms management. Also, MOT becomes an

Fig. 7.4 The connotation of MOT



inevitable trend with the transformation from technology economics to commercial application. MOT emerges at the background of that mature technology economics and intensified new technology need the efficient plan and management for technology.

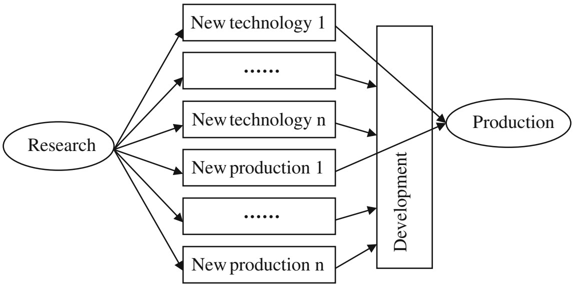
Technology economics is widely considered to belong to Applied Economics. It mainly originates from the study on the elements of economic growth. From Schumpeter eras, west scholars have discussed ardently about the relations among technological innovation and process and economic growth. Based on the relationship between MOT and technology economics, the theory of MOT relates to all the subjects of business management and engineering technology (Fig. 7.3). The academic literatures of technology management largely use the research methods and results of related science fields, such as sociology, economics, psychology, mathematics, political science, management and systems theory [6].

From the macro-economy perspective, MOT covers the broad areas from enterprise structure to science and technological strategy. Some scholars call MOT as "the new international standard language" in the world of economy [7]. The research content of MOT is more extensive, which can be summarized into three aspects that are shown in Fig. 7.4.

R&D management is the core of MOT, which is mainly implemented in the traditional industrial enterprises to promote technological innovation and realize the goal of enhancing the value of enterprises. R&D management is a management of the whole process from technology research to technology marketization. The process is shown in Fig. 7.5.

Obviously, research and development are two different processes. Research is a process of observing different phenomenons and their relationship and using the scientific method to carry out rigorous reasoning. So, the management of research should be emanative. It just needs the vision or strategy of enterprise or organizations as guidance. But development is a process of realizing the

Fig. 7.5 Research and development process



commercialization and marketization of research results. Enterprises must use scientific management methods in this process, such as project management methods.

In the high-tech enterprises, technological innovation has become the main source of enterprise value. So, enterprises focus on how to get lasting competitive advantage by technological innovation. Strategic MOT will choose those projects that are valuable to the future development of enterprises from the technological innovation, then implement strategic research and development input: confirming the input time and proportion of fund and personnel combining with their development strategies, finally carry out strategic market exploitation of the research and development production: deciding time, number and market scope of all the productions according to the strategic development need of enterprises. Enterprises can achieve the goal that the technology serves for the enhancement of enterprise value.

With the continuous development of science and technology, technological venture becomes another new hot spot in the area of MOT. Over the last decade, a large number of new enterprises which have successfully realized technological venture emerged in the world. Taking Microsoft as an example, its economic value which is created in 10 years is equivalent to GM's economic value which is created in 100 years. It can be fully proved that in a knowledge-based economy and information society, technological venture has strong vitality. It is different with R&D and strategic MOT that technological venture cannot be used in the existing organization, but creates new organizations and management entities. Technological venture will have a tremendous multiplier effect to promote the development of new industries and eventually drive the entire social economy's development. Then the ultimate goal of MOT comes true.

MOT mainly involves technological innovation, strategic technology planning and technology transfer, project's technology management, concepts and methods of MOT, human resources and social and cultural issues in MOT and other fields. R&D management, strategic MOT and technological venture are the core issues and hot issues in the MOT research. But human factors and cultural factors must also be considered in the digital manufacturing field. In a modern manufacturing system, human is the mainstay of all the activities and is the most important part.

Human factor and human engineering application must be considered to make technology and working system adapt to each other in the fields of product design, production manufacturing, organizational structure, incentive mechanisms and management strategy. In addition the management globalization of manufacturing enterprises has become the trend of development. The international division and collaboration within or between different enterprises become increasingly common because of the rapid development and expanse of multinational companies. But the clash between management model and enterprise culture that based on different cultural backgrounds has brought enormous challenge for the globalization. How to resolve this contradiction is the issue that must be studied in the digital manufacturing field. These issues can be included in human resources and social and cultural problems of MOT.

7.2 R&D System Framework and Management Mode

R&D is the core processes of manufacturing organization. It involves a lot of enterprise sectors, such as design, technics, production, quality assurance, supply and finance. It experiences numerous links, from the technical and economic feasibility study, engineering development to product-forming and batch production. Faced the global market competition in the twenty-first century, the managers have no way to enable enterprises be invincible but innovate endlessly in production variety, production performance and production technology. Enterprises must have the subject ability of forming R&D. Some data shows that in the United States enterprises complete more than 70% of the national R&D projects, and about 70% of the national scientists and engineers engage in R&D work in industrial enterprises. In other words, the R&D work in the United States mainly centralizes in industrial enterprises which are the main organizers and executors. The proportion of investment in R&D is continually growing in the enterprises of developed countries. In 1970, American industrial enterprises' investment in R&D was equivalent to 2.2% of the enterprises' turnover. In 1985, the proportion reached 2.8% and the data was more than 3% at the end of the 1980s. In 1981, German industrial enterprises' investment in the R&D reached 2.8% of their turnover, and in 1985, the proportion reached 3.2%. At the same period, the absolute value increased by 42.5%. In 1981 and 1985, German industrial enterprises' investments, respectively were 27.3 billion DEM and 38.9 billion DEM. The proportion of Japan's scientific research funds in 1990 was 2.99%. In South Korea, the proportion of all industries was only 0.39% in 1976, but it reached 1.2% in 1985 and arrived at 3% in 1991. Despite having abundant funds, some large multinational companies whose annual turnover exceeds 1 billion dollars or even more, still dare not relax. The proportion that the investment in R&D takes up in the turnover is also high. For example, in Samsung Electronics Company of South Korea, R&D funds accounted for 5% of the turnover in the 1980s and rose to 10% in the 1990s [8]. R&D capability is the core element of technological innovation

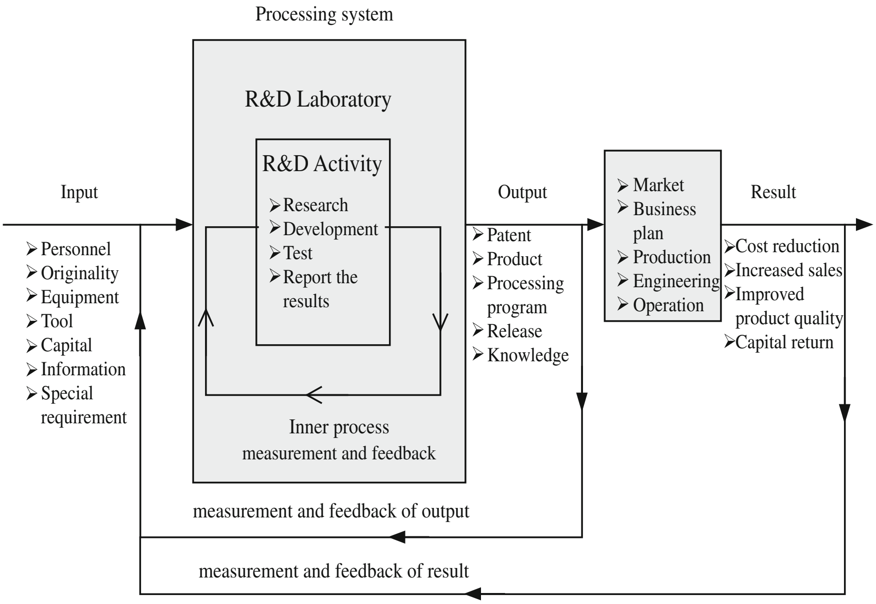


Fig. 7.6 R&D system schematic diagram

capability. With the weak R&D capacity, enterprises' technological innovation will just become a phrasemongering.

7.2.1 R&D System Framework and Management Emphases

7.2.1.1 R&D System Framework Model

R&D management can precisely meet the needs of the market. Thereby it can enhance the efficiency and win market and then realize the sustainable development of enterprises. In order to gain the definite key contents of enterprises' R&D management and choose a reasonable R&D management mode for enterprises, we must first understand the R&D system framework. In 1998, Brown and Svenson put forward the most famous R&D system framework model—B–S model (shown in Fig. 7.6), which has been widely used in R&D management study [9].

Like most systems, R&D system has three links including input, process and output. According to the B–S model, R&D system consists of eight main cells: input, processing system, output, acceptance system, result, inner process, measurement and feedback of output, measurement and feedback of result. For digital manufacturing enterprises, especially high-tech enterprises, the uncertainty of market and technology is much higher than traditional enterprises. So the connotation of input variable must be enlarged in system input cell including

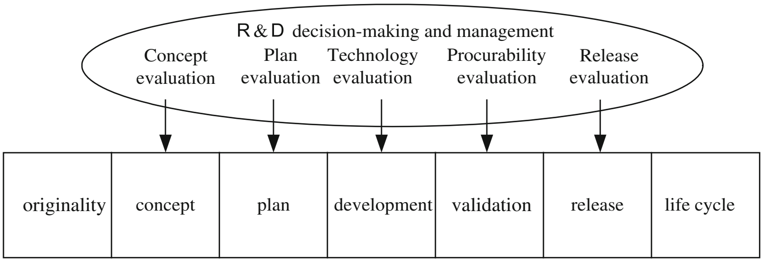


Fig. 7.7 R&D process model

customers' feedback/demand information, market information, technology trend and competitors' information, etc.

In general, an enterprise's R&D process can be divided into seven steps: originality, concept, plan, development, validation, release and life cycle, in which some steps have corresponding evaluation points (shown in Fig 7.7). According to the characteristic of each step, R&D process can also be divided into five stages: originality–concept, plan, development, validation–release and product to market [10].

Originality–concept stage is the early part of R&D activity. The emergence, exchange and processing of originality form the starting point of project and light the innovative spark. It means that originality is endowed with organization form, substance and shape to translate originality to concept. The source of originality–concept comes from the feedback information of technology sector, market sector, manufacturing, after-sales service and competitors. Originality–concept may even form virtual R&D organization through the introduction of external resources. Originality–concept of R&D activity can be verified through the test and communication of market and potential customers. An oppositely stable trans-department virtual organization should be established according to the requirements of project. The tasks of the organization include the resource allocation and management, the establishment of organizations, task breakdown, time schedule, project evaluation data and so on. In the development stage, enterprise's R&D investment remarkably increases and the enterprise enters into practical research and development work according to the established project plan. Validation–publishing stage is the later part of R&D activity. In this stage, enterprise should validate product's function characteristics, performance index, market reaction and other aspects. Then enterprise should perfect the product according to the validation results, finish the documents, standard, description and other tasks of the final product release and then release the final product and R&D achievement. In the stage of product to market, enterprise should track and serve the product that has been put on the market, aiming at the feedback of market and customers partly improve product to enhance the competitive ability and prolong the product life cycle, and provide decision-making basis and advice for termination of product life.

7.2.1.2 R&D Features

From R&D system framework and the entire process of R&D activity, we can see that product development stage includes not only product's entity development activity but also product's test and modification activities. That is, through the work of this stage, we can translate the product project scheme from concept into commercial results, various specific indices and tasks which have to be shelled out. For enterprises, R&D activity has the significant characteristics of complexity and risk.

Complexity includes the complexity of technology and management the two aspects. The so-called technology complexity means that a technology cannot be understood and designed by a single technologist, cannot be expressed in detail and exchanged spanning time and space. Technology complexity is represented in three aspects: (1) product complexity; (2) process complexity, and (3) the interactive complexity between product and process. In the process of product development, each stage and link is interrelated and interacted. After the dynamic feedback, stages and links bring the synergistic effect among all the links. Technology complexity may bring tremendous risk for R&D projects because of its unpredictability. To a great extent, management complexity originates from the strong professional trait of R&D activity. It is difficult to achieve effective management to the external members of R&D organization because of the constraints of knowledge and information. For enterprise manage layer, the project management complexity of R&D is mainly represented at the complexities of R&D result evaluation and project process management. R&D result evaluation itself is not only a very difficult issue, but also an important issue in the process of R&D management control study. Conclusively, since the R&D projects whose process can be monitored, and result can be easily evaluated, it has the lowest management complexity. Contrarily, since the R&D projects whose process cannot be monitored, and result cannot be easily evaluated, it has the highest management complexity. If the management complexity of R&D projects is very high, such as the entire research process of some basic research projects need prodigious innovation and that the innovation results cannot be reasonably evaluated, the enterprises needs to give R&D personnel great autonomy right and much more trend to let R&D team implement independent management control.

For enterprises–an economic subject whose main objective is for profit, risk correlates with the possibility of loss. Enterprises have the possibility of benefit loss, due to that some factors make the actual results deviate from the expected result. Specific to the research and development activities, enterprise R&D activity risk refers to the possibility of the failure of R&D projects, which is caused by the reasons as follows: enterprise erroneously predict the changes of the external environment or unable to adapt to the changes; enterprise overestimates its own research and development capabilities but underestimates R&D projects' own difficulties and complexities; the problems of management and control. Enterprise's R&D risk is mainly represented in three aspects: technology risk, market risk and management risk.

Technology risk mainly refers to the possibility that enterprises will suffer losses due to the project failure caused by the uncertainty of technology. The causes of technology risk include: the uncertainty of technology success; uncertainty exists in each stage of R&D project—even if the basic research likely be successful, but the development research may also fail; the uncertainty of technical effect; the uncertainty of technical life and the uncertainty of technical prospect.

The ultimate goal of enterprise's R&D project is to achieve its commercial value. But because R&D project needs some time to research, and during the researching period there are a lot of uncertainties in the market, which will result in market risk. Market risk is due to that the innovative product cannot adapt to market requirement and this leads to the inadequate and ineffective acceptance in the market which makes the output of R&D project cannot achieve expected economic benefit. Market risk is mainly reflected in two aspects: firstly, market acceptance risk—whether or what degree the research result can be accepted by consumers or users; secondly, market return risk–whether the expected market return can be achieved, and how much the realization possibility is.

R&D project management risk refers to the risk which is brought by the failure of R&D innovation that is caused by poor management in R&D innovation process. Different R&D projects require the collaboration of R&D staff in different levels. Some research tasks which rely on strict control of the organizations authority can be divided into almost non-related modules. Such projects have lower demand of management skill and lower corresponding management risk. But some research tasks need the R&D staff to keep compact communication and co-operation. Such projects request the project managers to have much higher management skill. So, the management risk is very high because that management effect greatly affects the success or failure of project. Therefore, enterprise must choose the right person as the project manager because those research and development projects have different management.

7.2.1.3 R&D Management Emphases

Because of those features above, R&D activity has its own particularities compared with the other tasks of a company: it is a high intellectual and professional activity; it faces many uncertainties, such as high investment and high risk. Thus R&D management emphases should be focused on the following aspects.

Research cost management. R&D cost management is an indirect management for R&D activity in which money or value is used as reference. It can be divided into three stages: pre-plan, middle-supervision and after-analysis from the view of general management cycle mode. Research cost plan is very necessary in the plan of R&D activity. In R&D process, it must be monitored that whether the expended research cost is effectively used. It is also necessary to analyze the economy of research result according to the research cost after R&D.

The setting up of R&D organization. It lies on the enterprise scale and management system. Enterprise's R&D organization generally have several types as follows: 1) enterprise's R&D activities are concentrated in a research institution so-called Central Research Institute; 2) each department sets up its own research institute without setting up the Central Research Institute; and 3) having both above; 4) the research institutes of each involved department are geographically at the same place with the Central Research Institute, that is, "centralized research, decentralized organization"; 5) enterprise's R&D activities are the branches of the Central Research Institute, but they disperse in each involved department or branch house, that is, "decentralized study, centralized organization."

Research staff management. R&D is a kind of special labor in which human factors account for a large proportion because R&D is built on the basis of human creative behaviors. Therefore, in R&D management, research staff management is a very important aspect. The main purpose of research staff management is to inspire their creative spirit and work passion. Enterprise should pay main attention to the management of research staff in the following aspects: 1) creating a good research environment. This is one of the important factors to improve R&D efficiency; 2) evaluating the capacity of research staff correctly to make sure that he is properly appointed; 3) personnel management of research staff in which enterprise should select and absorb those young and promising researchers to make sure research institute always maintain the vitality of creation; 4) the education and training of research staff.

R&D achievements management. Enterprise's effective R&D achievements management should cooperate not only with R&D department but also with enterprise's sales, materials providing and other departments to make R&D achievements play a greater role in enterprise operation and convert R&D achievements into patents. R&D achievements management has two main functions: 1) collecting and managing the information of R&D achievements to avoid repetitive research and overlapping investment by technology forecasting; 2) converting enterprise's R&D achievements into patents to control and monopolize technology and market and then enhance the economic value of R&D achievements.

7.2.2 The Main Modes of R&D

According to the difference of size, technical force, financial resources and natures and purposes of R&D projects, R&D activity of enterprises has different modes.

Independent research and development. From the status of international technological competition and the strategic choice view of technological competition between enterprises, enterprise must have a strong technology self-reliance capacity to win in the international market and maintain a stated market position. Large enterprise often has its own R&D institution, abundant human resource and financial resource, thus its R&D work, especially those R&D which involve the company's special products and technologies, generally progresses by its own strength. So it can keep exclusivity of the technology. For example, the main research test center of American DuPont Company is founded in Delaware. There are more than 2,300 researchers and technicians in this center. In 1987, the company's R&D funding was about 1.2 billion dollars. So far, DuPont has developed over 40,000 pieces of new products and acquired more than 25,000 pieces of patents, which is the top company in the United States. 57% manufacturing companies in Japan have their own R&D teams. The proportion in German is 33% [8]. China's Haier Group has its own technological development centre. Since the operation of this Centre is at its early stage, Haier Group now can averagely output a technology patent every three days and output a new product in 8–10 days. These enterprises are leaders in the industry competition and industry technology development. Behind their leading market positions, they all have the strong technical support from the strong and independent R&D technological capability.

Technology purchase and technology search. Technology purchase means to acquire the technical knowledge through market transactions and sometimes through merging other enterprise with innovative technologies. Technology search means acquiring knowledge through non-contractual, legal or even illegal way.

Cooperation in research and development. In the current dog-eat-dog market environment, if enterprises want to last for long-term development in the domestic and international market competition, they must have stronger competitiveness. From the view of technological competition, technological competition promotes technology progress and sets much higher requirements to enterprise's technological capability. It also urges enterprise to change their traditional competition mode, form new competitive advantage through cooperation, promote industry technology progress and participate in international market competition. From enterprise's angle, cooperation of R&D activity is the cooperation between different enterprises or cooperation between enterprises and scientific research institutions or universities. R&D cooperation of combining industry-university-research institutes is also an effective way to form new technical advantages and improve technical level.

Participation in national and international fatal science and technology development plans such as international Eureka plan, European Union's science and technology development plan and other large-scale plans. Enterprise can benefit from these plans in three aspects: firstly, enterprise can find ideal partners, including enterprises, universities and research institute; secondly, enterprises can obtain national subsidization; thirdly, enterprises can share the usufruct of achievements directly. Because most project achievements of those plans are already products, it can benefit the development of enterprises.

R&D internationalization. The internationalization of R&D is a kind of action that enterprise spread R&D to other regions outside its homeland and use several countries' technological resources to carry out transnational R&D. Generalized internationalization of R&D includes several following forms. Setomg up foreign R&D institution such as the cooperative production of "Airbus" in Germany, France and the United Kingdom. Establishing provisional consortium: enterprises and banks compose a provisional consortium aiming at one great cooperative project, and under

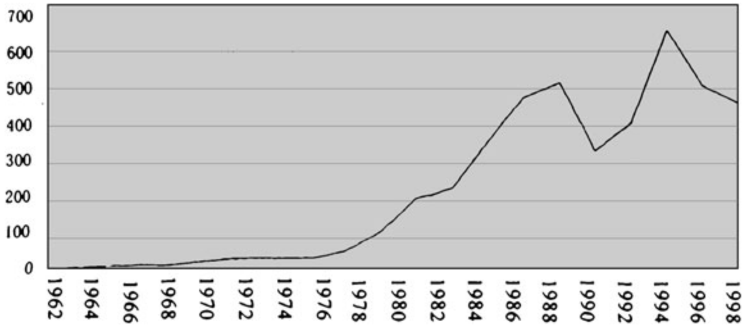


Fig. 7.8 The number changing trend of new established collaborative research and development among enterprises from 1960 to 1998 (*Source*: OECD, 2003)

the lead of one primary enterprise of the cooperative groups, in order to give financial support to the research and development project. This form is mainly used for those technology fields that need vast bankroll, longer time and vast personnel in different subjects. For example, France and Germany cooperated in the development of Spacelab and the broadcasting satellite named "Symphony". Cooperating with overseas companies or research institutions or hiring foreign R&D personnel. "Virtual company" is springing up and becoming the main form of cooperative R&D development among different enterprises in the future. It means a kind of organization union that different companies join up to seize the valuable market opportunity as soon as possible. Because it has neither headquarters office nor top-down organization form, as well as no visible shell, so we call it "virtual company" borrowing a computer term "virtual". Its main characteristic is centralized advantages which means that each member of the united companied has its strong suit in one product's design, manufacturing, sale and other links. Therefore, the combination will form an overwhelming competitive advantage.

7.2.3 The Collaborative Management Mode of R&D

7.2.3.1 Collaborative Research and Development and its Advantage

The invention and innovation of technology rely much more on collaboration. Integrated technology innovation activity that is collaborative research and development becomes the leading trend. It includes different forms introduced above, such as cooperation in research and development, participation in national and international fatal science and technology development plans and the internationalization of enterprise R&D. The research report of World Organization for Economic Cooperation and Development (OECD) also shows that the number of worldwide collaborative research and development among enterprises rises continuously (shown in Fig. 7.8) [11]. Figure 7.8 shows that in the 1960s and 1970s, the worldwide collaborative research and development among enterprises rose slowly and smoothly; from the late 1970s, collaborative research and development has displayed an accelerating growth trend; although in the early and late 1990s, drastic fluctuations occurred in the curve, but looking from the total trend, from the 1980s the number of new established collaborative research and development displayed an obvious rising trend.

This research and development mode mainly has the following advantages [12].

Obtain complementary resources and realizes resource sharing in the process of research and development. With the rapid development of modern science and technology, the development process of precise and advanced technology products is a term of huge and complex system engineering, which has rigorous demands about capital, technology, talents and organizational forms. On the one hand, technical breakthrough relies on the exchange and cooperation between projects and industries. On the other hand, the shorter product life cycle makes enterprise needs not only technological innovation but also requires the timeliness of technological innovation. Consequently, more and more enterprises, especially the digital manufacturing enterprises, need to occupy the market and set their competition advantage by rapid innovation. However, it is very difficult to obtain enough innovation knowledge only relying on one enterprise in a short time. So, the collaborative research and development becomes the inevitable choice in the process of enterprise's knowledge innovation.

Reduce the risk and cost of research and development. In the 1970s and 1980s, many industries' research and development cost have exceeded the degree of one individual enterprise can afford. At the same time, due to the fiercer competition in global market, it makes the labor cost and capital cost rapidly increase when developing new product or technology which is innovative and can be accepted by the market. The increasing and high research and development cost has become a bottleneck that restricts the development of enterprise. Under this condition, it is one of the efficient approaches for enterprise to rearrange its research and development strategy, and achieve the cost-sharing of research and development by the establishment of cooperative research and development alliance.

Enter the markets of collaboration members to increase market share. Digital manufacturing enterprises should necessarily find a technology and development collaboration alliance, especially collaboration alliance, on the product chain among enterprises in order to keep ahead in technology field, cut down the cost of technology research and development, improve the efficiency of technology research and development, and acquire and occupy local market.

Practice shows that enterprises gradually realize the function and status of collaboration in the process of research and development, and more enterprises are actively attempting cooperative research and development among enterprises to improve their technological innovation system. For digital manufacturing enterprises, collaborative research and development in technological innovation can bring more research and development income. It can effectively avoid the inferior position that enterprises lack knowledge, and it can enhance the innovation speed and innovation quality.

7.2.3.2 The Forming of Collaborative R&D Network

Information and communication technologies, especially the swift development of internet technology promote the rapid development of digital manufacturing technologies. It also makes global economy enter into a state of globalization. This kind of network-based economic activity is called network economy. Such technologies reflect that economic subject has greatly depended on the network. It makes the behavior of economic subject tend to be an invisible unity rather than a visible unity in almost every corner of the world. The globalization trend of network economy makes digital manufacturing enterprises consequentially seek for partners in the process of collaboration on a global scale. To maintain the exchange between partners through information technology, this new approach will not only further enhance the quality of collaborative research and development in digital manufacturing enterprises but also be recognized and canonized by enterprises and will gradually produce this new collaborative approach—collaborative research and development network.

Network organization is the combo of multiple independent individuals, departments and enterprises for the common tasks. Its operation does not rely on the traditional hierarchical control, but to finish the common goal on the basis of the definition of their respective roles and tasks, through dense multilateral contact and interactive cooperation. In the network, nodes can be individuals, departments of enterprises, enterprises or their mixture, and each node retains an interactive contact with equal status. Dense multilateral contact and full cooperation are the uppermost characteristics of network organization, which are the biggest differences between network organization and the organization form of traditional enterprise. Collaborative network of digital manufacturing enterprise is a crossing time, space and region organization mode. It is founded with modern information technology as the technology platform, and on the basis of the sharing of knowledge and technology among enterprises, to realize their goal of enhancing the speed and quality of technology development (shown in Fig. 7.9) [10].

Collaborative R&D network can adapt to the demands of global competitive environment. From the width of view the competition among enterprises virtually is a comprehensive bout on talents, information and market. So the R&D network formed by technology collaboration among digital manufacturing enterprises will undoubtedly have a direct impact to the production activity of enterprise. Network can enhance and consolidate the status of enterprise among its counterparts, and improve the core competitiveness of enterprise and also can provide specialized services for different aspects of the market to better meet the increased individualized requirements of customers. Moreover, it can use the existing marketing channel of cooperative enterprises to start marketing activities and thus greatly reduce the cost of market development and marketing cost. After entering into the cooperating network, research and development power of enterprise is correspondingly centralized. So enterprises can form the new research and development advantage, shorten the development cycle of new products and new technologies,

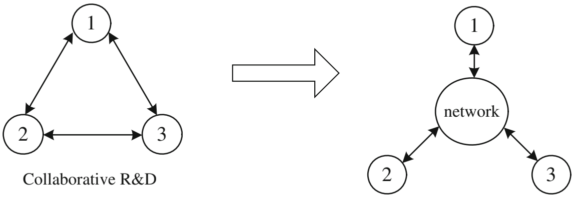


Fig. 7.9 Collaborative R&D network sketch map

accelerate the improvement step of product quality and enhance their innovation capability and comprehensive strength.

Collaborative R&D network can adapt to the development of technical standard. Technical standard is approved by recognized institution. For the purpose of generality, the recognized institution works out technical standard to regulate the rules, guidelines, characteristics of products or related processing methods and production methods. Technical standard firstly appeared at the beginning of large industrial development, and mainly be used in military field. Since the development of science and technology, standardization has extended to various economic and social development fields such as product standards, method standards and management standards. Technical standard has developed from the past problems which mainly solve the generality and replacement issues of product parts to an important barrier of national trade protection and the main form of non-tariff barriers. In fact, the technical standard strategy is not only a national competitive strategy, but also, should be the strategic choice when the national enterprises face standard competition. It is said that "first-class enterprises sell standard, second-class enterprises sell technology, third-class enterprises sell service, and four-class enterprises sell product". That is the true portrayal of technical standard market position.

7.2.3.3 Coordinative Management of Collaborative R&D Network

From the analysis above we know that collaborative research and development has become an important way for digital manufacturing enterprises to obtain innovative technology. With the development of the network economy, network has become an effective organization mode, and digital manufacturing enterprises also have gradually evolved from collaborative research and development to collaborative research and development network. As a new organization mode, in digital manufacturing enterprises collaborative R&D network has its own characteristics and advantages, but it involves the cooperation issues between network members. Since differences or conflicts exist among different members in culture, technology, benefit and other aspects, the operating efficiency of the overall network organization cannot be ensured and the overall innovation capability would be reduced without good coordinative management. Thus, effective internal and external coordinative management is necessary in order to achieve the objective of maximum network performance (shown in Fig 7.10).

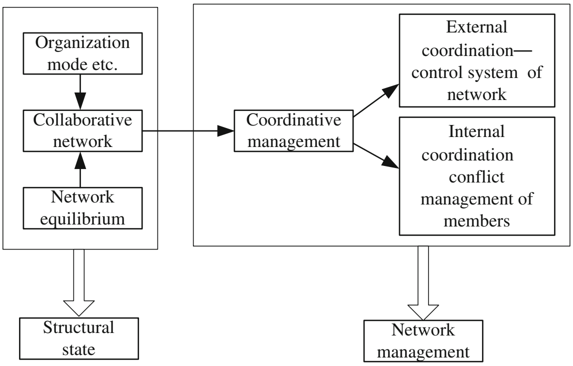


Fig. 7.10 Coordinative management of collaborative R&D network

External Coordinative Management of Collaborative R&D Network

In external coordinative management, network is analyzed as a whole to explore the effective control of network, and design effective control mode to achieve the objective of maximum R&D network performance. Effective implementation of management and control has its own requirements, the possibility and necessity of digital manufacturing enterprises collaborative R&D network management and control are reflected as follows: the effective operation of collaborative R&D network in digital manufacturing enterprises needs effective management and control because of the existence of many uncertainties in the links among enterprises; The goal of management and control is realizing the goal which was first set when the network was established. Of course, enterprises should strive to improve the efficiency of research and development; the establishment of network is to adapt to the needs of economy and technology development. Network managers should have a certain responsibility and ability to achieve the objectives of network, at the same time network members will endow network managers with sufficient rights in order to obtain the necessary innovative knowledge.

According to the dispersion degree of decision-making power and the loosen degree of network, the control modes of digital manufacturing enterprises collaborative research and development network can be divided into four main categories which is shown in Fig. 7.11.

Strategic level control. The technology of network members has close relativity with each other. Network members maintain effective control to the organization through good cooperation after the forming of network. At one time, network managers are fully empowered to ensure that collaborative network is comprehensively controlled. This mainly occurs in the research and development network which has very high degree of complementary products or technologies.

Organizational level control. Decision-making power is mainly concentrated in the hands of a few network members whose correct decisions largely determine the effective operation of network. So network managers will be given more

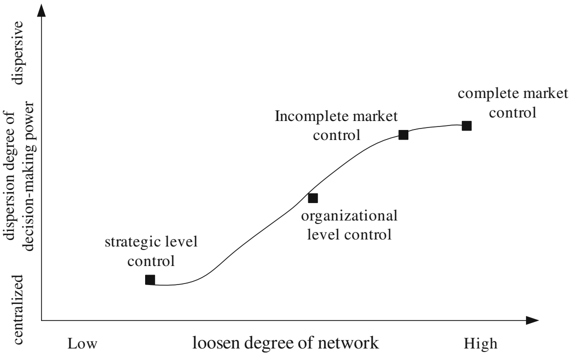


Fig. 7.11 Control mode of enterprise collaborative R&D network

authorizations. In this case decision-making mainly reflects the will of minority members, so the network which adopts this kind of control mode is mainly established by those enterprises with strong R&D strength.

Incomplete market control. Each member will gain more technology resources from a collaborative network, but due to the competitions among enterprises, the ultimate decision-making must reflect the common will of the members. This network undertakes the research and development activities of enterprise technology development strategy, and follows the operating mechanism of market rule. This control mode mainly occurs in the technology collaborative network of middle-small digital manufacturing enterprises.

Complete market control. The network decision-making lies on the result of negotiation and game between enterprises. Each member has equal status and the decision-making power is dispersed. Decision-making must be consistent with the common interests and value orientation of network members, or else network cannot be effectively operated. In other words, network operates strictly in accordance with market rule. This mode mainly occurred in the collaborative network which has relatively stable and mature existing technology, but the market demand impels enterprise to seek technology breakthroughs though collaboration.

In the actual operation process, the equivalence of technology status of network members and the stage of R&D activity must be considered when enterprise selects the control mode. Table 7.1 may be useful when enterprises make the choice.

Internal Coordinative Management of Collaborative R&D Network

Internal coordinative management mainly studies the management of conflicts among internal network members. For the members of an enterprise, the precondition of successful research and development is the accordance and cooperative operation among the members. So enterprise must firmly grasp the potential conflict types and master a reasonable solution to the conflicts.

Table 7.1 Selection table of enterprise collaborative R&D network control mode

Serial number	Network risk	Technology status among members	R&D activity stage	Control mode
1	Big	Equality	Prophase	Incomplete market/strategic level control
2	Big	Equality	Anaphase	Complete market control
3	Big	Inequality	Prophase	Incomplete market control
4	Big	Inequality	Anaphase	Complete market control
5	Small	Equality	Prophase	Strategic level control
6	Small	Equality	Anaphase	Strategic level/incomplete market control
7	Small	Inequality	Prophase	Organizational level control
8	Small	Inequality	Anaphase	Organizational/strategic level control

Digital manufacturing enterprises collaborative R&D network organization not only can encourage knowledge innovation, and increase the understanding and acceptance of concept but also can improve the sense of responsibility and inspire potential. However, as a general organization, it also has some unfavorable factors. It may stifle creativity, bring compliableness and further the liberal behavior. It is also the hotbed of conflicts [13]. Research shows that there are different levels and types of network conflict. According to the characteristics of network, we classify the conflict types of enterprise collaborative R&D network as:

Relationship conflict. It mainly involves the tension and friction in emotion and indifference among the members even distaste, dysphoria, frustration and anguish which are mainly caused by the uncoordinated interpersonal relationship [14].

Task conflict. This conflict arises from the different attitudes and viewpoints to the organization task of the network members. It is similar to the cognitive conflict which was put forward by some foreign scholars, such as the different methods, measures and advises, which are used to solve and analyze the organization task, can easily lead to task conflict. Task conflict can inspire the discussion among organization members and individual interest. But it is also likely to trigger the strained interpersonal relationship which is correlated with relationship conflict and bring a negative impact [15].

Process conflict. In the progress of organization task and objective, the conflicts and disputes about how to complete the task are related to the arrangement of responsibility, power and benefit among organization members. When organization has divergence to the responsibility of some member, process conflict will occur [16].

There are some connections between conflict level and organization performance. With low conflict level, the innovation and change of organization are difficult to implement. And organization is difficult to adapt to the environment because of their interruptive behaviors; with too high conflict level, all kinds of confusions occur and endanger organization's survival. Too high or too low conflicts are all destructive (destructiveness conflicts) and they will have a

Table 7.2 Conflict management table of R&D activity

Conflict styles R&D stages	Relationship conflict		Task conflict		Process conflict	
	High performance organization	Low performance organization	High performance organization	Low performance organization	High performance organization	Low performance organization
Originality concept	Low	High	Higher	Low	[a]	[a]
Plan	Low	High	Moderate	[a]	Low	High
Development	Low	High	Higher	Low	Low	High
Validation release	Low	High	Low	High	Low	High
Product to market	Low	High	Moderate	[a]	Moderate	Low

[a] Conflicts uncertainly and inconspicuously that affects the organizational performance

negative impact on performance. Only the conflict which is in an appropriate level has a positive impact on performance (functionality conflict) [17].

In the front we divided R&D process into five stages: originality–concept, plan, development, validation–release and product to market. The conflict of each stage has different characteristics. Each conflict at different stages of R&D activity has different impact to the network performance. Because the characteristics of each type of conflict are not the same, we can evaluate the type and intensity of conflict through the corresponding expression mode and use quantization technique to determine the index of conflict. According to R&D conflict management table (shown in Table 7.2), we can scientifically analyze and control the time, type and intensity of conflict to get the effective conflict management.

7.3 Technological Strategies Management and Technological Venture

7.3.1 Technological Strategies Management Based on Resource Theory

7.3.1.1 Technical Capacity of Strategic Management

The application of Enterprise Resource Theory is going along a main line, which explains the source of enterprises competitive advantage in the field of economics and strategic management. Seeing from the logical links of the theoretical development, we can get that there are three perspectives for enterprises to explain the source of competitive advantage: the first is the viewpoints of neo-classical economics, the second is the viewpoints of school of industrial structure, and the third is the viewpoints of enterprise resource theory.

The competitive advantage in neo-classical economics theory is actually a theory of zero competitive advantage. In the new classical economic, the enterprises in the market have the same characters, so there is no competitive advantage between them. The result is that the market achieves at a balanced state, and all enterprises have the zero economic profit. In practical economic activities, however, objective differences existing in the profits level between enterprises, the fully competitive market assumption of the neo-classical economics cannot explain this issue.

Because of overemphasis on the impact of industrial environment for enterprise competitive advantage, the school of structure overlooked the heterogeneous structure of enterprise. The researchers believe that competitive advantage are not depended on external. If we review the competitive advantage of enterprises from the perspective of the internal factors that are resource of enterprises, we can get a different view comparative to the traditional industries viewpoint. According to basic theory of resource, corporate is composed of a series of resource beams, and each has a variety of purposes. The competitive advantage of enterprises derived from their owned resources. The structure of outside-market and the market opportunities have a certain influence on the competitive advantage of enterprises, but they are not the determine factors.

R&D department is the core and fundamental force to create firm values, and the strategic value they created fundamentally determines the company's long-term competitive advantage. R&D resource is a key strategic resource for enterprises which is essential to maintain sustainable competitive advantage for the specific business. If any enterprise owns these resources, and then make some effective integration on these resources to match with the organizing ability, it will be able to get some income beyond the average level within the competition.

Technical capacity of the strategic management has positive significance to the strategic management of digital manufacturing enterprises. In the twenty-first century, technology innovation and development of enterprises are achieved under new economic environment that is composed of information economy, the network economy and the knowledge-based economy. The environment of enterprise management technology has significantly changed, and in such an environment condition, the enterprises enhance the technical capacity of strategic management that will undoubtedly provide a powerful tool to understand and manage the strategic elements such as strategic intent and strategic behavior. Then the enterprise strategy management will be much more workable, understanding, portentous and effective and the enterprises will get a sustained competitive advantage.

The purpose of technical capacity of the strategic management is to enhance the technical capacity of enterprises, and then they can improve and enhance their overall ability to innovate. Its central task is to create, establish and develop the core technology system, and also including to make efficient technological innovation around the core technology system. The core technology system is a technical which can lead, dominate product innovation of enterprises, leading design of processing innovation, core production technologies and corresponding core management techniques. All of these are under the restraints of certain conditions, such as technology, production, the organization and the market. Minor changes on the existing dominant design, the core production technology and the corresponding core management technology can launch new products, new production technology, as well as endless stream of technological innovation.

7.3.1.2 The Way to Foster Technological Capacity in Digital Manufacturing Enterprises

If the core technology which is abided by the digital manufacturing enterprises in the past is challenged by the more experienced new system, more effective technical system, the previous core technology system correspondingly have become the shackles of sustained innovation for enterprises. In this case, the enterprises should closely follow the cutting edge of technology, and aim to develop new core technology system. There are many advantages to put the core technology system as a center for technological innovation, which is described as follows. Firstly, it is easy to create product innovation clusters. Secondly it has a relatively low-cost of innovation. Markets of a variety of products complement with each other, leading to the absolute increase in the economic efficiency of enterprises. The technology correlation and complementarities of different technical paradigm lead the marginal cost of the innovation of each technical paradigm to reduce, and also make the marginal benefit increase. Therefore the economic efficiency of enterprises will increase relatively.

The central task of enterprise technical capacity building is to cultivate the core technology system, including improve and reinforce the core technology system that is forming. If necessary it also includes the overall elimination of the core technology systems and the development of new core technology system. So that enterprises can be conducive to the sustained innovation.

Long-term accumulation of technology. This is the most important way to enhance technical capacity of digital manufacturing enterprises. That is through long-term research and developing, studying and using of technology to develop new technological capabilities constantly. Technology accumulation is divided into three areas: the accumulation of product design capability, the accumulation of technology capacity of production and the accumulation of technical management capacity.

Combination of technology projects. Single technology can achieve only finite functions. Different technology projects can be combined to achieve new features according to their internal relations and requirements. The modes of technology portfolio are as follows: the portfolio that is done within internal development projects will help enterprises enhance the research and development capabilities. It will enable enterprises access to the first on technology and market, which can produce a new core technology competencies. Enterprises make resource integration through the acquisition, cooperation of the internal resource and external resources, then access to advanced technology in a relatively short period of time and finally rapidly establish its own higher level of core competencies. Mixed mode is the portfolio of the external technology projects and the internal research and development projects. It can produce a new technology platform and form a core technical ability. This process can achieve complementary of advantages, restructuring of advantage resources, and the rapid accumulation of technological capability. In this way, we can not only quickly contact the forefront of international or advanced technology and shorten the gap of ability, but also make completion of the digestion and absorption of advanced technologies with less input and fast rate. This can improve the technological platform of enterprise and form core technologies system as soon as possible. For example, the mixed mode of Japan and South Korea rapidly improved increases the technical capacity of domestic enterprises in the late twentieth century.

Technological learning. Enterprise learning can be divided into two parts by the source of innovation knowledge: internal study and external study. They play different roles in the enterprises learning process. The best way for enterprises is internal study because enterprises must enhance its own unique core competitive edge. This means that the achievement of new knowledge mainly rely on the creation of itself. But in today's technological environment, if it only relies on its own, it is very difficult for enterprise to complete the general knowledge innovation process. Moreover, it is also difficult for enterprise to keep up with the pace of technological development. Therefore the enterprises have to accelerate the integration process and absorb the external knowledge to enhance their rate of innovation and enhance their ability to innovate. The so-called internalization of external knowledge mainly refers to the learning process in the digestion and absorption of external expertise. This can enable external knowledge to gradually become part of the composition of enterprise's own knowledge. The enterprise completes the integration of knowledge through the loop way of studying-digesting-studying. The specific integration model can be expressed through Fig. 7.12.

7.3.2 Technological Venture

7.3.2.1 The Obtaining of Technological Venture Resource

Venture is a process that can find, create and use business opportunities, and create new careers according to the combination of production requirements in order to obtain commercial success. The aim of entrepreneurs venture is to achieve commercial success and commercial profit. If entrepreneurs want to find these business opportunities, they firstly need to understand the original driving force for forming entrepreneurial opportunities, including new technological breakthroughs and progress, changes in market demanding and structure, adjustment of government policies and laws and changes of the international economic environment as well. In drive of these dynamic forces, it can often generate three entrepreneurial opportunities: technological opportunities, market opportunities and policy

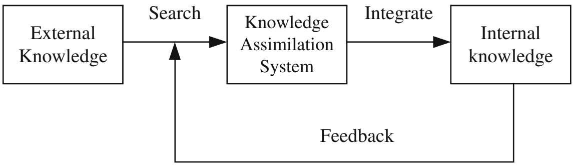


Fig. 7.12 Integrated system of the external knowledge of enterprise

opportunities. Usually technical change or the composition of multiple technologies can bring entrepreneurs with business opportunities [12]. However, it mainly exists in the following three conditions.

When a certain field of technology has made new breakthroughs, they replace some older technologies and generate business opportunities. For example, the traditional Freon refrigeration technology received challenges of the "Global Agenda in the twenty-first Century" because of the damage to the environment. Therefore, the international scientific community will quickly launch a new refrigeration technology. Of course those enterprises that use this technology earlier will get the new opportunity to expand their career.

Now we talk about the emergence of new technologies such as implementation of new features and creation of new products. When the achievement of a new feature and the new technology of creating new products appear, it will bring business opportunities. For example, the computer network technology gives birth to a large number of e-commerce companies based on e-commerce model.

New technologies bring new problems. Everything has two sides. The emergence of new technologies has no exception. When it brings people with the interests, it will also bring new problems to people at the same time. In order to solve these problems, people have to develop new technology. Thereby it will create new business opportunities. For example, the development of computer network technology has brought the problem of preventing the virus. In order to solve these problems, a large number of information security technologic companies have been established.

If the scientific creation enterprises want to get the technology that started project relies on, they can follow these ways: the technology holder begins venture. This is the typical paradigm for technology entrepreneurs. The second way is that the entrepreneur attracts technology holders to join the venture team. The third way is that the entrepreneur buys mature technology from others. The fourth is that the entrepreneur buys prospects technology form others. The last way is that the entrepreneur purchases the technology and technology holders. In a sense this is the best way to purchase others, technology and go further entrepreneurship. In this way entrepreneurs can quickly digest, understand, improve and use the purchased technology.

7.3.2.2 The Assessment of Venture Risk

Facing with a business opportunity, entrepreneurs will bear the corresponding technical risk, financial risk, market risk, policy risk, legal risk, the macro-environment risks and team risk. This is the problem that all entrepreneurs are likely to face. However, the structure and degree of the risk faced by a particular businessman may vary. There is a lot of technical uncertainty in the entire process of technological entrepreneurship, and it is very likely to lead business to fail. Technology entrepreneurs usually need more investment, otherwise it will be difficult to develop the ideal product even if you have developed a competitive product. If the lack of funding sustained, it would still be in trouble during mass production stage.

Seeing rationally, entrepreneurs must make entrepreneurial risk assessment on specific business opportunities and entrepreneurial activities. They must analyze and judge the specific sources of risk, probability, extent, risk benefit and risk-bearing capacity [12].

The risk source analysis of entrepreneurs can begin at different types of risk. We can also analyze it on both systemic risk and non-systemic risk.

We can find the risk factors with greater probability through the process of estimation. We can also exclude the risk factors of smaller probability and thereby determine the focus of the future risk management.

The entrepreneurs should estimate the risk earnings. It is worthy for entrepreneurs to catch the specific business opportunities in adventure when the receipts risk achieves at a sufficient state. Generally speaking, the risk of revenue can be measured as the following formula:

$$FR = \frac{(M_t + M_b)BP_sP_m}{C_d + J_d}S$$

FR	The income coefficient in specific business opportunities
M_t	The market advantage index in specific business opportunities
M_b	The strategic advantage index of entrepreneurs
B	Earning estimates of specific opportunities for sustained period
P_s	Probability of technical success
P_m	Probability of market success
S	Index of venture team's cohesion
C_d	The amount of tangible assets investment in specific opportunities
J_d	The amount of intangible assets investment in specific opportunities

It will be worthy for entrepreneurs to catch the specific business opportunities only when FR is higher than the entrepreneur's expectations.

The entrepreneur should also make assessment of risk-bearing capacity. After the analysis of the aforementioned factors in the index, entrepreneurs also need to estimate their own risk tolerance in a specific business opportunity. It is very necessary to forecast and estimate your own risk tolerance even if there will be a higher risk of earnings. Assessment is usually carried out in four areas which are the technical risk, market risk, financial risk and policy risk.

7.3.2.3 Management of Entrepreneurial Team

Most business activities cannot be promoted, organized and completed by an individual, instead, they need a team's effort. Therefore, the formation of an efficient team in the venture is one of the important issues. But in the process of technological venture, we will often encounter many problems: such as, lack of entrepreneurial team leader; unreasonable collocation of team members; such as, lack of common goals, interests, ideas, programs, specifications among team members, problems of team running-in and psychology of fearing difficulty in some individual team members. If these issues cann't be resolved, they could lead to the collapse of a team, and thus lead to failure of the venture. In order to set up a highly efficient start-up team, we must proceed from the following aspects.

There would be a reasonable collocation of role and division of labor between team members; The entire team should form the same entrepreneurial ideas after the collision, which is the basis of team cohesion; Team should have its own programs and rules of action; The entire team should enhance the assessment of team performance, adjust the composition timely and provide continuing stimulus. By these means team members can see the future prospects and interests. At the beginning of entrepreneurship, the team members are often the key persons to future business. So the entire team should often give them incentives such as incentives of interest, incentives of payment, incentives of working environment, incentives of the trust and the position and encouragement and incentives of property rights.

7.4 Human–Machine Engineering on Digital Manufacturing Process and Production Patterns

7.4.1 Human Factors in the Advanced Production Pattern

In the twenty-first century, digital manufacturing industry based on information technology, will be a manufacturing industry of intensive parallel production. The aims of enterprises will transfer from focusing on quantity and quality to services (including quality, price and service after sale). The request on products will transfer from large batch and many varieties to personalization, participatory approach, short cycle and fast response. The digital manufacturing enterprise management will change from focusing on concentration and independent to coordinating and completely playing the innovative role of human in the production process. In the huge transformation, what is the importance of "person" in the digital manufacturing system, how to play the role of people in digital manufacturing system and how to establish a new type of human–machine collaboration? These issues should be deeply studied. It has been proved that we still cannot ignore the importance of people in digital manufacturing systems, even in the day that the automation and intelligent manufacturing has become an important feature. Many farsighted public figures have done a comprehensive ponder about the artificial intelligence technology and CIMS technology. Authorities on system science and artificial intelligence science have presented the ideas of human–computer intelligent systems based on understanding the limitations of the intelligence, have emphasized the importance of human in the systems, especially in the process of realization of CIMS "people should play a more important role …" [18]. In a survey of the Association Engineers of German in 1990, it is presented that 30% of the impact on the success of the CIMS factors are from human factors. The advanced manufacturing technology research company of United States also pointed out the same ideas in its report in April 1990: 70% of the resistance to the implementation of CIMS comes from human-related factors [19].

If we want to emphasize on the importance of people in digital manufacturing system, we must establish human–computer integration systems and new ideas, new concepts and theoretical systems of technology. The so-called human–machine integration system is that people are the leaders who use the human–machine integration technique route, and a system is formed by human and machine together. In the system people and machine execute the work which they can do better. Thus we can break the traditional concept of "intelligent systems" to form superhuman intelligence system which can exceed the capacity even the intelligence of human. The core content is that stressing the importance of people in the system. It formed a new mechanical system with people as its center. As an important part of human–computer integration systems, the computer system makes communication between people and conventional machinery. Thereby it leads to the coordinated development of human and machinery [13]. This new type of human–computer integration systems want to re-arrange the location of people and machine. It will be a breakthrough in the current system that people are excluded in the old setup. It studies the new relationship between man and machine and develops a new generation of mechanical systems–human–machine integration system. It can realize that "thinking becomes mechanization" in a real sense. And we will design a new generation of working machine and design system as the center of "person". People and machine give full play to their own expertise to get machine and systems having the best value.

Because of the different structure of man and machine, there is a very large difference on the performance of them: computers exceed over people in computing power, the reaction time and ability to work for a long time. But human have the unparalleled advantages and no replacement role in the ability to summarize experiences, learning ability, creativity and adaptability and so on. For example, in practical engineering, design process is a cognitive activity. It is also the process of cognizing target for designer, seeing from viewpoint of thinking scientific. It is the process of modeling the objective world and a description of the real world. However machine does not have these capacities even more intelligent machine. And machinery only has a very limited capacity to create new things. At the same time, machinery particularly computer has a very powerful computing and memory storage capacity. And it also has a very strong advantage on the following aspects: to meet a specific law or the reasoning process, a lot of double counting, accurate information processing and the scope of information perception out off human perception, large-scale data processing and quantitative strict logic, execution process of high-power machinery and other aspects. Human and machine have their merit, respectively. In the system which is composed of human and machine, people and machine should make the full implementation at their best work. People and machines work together to complete the scheduled tasks. Any system cannot find the optimal solution if they get detachment with person or machine from the system. If without the first choice of the human experts, the choice of a simple machine will fall into the inexhaustible calculations, it cannot effectively solve the problem. And we cannot get optimal results without a large number of computing of the machine.

Many domestic and foreign scientists and scholars coincidentally proposed a new concept of the intelligence system which combined human and machine from different views. Lenat and Feigenbaum in Stanford University of U.S, Qian Xuesen, Lu Yongxiang, Chen Ying and other scientists of China have proposed many kinds of systems from different viewpoints such as "Man–Machine Synergy Prediction knowledge systems", "Hall for Workshop of Metasynthetic Engineering", "Metasynthesios Intelligent System", and "Humachine System". Different ways achieve the same results. The nature of each system has pointed out that: it should form a common system by people and the machine (computer), and people are its center, they respectively make the completion of the work which they can do best, and they get recognition, get perception and make decision together on the basis of equal cooperation. In practical wording environment, they must get mutual understanding and interaction; learn from each other and work together to break through the traditional concept of "artificial intelligence systems", and then they can form the "super intelligent" system which is beyond the capacity even the intelligence of human; make the human–computer integration systems achieve the best economic targets and the best overall efficiency [20].

7.4.2 The Application of Human Factors Engineering in the Digital Manufacturing System

The modern digital manufacturing industry has a variety of dynamic changes on two levels of technology and organizations. There is an urgent need to fully consider (especially in the design stage) "human factors" in manufacturing industry and manufacturing system. If we want to make technology and working systems with mutual adaptation in the field of products design, production manufacturing, the structure of organization, incentive mechanisms and management strategies, we need to consider the human factors and the application of Human Factors Engineering. Human Factors Engineering also calls Ergonomics. It is a relatively young, independent and unique practical subject. The focus of its research and application have gone through the stage of the military, Human Factors Engineering in industrial, consumer products and services, Human Factors Engineering in computer and so on. The focus gradually shifted to the industrial systems due to the rise of the research on macro Human Factors Engineering and cognitive Human Factors Engineering in the 1990s.

In the twenty-first century, it comes true that technology-centered system gradually transformed into a people-centered, human and computer integrated system through the interface technology of people–machines, human-organizations and organizations–technology. People play an important role in the digital manufacturing system. The modern Human Factors Engineering plays an important role in the process of the realization of digital manufacturing techniques and social goals [21].

Digital manufacturing technology system is composed of people and machines, so it is a technology system, it is also a social system, in this sense, and the research contents of Human Factors Engineering in digital manufacturing engineering can be divided into two aspects: factors of Human–Machine Synergism and factors of Human–Human Synergism [22].

7.4.2.1 Human–Machine Coordinated Factors

Because of the wide range of applications of information, computer, automation and other high-tech in digital manufacturing technology system, and the relationship between human and machine or the role and status of human in the manufacturing system have indeed made profound changes. The roles of human have changed from directly engaging in the manual work in the traditional manufacturing industries to the surveillants, controllers and managers of the system today. The main roles they can overtake include the following: monitoring automated system, regulating the process of automation system; monitoring, diagnosing and remedying the system failure of not taking into account; communicating with other departments, making some necessary concessions or making a good choice in a variety of tasks plan to complete the tasks; processing the sudden and accidental events within system. Majchrzak, Paris and others [23] conducted a survey which showed that: if we make an integrated design prior to the three aspects of technology, organization and human factors (human resources), and make complement and integration with each other, the use of technology will become more successful. The findings also answered the question that why do the efforts end in failure when we make the application of advanced technology. The reason is that there is a lack of understanding in the changes of organizations and human factors by the designers and technical managers. These changes come from the following aspects: design of the process, work design, operating/distribution functions between human and the machine, organizational structure, hardware Human Factors Engineering (prevention operation for safety and accident) and software Human Factors Engineering (providing the user the feedback). We can see that they are closely related to human factors in manufacturing systems.

In order to achieve that people and the machine can really work cooperatively, we must consider the following factors.

Appropriate Automation of Systems and a Reasonable Division of Labor for Human–Machine

When studying the digital manufacturing technology systems we should get to know: how to determine their degree of automation in its overall design, where does the automation use and where should not be automatic, as well as what the role of people and machinery should assume in the system. Thereby we can make human–machine system into a system of mutual cooperation and mutual complementation system. The principle of these is to give full play to the characteristics of people and machines. The features of human are: the emergency ability of dealing with random and sudden events, the ability of fuzzy reasoning and strong ability of judgment and creation. However the machine is suited to do the various physical and computing works of heavy, dangerous, repetitive work, precision control and programmed. It has fast and high accuracy. In this division of labor, it is stressed that the two aspects should learn the strong points from each other and make coordination with each other. But people are active in creativity. Rational division of labor between people and machine can make a "super intelligent" and efficient new combination system. This can achieve economic reliability and security of the digital manufacturing system.

Optimum Design on the Interface of Human–Machine

The interface of human–machine is an important aspect to achieve the cooperative work of human–machine systems. Generally speaking, the interface of human–machine includes five levels: Instrumental Factors, Environmental Factors, Information Transferring and Treatmenting Factors, Cognition Thinking and Decision-Making Factors and Cultural Factors. However, the first three are the main contents of the Traditional Ergonomics, and the last two are the research content of Cognitive Ergonomics. And they are very important on the development and applications of the digital manufacturing technology systems. The five-level personal interface can be seen in Fig. 7.13.

Instrumental factors. It is one of the most direct and simple relationship between human and machine, and it is also known as human–machine interface technology. Such relationship requires the design of shape, size, power, manipulation and stroke of the machines meeting the human body (such as the shape, size and capabilities). This includes the design of the seat of various machinery and equipment, and the design of the shape of the joystick. The aim is to make us feel appropriate, comfortable, convenient, safe and reliable in the course of using force. Research in this area is the mainstream applications of the human–machine engineering during the past 30 years. It initially studies on the physical and

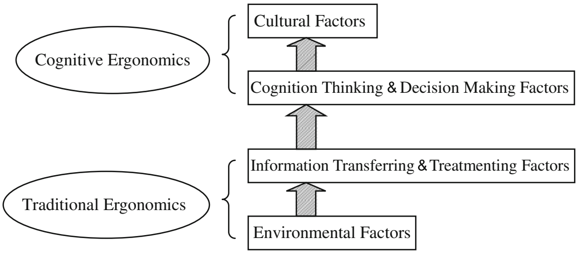


Fig. 7.13 Levels of the human–machine interface

perceptive characteristics. And it uses the related results in the process of the operating and displaying, as well as the analysis, design and evaluation of the layout of the workspace. Today this is still the attractive field of the research and applications of Human Factors Engineering. In the 1950–1960s of the twentieth century, the rapid rise of human–machine interface technology was used in factory production systems, traffic systems and aircraft design and manufacturing industries. And in late 1960s, as the development process of computer technology and the related automation of office and factory, the applications of the technology of people–machine interface extended to many other types of systems.

Environmental ergonomics or environmental factors. This is also one of the most direct and the most primitive relations between people and machines. Such relation requires the work environmental conditions (such as machinery vibration, noise, environmental temperature and humidity lighting.) to be designed to fit in people's physical characteristics to let people feel comfortable, healthy and safety. In recent decades, the technology has been applied and developed increasingly, along with the in-depth study of the relationship between people and their nature and man-made environment. In addition, we continue to study the classical approach of Human Factors Engineering (such as mission analysis) at the same time; we also enhance the ecology research on people's capacity of modeling.

Information transferring and treatmenting factors. Such factors are mainly involved in all kinds of feeling information of people and the feelings of machinery information of output organ. It also involved the physical characteristics and capabilities of the transmission and processing of machinery information. It requires the design of machine information system (including audio–visual, touch, language, etc.) to meet all the transmission of information on the characteristics and capabilities. Thereby it can make people getting information from the display of machines. It should make the process of the transmission of mechanical control command being efficient, accurate and secure, through control system on the machine.

Cognition Thinking & Decision-Making Factors. In the process of manipulating machines people and machines not only contacted physically (instrumental factors and environmental factors) and contacted at the information level (information transmission and processing factors), but they also often carried out rapid thinking and decision based on a variety of changes. If the processing in the operation of machinery system has experienced failures, the work should make quick thinking and decision based on the information of the instrument, they also should quickly rule out dangerous situation and avoid accidents. People make the right decisions according the analysis, judgment and reasoning of the various factors of uncertainty. However the machine system often cannot complete this task. It must rely on the ability of people's thinking and decision-making. The focus on researching such factors is the right to determine the reasonable division labor between people and machine. What information should machines provide, what function and role should the machinery take in the decision-making process of human–computer interaction and the knowledge, thinking and decision-making model of people (Cognition Thinking and Decision-Making Mode1), all of these have an impact on correct manipulation. We should focus on these issues. Such issue is the important issue of human factors in the age of information and highly automated machine. Such research also has an important significance on artificial intelligence research.

Cultural factors layer. The cultural factors here means that: the design of the shape of a machine system, the design of using and operation process, the scheme, symbol and language used in human–computer interface, all of these must consider the individual aesthetic habits, national and ethnic cultural differences. With the increases on international trade currently, the manufactured goods are often sold to other countries and other people. Designers must take the differences in cultural traditions of users into account, in addition to the performance of their own products. Only in this way can make the customer satisfied.

7.4.2.2 People–People Coordinated Factors

In the traditional manufacturing techniques and methods, they conduct the division strictly and meticulously according to the department and profession. Therefore, people's work is generally carried out independently, with little need for mutual cooperation. In digital manufacturing technology systems, the departments of market research, design, technology, manufacture and maintenance services have gradually become integrated through adopting this integrated computer tools. At the same time we need to respond to the quickly changing market, and make the development and production to produce all types of new products and embark them on the market. Therefore we must make full use of coordinated force of the parties to jointly complete a certain task or project.

The digital manufacturing systems in future is not just a technical system, it is also a social system. In this social system, the power of digital technology system can be fully developed only by the realization of the close cooperation between people. Therefore, we must do the following research.

People–People Cooperation Mechanism and Organization–Organization Cooperation Mechanism

For example, in collaborative R&D network, team members have to solve the problems of the co-operation mechanism between group members, when the traditional independently working mode is changed to the inter-company multi-disciplinary collaborative mode. Research may include they following: profession and experience of everyone, working background of the department and the impact of the risk of working attitudes, values, cultural training and their cooperation with other members. We determine the correct means of cooperation and rules according to these.

Requirement and Training on the Skills of Workers

In digital manufacturing technology systems, the request for people is not weakened, but greatly strengthened. The request is multifaceted on digital manufacturing technology systems. There are both the technical aspects, and the social aspects. On the technical side, he must master new knowledge and new technology related to all kinds of high-tech (computer, automation, information, etc.). And he also must have kinds of specific operational capabilities of programming, monitoring, maintenance, repairing, management, handling unexpected failures and so on. At the same time people must also have the ability of making the cooperation and coordination with others to solve the problems. If we want employees to have these requirements, we must strengthen education and training on workers and it obviously includes the above three areas. The skills requirements and education training of people have an important impact on the implementation of digital manufacturing technology system. These affects are the important content of the research and development and the applications of advanced manufacturing technology system. And they must take it into account.

Organization Management Measures and Organization Culture Environment

Since the system of digital manufacturing technology is also a social system, there is a social organization. Therefore the impact of cooperative work of people–people is not only the problem of its cooperation mechanism, skills requirements and training. Obviously the various management measures in organization and organization culture environment are also very important factors. They mainly include following aspects: the design of Business Process, the structure of the organization, the range and level of organization management, the evaluation methods of staff's working performance, incentives methods of working, the methods of leadership, the various informal relationships of the organization and the cultural enterprise. All of these are the important factors which very affected

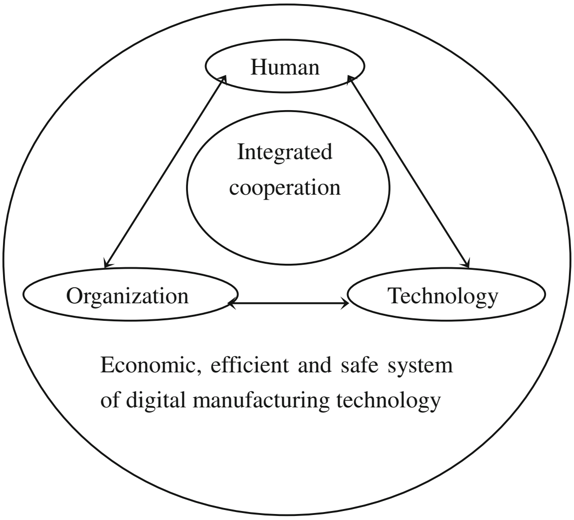


Fig. 7.14 Economic, efficient and safe system structure of digital manufacturing technology

whether people can together play the full role of advanced manufacturing technology.

In a word, a really economic, efficient and safe digital manufacturing technology system should be a high degree integration and coordination system formed by technology, people and organizations. In a digital manufacturing technology system, these three aspects are not isolated, but interrelated with each other. When we only begin from the viewpoint of system, and effectively make the integration synergies of them together, we can really reach the expectations of tremendous benefits on digital manufacturing technology systems. Therefore, if we see from the viewpoint of human factor, the pursuit of highly integrated and coordinated of technology, people and the organization on digital manufacturing technology systems is the direction of its development (Fig. 7.14).

7.5 MOT Mode Based on Cultural Differences and Ways of Thinking

7.5.1 MOT Based on Cultural Differences and Ways of Thinking

With the rapid development of science and technology and the integration of world economic, the continuous deepening of regional economic groupings, the global unified market is taking into formation; international operation has become the trend of the development of digital manufacturing enterprises. In this trend, the multinational companies are developing rapidly and expanding, and many digital manufacturing companies are also frequently making cooperation for specific market opportunities, and manufacturing resources distributed in different geographical are integrated rapidly, they are attached to the specific resources and environment of manufacturing industry, and they are guided by the strategy of region-specific knowledge innovation, and then they make mutual interaction gathering and development. All this has realized a wider range of the international division of labor and cooperation within enterprises and between enterprises, and so the "borderless" nature of economic development can be fully reflected, but the attendant is that there are cultural frictions leaded by different cultural backgrounds, and this issue is specially obvious for multinational corporations.

The word culture originated from Latin language (cultura), and its original meaning includes farming, education, training, development and respect and so on. The British scholar Taylor firstly studied the scientific concept of culture on social culture. He defined the culture as "a complex system including knowledge, beliefs, arts, ethics, law, customs and the ability and habit of individuals who are as members of society." However modern sociologists and anthropologists defined culture as "a system of common values and significance recognized by a social or some people, and this include the material specific entities of those values and significance." We take Oriental and Western culture as an example. Western culture with the representation of United States and Oriental culture with the representation of Confucianism are two different cultural systems. With the increased frequency and the expanded scope of the international exchanges, these two cultures have received the absorption and integration of each other's advantages. However, they still have distinct personality.

Culture is the product of human society. Cultural differences are also through the actions of organizations to influence the efficiency of its organization. The impact on organizational efficiency and organizational behavior can be analyzed from the decision-making, interpersonal relationship and communication and other areas. First of all the impact of cultural differences on the decision-making exists two possibility. Firstly, policy-makers are often to make value judgments on information from different cultural background on the basis of their own culture. What they can improve is the only aware of the possibility of errors and timely makes information amendment through feedback of decision-making. Secondly, people with different culture background exist in the decision-making groups. This makes some changes on the decision-making model. In the decision-making groups, people of different culture backgrounds are often in conflict because they hold different views. Now conflict is not necessarily a bad thing in today's viewpoints of conflict, of course, much of the conflict will spend a lot of time and resources of other organizations, thus it has a negative impact on organizational efficiency, but too little conflict; and it will make people addicted to the status quo without enthusiasm for innovation. Therefore, the different cultural patterns make decisions on different mode of communication, if the communication between the two sides comes from different cultural backgrounds, there exist communication barriers. Information sender is obliged to make the receiver getting correct understanding of the information. Therefore, the difference on this communication mode is difficult to avoid in the course of transnational business. Finally, the cultural differences make the groups communication in the domestic business changing from easy to existing significant obstacles. Language barriers or inaccurate translation makes misunderstanding; they lack understanding of the social environment and cultural self-awareness, and take their own viewpoints as others'; they lack understanding of each other's business environment, and lack of mental preparation for difficulties and problems; they have been unable to establish some trust coordination mechanisms.

In the collaborative management mode of R&D in digital manufacturing field, the forming of collaborative network is based only on the resource and technology factors. The differences between culture and area are not considered. The technology management of the digital manufacturing enterprises in the network will be affected by the differences. Therefore effective Cross-cultural management is very important in this situation.

Cross-cultural management business is good at making the local cultural ideas melting at the operating management. In the aspects of resource integration, product innovation, brand creation, marketing, transnational operating of enterprises is more accord with the localization. Through cross-cultural management, we should achieve inter-communication and mutual integration, and eliminate cultural barriers. In order to improve the management level of cross-cultural, digital manufacturing enterprises can do from the following aspects.

Enterprises must understand and coordinate the cultural differences. They should also consciously make decision to establish various formal or informal, tangible or intangible organizations of cross-cultural transmission and communication channels of cross-cultural.

Enterprises should host culture training, and establish high-quality management team. In the process of choosing managers, in addition to good professionalism, technical and management capabilities, they must also have flexible thinking, do not observe the old rules, have a stronger capacity of transference and emergency ability; at the same time, they must have a strong conception of respect and equality, able to accept different ideas, have strong spirit of cooperation. Preferably they have received different cultural education, and they can use different languages.

The enterprises also should establish common value outlook, establish the "fusion" corporate culture. In the enterprise, they should form a unity values system based on the understanding of cross-cultural and a corporate culture which can be recognized. And under these conditions enterprise should form a high efficient, cohesive leadership and their core skill; this determines the success or failure of the enterprise.

The enterprise should make continuously improvement of enterprise culture. Cross-cultural management business is not a permanent success, the purpose of the cultural integration in cross-cultural management of the corporate is to manage more effectively and improve the operational efficiency of enterprises. With the internal changes in the environment, originally established corporate culture may be the resistance of the development of enterprises. So they should establish a set of scientific feedback control system, according to business changes in the external environment and internal emerging issues, and constantly improve the existing business culture.

7.5.2 The Digital Marketing Based on Cultural Differences and Ways of Thinking

Today's world economy develops as an unstoppable trend toward global market integration, business survival figures, international business competitiveness. In the present economy environment, the Internet, the knowledge-based economy and high-tech are the representers. This can meet the rapid development of the new economy, and customer requirement is its core idea should be fully considered. In such a highly competitive, rapidly changing macro-environment, businesses need a new concept of marketing. This marketing concept should be able to effectively respond to the changing market, and can be more concerned about the customers' hearts and be able to set up a bridge between the side of supply and the side of demand. It can be said that digital marketing is emerged which follows this trend.

The so-called digital marketing refers to a marketing method which is at the help of the Internet, computer and communications technologies and interactive digital media. Digital marketing will as much as possible to make use of advanced computer network technology to seek new markets and develop new consumer excavation at the most effective and economical way.

Digital marketing is not just a technical means of revolution, and includes a more profound concept of revolution. It is the integration of goal marketing, direct marketing, decentralized marketing, customer-oriented marketing, two-way interactive marketing, remote or global marketing, virtual marketing, paperless transactions and customer participation marketing [24]. Digital marketing gives a new meaning to the mix marketing, their main function is to exchange information, purchase online, publishing online, electronic money, advertising online, public relations and so on, and it is the main marketing and development trends in the digital economy era.

7.5.2.1 The Characteristics of Digital Marketing

Because of making the use of the various attributes of digital products, digital marketing increases the number of new features on the basis of the transformation of traditional marketing methods.

It is characterized by integration which means it achieves the closer integration between the proscenium and backstage, this integration is the basis of rapidly responding customer requirements.

It is also characterized by personalized service. Digital marketing provides personalized products in accordance with the customer requirement, but also track each customer's sales habits and hobbies and recommend related products.

It has a greater space of choice. Digital marketing will be exempted from the constraints of the shelf and inventory, providing the stage of display and sales for great products, so that providing customers with virtually unlimited choice.

It has the characteristics of advantage of more low-cost. Publishing information online, the cost is limited, this will sell products directly to consumers, and the retailing session can be shortened. Anyone can independently obtain the published information and the scope of sales can be broaden, this promotion can save costs, thereby reducing costs and making products with price competitiveness.

It has the characteristics of more flexible marketing. The types, price and marketing means of products can make adjustments in a timely manner, according to customer demand, competitive environment or inventory situations. The network can transcend the limitations of time and space and functional areas of multimedia sound and light, it can also play the innovation of the marketing stuff.

It has the characteristics of optimization services. The one-on-one services of number marketing give customers more freedom to consider the space and avoid impulse shopping, you can compare more places before making a decision.

In addition, the digital marketing also has the characteristics of multimedia, cross-time, interactive, personalized, advanced, high efficiency, economic and so on.

7.5.2.2 Cross-Cultural Marketing Strategies

In the development trend of globalization in manufacturing industry, digital marketing and traditional marketing methods both face the problem of cross-cultural marketing. In the international market, enterprises should not only overcome the obstacles brought by cultural differences, but also should make cultural marketing using different cultural characteristics. Enterprises can adapt to the unique cultural characteristics of a certain ethnic or nation and cultural factors, take and use of a series of strategies and measures, and establish appropriate marketing idea, and establish a good image and reputation of enterprises and their products and build confidence on their target market, thereby, it can achieve the purpose of expanding sales.

Cultural differences strategies. That is to say, cross-cultural marketing must make objective analysis and evaluation on the culture of the target market, and identify cultural differences, as well as understand cultural differences.

Cultural adaptation strategies. This stressed that enterprise must respect for national customs, traditions, taboos and fulfilling way. Cross-cultural marketing must adapt to the requirements of the local culture, and it must be as far as possible to obey with local cultural characteristics. This policy applies to the country which has a strong local culture and be difficult to change, but it is more difficult to make implement.

Cultural cross-cutting strategies. It holds that culture changes with the changes of times, products and services may not to able to reflect their cultural identity at some stage, and it will eventually be accepted regardless of culture. The cause of cultural change is the results of economic exchanges between cross-border and inter-cultural, and it also comes with social development.

7.6 Summary

Digital manufacturing as a new manufacturing technology and manufacturing model, is a complex system related to many aspects. In order to establish better mechanism of market competition in the domestic and foreign aspects of digital enterprises, we must enhance and innovate the organization management model and management level of digital enterprises. Technical management involves technological innovation, planning and transfer of strategic technology, technological venture, technology management methods and human resources in technology management and social culture issues and other fields. This is a very good way to solve the management problems in digital manufacturing enterprises.

This chapter combined with the features of digital manufacturing enterprises, described the formation and advantages of collaborated R&D network, and analyzed the technology strategy management method and the application of human factors in digital manufacturing system, and proposed the management countermeasure on cultural differences which caused by the current international trend of digital manufacturing enterprises. Technology Management as the integration of digital manufacturing science and scientific management, will be constantly tested and get continuous improvement in practice.

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Chapter 8
Key Technology of Digital Manufacturing Science

The key technologies of digital manufacturing science are the technology system formed by a series of advanced digital technology, which are based on the basic theory of digital manufacture science, and take the optimized implementation of digital manufacturing system as target. They will realize various key links and system support platform of digital manufacturing system, and they are also an indispensable important part of digital manufacturing.

This chapter will discuss the key technologies of digital manufacturing science from five aspects, including various digital technologies in the product lifecycle, resources and environment technology facing digital manufacture, management technology in digital manufacturing process and system, control technology in digital manufacture, as well as digital recognition and integration technology in products, binding the key characteristic of digital manufacturing science's development.

8.1 Various Digital Technologies in Product Lifecycle

With the rapid development of information technology, manufacturing enterprises using information technology in production process increased rapidly, and the concept of "digital factory" which refers to use digital technology to reform the existing manufacturing model appeared [1–3]. The digital factory designs the brand-new value idea and digital environment for customers and enterprise staffs by using digital technology, discovers the new method which may create and capture profit and realizes comprehensive informatization and digitization in interior, exterior and the entire operation flow by using digital technology.

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8.1.1 CAx Technology Integration

8.1.1.1 CAD/CAE/CAPP/CAM

With the development of computer technology and the combination of computer graphics and mechanical design, the computer-aided design (CAD) system which takes the database as a core, the interactive graphics system as the method and takes the project analysis and calculation as the main body, and this system also obtains widespread application in the digital manufacturing domain [4]. CAD completes the product design including generalization to document establishment with the help of computer technology and graphics software technology. The CAD system precisely describes objects in two-dimensional (2D) and three-dimensional (3D) space in the form of digitalization, thus promoting the descriptive ability and productivity effectively in the process of production. With numerical control technology and NC machine tool, the production and development of CAD technology lay a foundation for the digitization and automation of manufacturing industry product design process.

Computer-aided engineering (CAE) is an extension of CAD technology, which carries out comprehensive engineering analysis, calculation, verification and simulation for part models in the process of manufacturing by using computer system, thus carrying out effective evaluation and giving judgment results for the function, performance and various index of product design.

In the process of product manufacturing, we transform the CAD design into information of manufacturing, process rules and make processing machinery to carry out effective combinations and sorting according to the scheduled procedures, and select the appropriate tools, fixtures and measuring tools to determine parameters such as cutting parameters, thus calculating the manoeuvring time and auxiliary time, which forms the computer-aided process processing (CAPP) technology. CAPP technology not only overcomes various deficiencies in traditional technology design and adapts to the demand of modern manufacturing process which is becoming automized and intelligent day by day, but also provides necessary technical basis for the realization of computer integrated manufacturing in digital manufacturing.

Computer-aided manufacturing (CAM) is the sum of all direct and indirect activities from the blank to the finished product completed in product manufacturing process using computer-aided technology [5].

We transform programming which includes manufacturing, detecting, assembling, dispatching as well as all related digital information facing product design, manufacture, management, accounting and etc., into data which may be understood by computer and shared fully in the manufacturing process, which formed the so-called CAx integration, causing the computer-aided technology to rise to a higher level [6, 7]. In recent years, the fast-developing computer network technology has provided on-line cooperative and cooperative platform for CAx integration. With the development of network technology and information technology

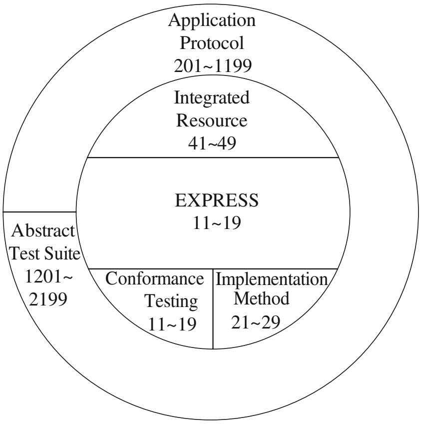


Fig. 8.1 The composition of STEP

as well as the exchanging and sharing between multimedia visual environment technology, product data management (PDM) system, distributed cooperative design and cross-platform, cross-regional, synchronous and asynchronous information, group collaboration and intelligent design between multi-enterprises, multi-teams, multi-people and multi-applications have obtained deeper research and entered practical stage.

8.1.1.2 Integrated Modeling of CAx System

On the view of information integration, integration refers to the integration of information's extraction, exchange, sharing and processing between various modules of CAD/CAE/CAM/CAPP, namely the whole integration of information flow [6]. Two basic elements are needed in order to realize the integration: CAD system which provides comprehensive data and unified product information model which conforms to some standards, and make the CAPP and CAM links gain the required information from this model and finally transform CAD model into manufacturing model. Data are transferred and exchanged unobstructedly between various modules of CAD and CAM, and the switching mode is the database interface which either formats file or database in accord with various standards.

STEP is a set of international standard concerning data's expression and exchange in product lifecycle. It has provided a intermediary mechanism not relying on concrete systems to support the integrity and consistency of integration and exchange between different computer application systems. It is not only suitable for the intermediary document exchange, but also the foundation to realize the long-term archive of the sharing product database and product data. STEP's standard structure is shown in Fig. 8.1, whose core part is the scope in which the middle circle includes, and it consists of the formalized modeling language, Express language standard, STEP implementation, integrated resource and uniformity testing criteria. The outer layer indicates each application agreement of the

STEP standard as well as the abstract test suite which is regulated by STEP standard to test whether a certain application agrees with the STEP standard. STEP uses the formalized data standard language Express to describe product information. The integrated resource has provided the resource component expressed by product information. Similar information in different applications are expressed by resources component, and the resources component supports special application through revising and increasing restraint, relation and attribute. The integrated resources defined the global information model of product data. The application agreement defined in STEP meets the information requirements of specific application through interpreting integrated resources.

The integration of many CAX systems is based on STEP. STEP supports integrated product model data, including geometric information, such as curve, surface, solid, shape features as well as non-geometric information such as tolerance, materials and surface roughness information, etc. It includes all of the information needed in product lifecycle (design, manufacture, quality control, detection and maintenance, etc.). However, STEP itself is becoming substantial and mature gradually, so we use the technical line of “characterization” to the solid modeling system, thus we use the existing CAD resources and create component information model which meets the need of integration in solid modeling system through expanding characteristic definition function, which is an effective way of CAx integration.

8.1.2 Digital Equipment and Digital Processing Technology

8.1.2.1 Digital Equipment Technology

Digital manufacturing system is composed of various independent devices. Devices are the basic component of digital manufacturing system, including processing devices, instruments, tools, material processing devices and transport system. These devices are arranged and connected in a certain way, completing together the operations of processing, transportation, testing of raw materials and intermediate products. These devices are called digital devices which are the digital description of physical devices and are also the mapping of physical devices in information domain. It should manifest the consistence between functional characteristics, geometric characteristics and physical devices. Typical digital devices include numerically-controlled machine tool, machining center, industrial robots, digital measurement and detection devices, rapid prototyping devices and so on.

1. Digitized modeling of equipment

The digital equipment model should have the following functions: the digital expression of physical equipment’s geometric features, which expresses the 3D solid model, voxel characteristic and material textural characteristic of physical equipment; the precise expression of system operation which expresses the kinematic and dynamic information of equipment behavior in the form of animation and the precise estimation of system's performance, reliability and sensitivity.

In order to realize the above functions, we must carry out the functional characteristic and geometrical characteristic analysis of the physical devices. The functional characteristic describes the digital equipment's control attributes, and the geometrical characteristic represents its shape attribute. Therefore the physical devices are generally divided into hypothesized controller and geometric model.

As the image of physical device controller, virtual controller receives control information from exterior and the feedback information of virtual sensors, carries out the information processing and judgment, outputs decision-making control signal, changes the position and the posture of driving-related geometric model and creates digital object behavior.

Geometric model is the description of physical equipment's shape characteristic, and we produce equipment's stereoscopic model and virtual scene by using virtual reality technology, in order to make users have the sense of immersion. Geometric model represents physical equipment's shape, and it expresses physical equipment's behavior through receiving the data stream of virtual controller. The data actually represents the angle of electrical machinery, displacement of workable, the movement of object on transport band, the time when movement occurs and terminates and so on.

2. Digital equipment's networking

The computer network has provided the possibility for digital equipment information's transmission, manufacturing resources' sharing and manufacturing system's optimized operation, and laid the foundation for the synthesis automation of remote-controlling network manufacture and enterprise. We formed the digital equipment network system with the support of computer, network and communication technology, and supported enterprise integration through information technology, manufacturing technology, production management and the integration of manufacture and control, making enterprises realize digital manufacture.

The digital equipment network is proposed on the basis of computer network. All kinds of information in the system are transmitted by network. The TCP/IP architecture is the architecture used in Internet, and is very important architecture in computer network. In the current market, a large number of network products use TCP/IP protocol, almost all the workstations are equipped with TCP/IP protocol, and the TCP/IP protocol has naturally become a standard of computer network, commonly known as industry standard. Therefore, we generally use TCP/IP network architecture in digital equipment networking system. In addition, we should consider from four aspects such as real-time, reliability, high performance and large amount of data transmission when choosing the communication protocol of digital networking system, in accordance with digital equipment's characteristic and digital manufacture's performance requirement.

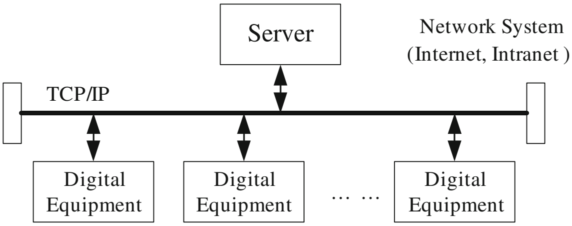


Fig. 8.2 The composition of digital equipment networking system

At present, the digital equipment networking supported by client/server technology has become possible on the basis of TCP/IP protocol. A typical composition of digital equipment system is shown in Fig. 8.2. In the system, the client sends specific requests or commands directly to the server, and then the server returns information to client viz., realizing information transmission between digital devices.

The server has a powerful network communication function, which obtains component data information and processing control information from network, releases processing status information to network and also manages tasks of local processing and remote processing. In the server's application layer, we design four main threads: communications management thread, NC code explanation thread, interpolation thread and processing control thread.

Digital equipment networking impels manufacturing industry to achieve digital manufacturing technology process, promote the integration of digital design, manufacture, and management on product, and promote the development of enterprise digital manufacturing technology on aspects of the holistic solution of digital manufacturing, production data collection, production process monitoring, enterprise integration, equipment remote fault diagnosis and maintenance service, realization of reconfigurable manufacturing system, and so on.

8.1.2.2 Digital Processing Technology

1. Digital processing process

The machining process in digital manufacturing environment is the process of the interaction of manufacturing equipment object and manufacturing product object,it appears as the alteration of object microstate, which includes both the change of object's geometrical shape and size, as well as the change of location parameter, direction parameter and physical parameter (strength, deformation, temperature and so on), and it is a compound controlled behavior [1].

The research of digital processing contains two aspects: the first one is tool path simulation that is, to establish the 3D model of parts, tools and machine tools, make cutting tools process along the track established by technology and discover in real-time and evaluate the interference situation of cutting tools and jigs; the second one is to evaluate whether the technological parameters described in

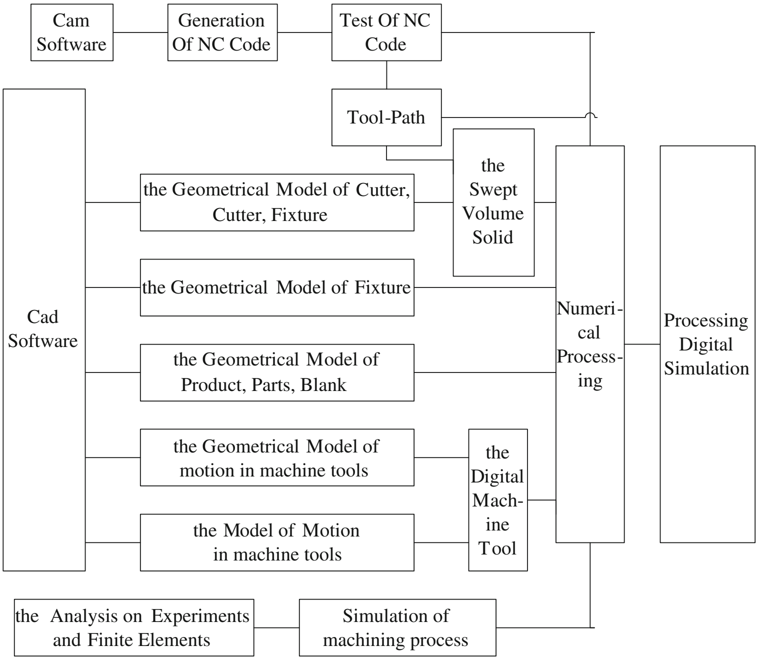


Fig. 8.3 The composition of digital processing

processing technology are reasonable, such as feeding depth which will cause flutter and destroy tools and parts, and a high-feed rate would lead to unacceptable surface roughness and so on. Under the digital manufacturing environment, we combine the physical effect models which expresses the cutting with the solid models and which expresses processing geometry, and expresses the machining process completely. At the same time, the digital description and system integration of physical model and entity model will be able not only to evaluate the existing technological process, but also provide powerful method for the innovation and design of new technology.

Digital machining process is shown in Fig. 8.3. Digital machining process consists of the moving process of machine tool model and the deformation process of work model under NC order-driven. In the process of carrying out each section of NC instruction, the cutting tool driven by lathe models will sweep certain volume in the virtual space, moving from the beginning to the end position. Generally we call the space shape enveloped in the moving process of cutting tool as “swept volume solid”. We obtain the change of work piece’s shape in machining process and remove the simulation material after the Boolean operation of work model and swept volume solid. The calculation of swept volume solid with machine tool and jig model tests the collision and interference in machining process.

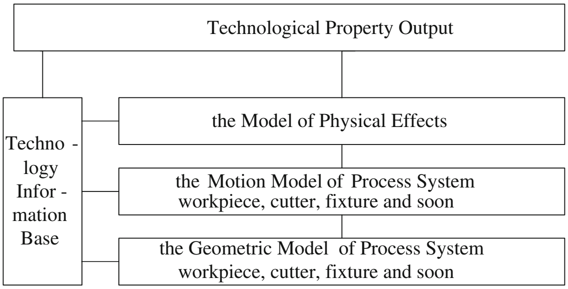


Fig. 8.4 The structure of digital processing process emulation

In order to truly reflect the processing accuracy and surface quality condition of virtual parts, we should create physical effect model of machining process. In digital manufacturing process, the detail design stage of product is actually the simulation of product machining process, that is, the analysis and forecast of various information in technology system which is composed of machine tools, work piece and cutting tools, including geometric simulation and physical simulation. Geometric simulation includes the verification of tool path and verification of interference between work piece, machine tools and cutting tools; physical simulation contains the analysis and forecast for various physical factors, such as cutting force, tool wear, cutting vibration, cutting temperature, workpiece surface roughness and so on. There is a close loop between the two, and the structure of digital machining process emulation is shown in Fig. 8.4.

2. The tool compensation in numerical control processing

The numerical control processing in digital manufacturing has significant advantages of high-processing precision, high efficiency and stable quality. However, in early days, there was no concept of compensation in numerical control processing, which makes programers to consider the relative relation between the theory route and actual route of cutting tools when programing. This method is easy to make mistakes and cause programing efficiency to become extremely low.

The plan of tool compensation was proposed against these drawbacks and has well solved the problem. Using the method of tool compensation reasonably, using cutter radius offset function freely and setting the right tool radius to compensation value is an effective way to enhance digital manufacturing processing precision and ensure stable operation of the system.

The tool length compensation and tool radius compensation are the two most common compensations:

The tool-length compensation. It is mainly used in the following two situations: cutting tools of different sizes that process components of the same outline and size, or the size of the cutting tools which are used to do the same changes because of changing cutting tools for re-adjusting or processing attrition. When cutting tools of different size process components of the same outline and size, we should assign the program coordinate at first and complete the "to zero" with the standard cutting tools to determine the position of programing origin in machine tools. Other cutting tools measure the deviation by comparing the standard cutting tools with tool auto-checking instrument and establish the parameters list of tool length compensation, providing the basis for tool length compensation in the machining process. The tool length compensation in the machining process is realized through carrying out G43, G44, G49 and the H instruction: The G43 instruction means the addition of compensation quantity in register and the terminal coordinates of program instruction, on the contrary, the G44 instruction means the subtracting of the two; The G49 instruction is used to cancel tool length compensation and the tool compensation quantity is deposited into register where the H code assigns.

The tool radius compensation. It is mainly used in the application for cutting tools of milling cutter type. The cutting tools' center should offset a certain distance to work piece's inside or outside when using milling cutter to process work piece's outline inside or outside, and this offset is the tool radius compensation. All cutting tools' real radiuses are placed in biasing register of tools radius. Processing system automatically calculates the cutter center track according to program and tool radius and carries out part machining. The program will automatically modify the value in register to compensate. The tool radius compensation in machining process is realized by G40, G41, G42 and D instructions: the G41 instruction refers to the left compensation of tool radius, and the G42 instruction refers to the right compensation of tool radius; the G40 instruction is used to cancel cutting tools' radius compensation; and the D instruction is used to choose biasing register of tool radius.

8.1.3 The Technology of Digital Maintenance and Diagnosis

8.1.3.1 The Technology of Digital Maintenance

The digital maintenance of product is an important content in digital manufacturing domain, which studies the basic technical questions to solve digital quantitative expression and visible expression of product maintenance and establishes platform for maintaining networking and digitalization. It is the supporting technology based on the network products remote maintenance and failure diagnosis system, as well as on the basis of building the system on product's maintenance guide.

The key technology of product digital maintenance is shown in Fig. 8.5. It is shown from this figure that the key technology of product digital maintenance mainly contains the following aspects:

The product digital general platform facing maintenance. We should use CAD and virtual design manufacturing technology and study the design technology of product 3D digital solid model to establish product digital general platform which faces maintenance.

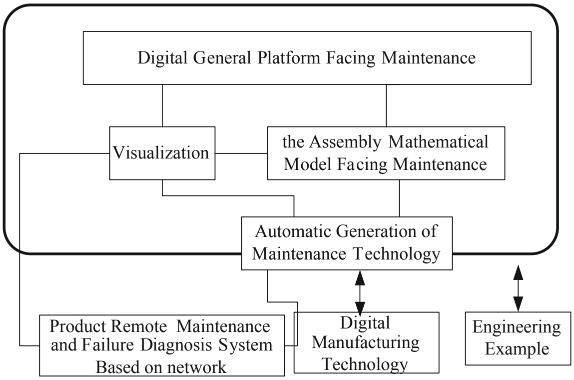


Fig. 8.5 The key technology of product digital maintenance

The mathematical model facing product assembly maintenance. We should study the mathematical model of product assembly according to the maintainability of product, the economy of maintenance simulation and the optimization of maintenance time and cost. It mainly includes the digital indication of product's structure relationship, assembly relationship and dismounting limited constraint relationship.

The visible technology of product structure and assembly. It includes the visible technology for expressing product's structure relationship, assembly relationship and dismounting sequence.

The automatic generation technology of product's maintaining technology. We study the automatic generation technology of product maintaining technology as well as guide and maintain work according to failure.

To sum up, the product maintenance digital technology is based on product design theory, which faces maintenance and assembly, uses CAD and virtual design manufacturing technology and studies design theory and method of product digital general platform which faces maintenance. According to the expert knowledge and product characteristic, it studies the digital expressing method of the structure relationship, assembly relationship as well as dismounting limited constraint relationship of product and establishes mathematical model which faces product assembly maintenance based on neural network principle; it uses the virtual environment technology, multimedia technology and object-oriented method to study the visible technology for expressing the structure relationship, assembly relationship and dismounting sequence of product; it studies the automatic generation technology of product maintaining technology with the help of CAPP technology according to failure. Figure 8.6 shows the structure of product digital maintaining technology.

8.1.3.2 Remote Failure Diagnosis Based on Network

Failure diagnosis is an important part of digital product maintenance system. The failure diagnosis of remote equipment is one kind of new diagnosis technology which is composed of traditional failure diagnosis technology, network

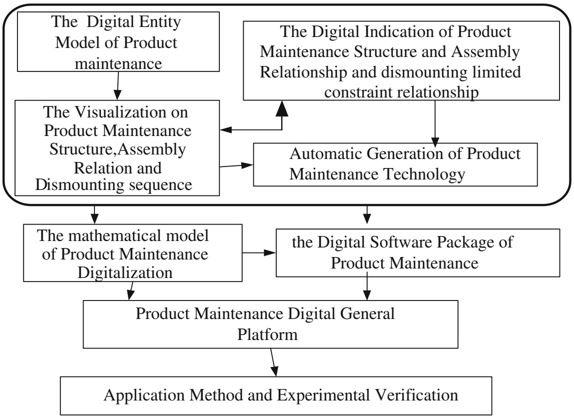


Fig. 8.6 The structure of product digital maintaining technology

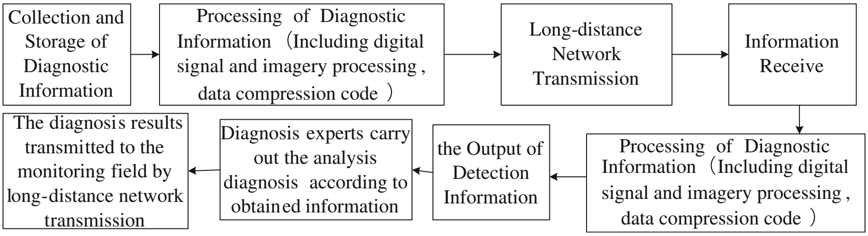


Fig. 8.7 The function of remote failure diagnosis system

technology, computer technology, as well as modern communication technology. When equipment in the industrial field shows fault symptom or goes wrong and maintainers on the pot or failure diagnosis system cannot make a diagnosis, it will promptly carry out the diagnosis and give the diagnosis result by experts or failure diagnosis system of remote diagnosis center or other advanced diagnostic technology.

As is shown in Fig. 8.7, the major technology used in remote failure diagnosis system includes:

The acquisition of equipment fault information. In order to diagnose equipment fault information, we should obtain information related to failure. Information is an important basis for providing people with judgment or state recognition, which is the carrier of information. Signals which are obtained from diagnosis have vibration, sound, force, temperature, ultrasound, oil pollution and so on.

Data compression technology. Because the information obtained is multimedia information, while multimedia information occupies wide frequency band, it has great consumption and causes high operation cost, we must use digital signal. However, after the sound and images are digitalized, the volume of the data also becomes very large, so we must seek a more effective signal compression algorithm under the premise of ensuring signal quality.

Data transmission technology. Fault information includes data signals, video signals, audio signals and control signals and these different types of signal have different transmission characteristics and transmission requirements. In addition, these signals are transmitted by means of communication network, but there are various communication networks, and not all transmission channels are able to meet the transmission requirements of fault signal after compression. In order to meet the requirements, that transmitted images have better clarity and dynamic property of fact, transmission network must be able to provide adequate network bandwidth and transfer rates.

Equipment fault diagnosis technology. Because of the diversity of equipment fault and the complexity between fault and symptom, the characteristic that equipment fault diagnosis is an explorative process was formed. The traditional fault diagnosis method is to use various physical and chemical principles and means to directly detect fault through various physical and chemical phenomena associated with fault; Secondly, using the corresponding symptom of fault to diagnose fault. As there is no simple relationship between fault and various symptoms, the use of symptom to carry out fault diagnosis is usually a process with iterative exploration and solution.

Remote diagnosis system includes the centralized online monitoring system and distributed online monitoring system. We use several central computers as diagnostic server and establish status monitoring point on key equipment. We obtain the operation information of equipment through sensors installed on the monitoring points and are input into the on site monitoring computer after signal pretreatment and conversion, then carry out unitary transform to signals and realize continuous real-time equipment statistical data collection, thus providing remote technical support and guarantee for enterprises in remote analysis and diagnosis center with strong technical force. Any monitoring system can request the service requirements through connecting the monitoring points into a complex monitoring sensor network by network. The heterochthonous diagnosis and service center provide various services and return diagnostic information after receiving the request service information. At the same time, remote service center also directly obtains equipment condition signals and historical data of current monitoring points from network, thus forming a complete monitoring system. Once the important equipment shows a hidden trouble or a fault, we mobilize all of the diagnosis resources on network in a short period of time to achieve the early diagnosis and timely maintenance on equipment fault.

8.1.4 Digital Logistic Technology

Material flow, information flow and energy flow are the three basic “flow element” existing in digital manufacturing system. Among them, material flow occupies most of the production time in the life cycle of digital products, which are closely linked with processing production efficiency, equipment utilization and product quality, thus determining the production cost and market competitiveness of products.

Logistic Technology has experienced three development stages of traditional storage and transportation logistics, logistics system optimization and information logistics. In order to achieve the information technology, automation, networking and flexibility of modern logistics, it is needed to integrate the digital information technology into logistic management system to guide the planning operation of product logistics [8, 9]. Under this situation, the concept of digital logistics produced, which is not only the driving factor of modern logistic development but also an important part of product lifecycle in digital manufacturing.

8.1.4.1 The Concept and Key Technology of Digital Logistics

Digital logistics [11] refers to the expression, management and control on object and behavior involved by logistics by synthesis application of digital technology, with the support of technology of computer emulation and virtual reality, artificial intelligence, computer network, database and multimedia [9].

The key technologies of digital logistics [11] mainly contain:

Logistic informatization. It was mainly manifested as the commercialization of logistic information, the encode and data base system of logistic information collection, the digitalization of logistic information storage, the computerization of logistic information processing, the real-time performance and standardization of logistic information transmission and so on. Related technology includes bar code technology, network communication technology, database technology, electronic commerce technology, enterprise resource planning, etc.

Logistic intelligence. It refers to using intelligent integrated technology, making logistic system have the ability of thinking, perception and reasoning judgment, thus resolving the problems in logistic operation. Here the meaning of intelligent integration mainly includes two aspects: The first one is soft intelligence which manages and plans logistic behavior, namely intelligent optimization integration technology; the second one is the hard intelligence of logistic equipment, namely intelligent ability logistic equipment has itself.

Logistic Virtualization. It refers to the description and expression on essence of actual logistic process. Its foundation is to use computer emulation and virtual reality technology to express, model and emulate all effective logistic behavior and factors, and to depend on group cooperative work on computer to establish 3D full-digital model of the whole logistic process, in order to realize the analysis and evaluation of logistic process in logistics design stage. Logistic virtualization aims at evaluating risk in advance, real-time planning and scheduling as well as global optimization.

The key technologies of the above three aspects are not separate from each other; however, they complement each other and mutually promote. The integration of logistic informatization, intelligence and virtualization formed the basic framework of digital logistics.

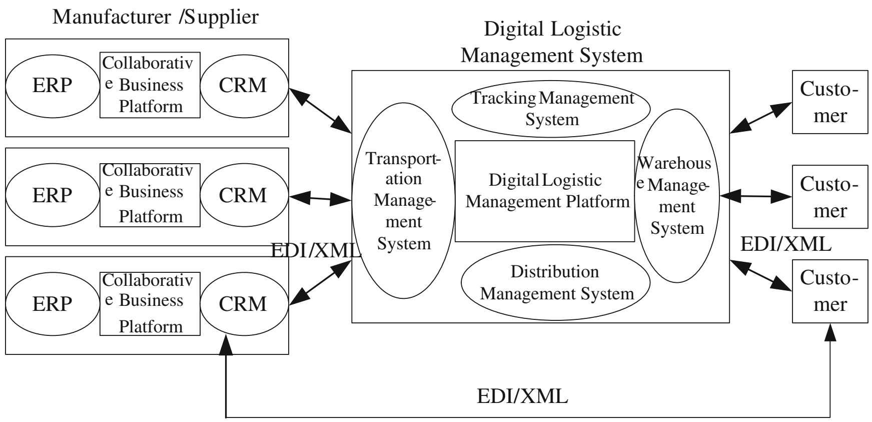


Fig. 8.8 The structure of digital logistic system [11]

8.1.4.2 Digital Logistic Supporting System

Digital logistic supporting system is the integration of various advanced information technologies, which is applied to different segments of the entire system to constitute a comprehensive digital logistic operating system and provides supporting service for logistic operation [10].

Figure 8.8 described a typical digital logistic supporting system which includes [11]:

Digital logistic management platform. The platform realizes the logistic operating digitalization between enterprise interior, alliance partner and customer, which carries out intelligent and digital management (DM) to enterprise logistic process through the fast and accurate transmission of data between various types of members to enhance the management capacity and efficiency of enterprise logistic operation.

Warehouse management system. The system improves traditional warehouse enterprise and carries out effective management and disposal to goods. Realizing the electronization of warehousing work flow is the most important function of the system.

Transportation management system. The system is the logistic transportation management software which is designed by an overall measurement, analysis and standard haulage operation process and the use of modern logistic management method based on network environment. The system is composed of functional modules such as negotiation, valuation, scheduling, tracking, commission, documents management, accounting management, operation optimization and so on, which assists the managers to carry out logistic resource distribution and job scheduling. In addition, the system also has a good expansibility to carry out customization design for customer's individual demand.

Distribution management system. This system has functions on delivery of central work flow as well as logistic management. These functions contain cross-database management, automatic replenishment, order picking, order plan, and, packaging, inventory control, distribution scheduling arrangement, route optimizing and tracking excepting basic warehouse management.

Tracking management system. The system has the functions of GIS data management as well as GPS satellite navigation and positioning, providing users with services of inspection supervision and management scheduling.

The advantages of digital logistic supporting system based on network are as follows; the first one is that it uses the existing condition and facility on the foundation of non-repeated construction, carries out effective integration to logistic resources through computer network technology and consolidates the relationship between various logistic functions and logistic formations, thus breaking adverse effect brought by traditional logistic function partition; the second one is that each professional logistic enterprise establishes long-term cooperative relationship with a number of logistic agents based on this system. The professional logistic enterprise operates the traditional logistic business as usual without network logistic business. When agents put forward logistic request through network, we will quickly establish logistic supplying linkage and provide related service. It is not only beneficial to enhance the utilization of idle logistic resources, but also favorable for the smooth transition of small-medium logistic enterprises to modernization, networking and informatization.

8.2 Resource and Environment Technology in Digital Manufacture

As an important factor in manufacturing activities, manufacturing resource runs through the entire process of production. The distribution of manufacturing resource on the whole is uneven and is highly dynamic. Therefore, we must realize the resource integration and sharing of enterprise on design, manufacture, assembly, sales, management and other related links, in order to achieve optimal allocation of resource, continuously improve the efficiency and level of enterprise management, and improve the economic efficiency and core competitiveness of enterprise. We use modern management science and information technology to establish modern information network system through developing and establishing the manufacturing resource platform of enterprise. We realize the integration of logistics, capital flow, information flow and work flow and the dynamic management, scheduling and optional allocation on manufacturing resource of enterprise's design, manufacture, assemblage, sales, management and other related links through information's fast circulation and effective services.

8.2.1 Resource Organization and Management Technology

8.2.1.1 The Connotation of Digital Manufacture Resource

Manufacturing resources refers to hardware and software which are used to all production activities during product lifecycle, including machining device, materials, personnel, management systems, and etc.

In modern manufacturing system, manufacturing resource has the following characteristics [12, 13]: the integrating and sharing of geographically distributed manufacturing resource.

Manufacturing resources may be production equipments Design resources, also it may be management resourses. These resources belong to different enterprises, and even though belong to the same enterprise they also may be at different locations.

Autonomy and multiplicity. Autonomy refers to the owner of manufacturing resources has authority to utilize and allocate these manufacturing resources. And multiplicity refers to the non-owner of manufacturing resources is able to utilize these manufacturing resources with an agreement with the owner.

8.2.1.2 The Sharing of Digital Manufacture Science

1. The manufacturing resource information sharing based on STEP

Intermediate document mechanism. The Intermediate document realization form defines a clear set of text encode, and it is used to exchange the complete set or part of product data expression, whose document is ISO 10303-21, and it is the most common form of realization. Intermediate document uses the explicit text binary coding (the current definition of exchanging structure realization is to show the text coding document structure) to provide the read-write of the product data description in application agreement, namely the document switching mode. The process of data exchange realized by the form of medium document is shown in Fig. 8.9.

Database mechanism. In the integrated environment of digital manufacture, we need to transmit information between CAD, CAPP, CAM, CAE and other systems. Due to the large volume of data transmission and complex structure, it is very difficult to meet the requirements by using file switching mode, so we need to use the database. This is a higher level of exchange, including the use of database management system for data access to meet the requirements of data sharing. The application program uses the standard language of database management system (such as SQL) or standard data access interface (such as SDAI) to access data. The other functions of database management system, such as digital dictionaries, are also used to explain EXPRESS model for application system. The constraint defined on the conceptual model should also be simultaneously defined here. The exchange realized the simultaneous access of all users in multi-application

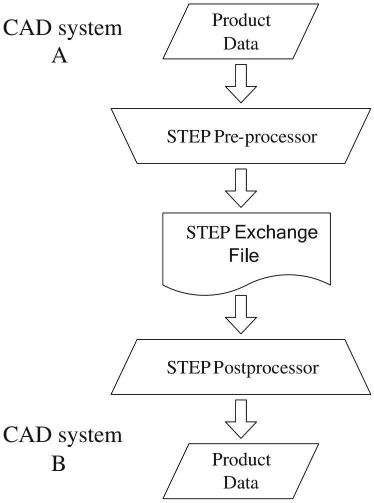


Fig. 8.9 The exchange process of STEP neutral document between CAD systems

procedures on data, that is to say, it realized the data sharing. The development goal of this layer is to solve questions of multi-enterprise, multi-platform, multi-storage mechanism and various network managements [14].

Standard data access interface mechanism. SDAI is the standard application programing interface of STEP. It stipulated the method to realize the standard data access interface of STEP. Through the interface, application procedure accesses STEP data defined by EXPRESS language.

We use STEP application software development environment ST-Developer of STEP TOOLs to develop STEP application procedure, establish and manage the information model described by EXPRESS language and carry out conformance testing to STEP data. SDAI C++ provided a development environment in the form of library function. We create a STEP database to operate STEP data stored in database and sequential file in this development environment. The development library uses ROSE C++ Class Library to transform each entity of EXPRESS model into C++ class, and application procedure reads the attribute data quickly. EXPRESS model creates C++ class and SDAI data dictionary through EXPRESS2 C++ and EXPRESS2 SDAI. We use database adapter, ST-Database adaptors, to complete the bidirectional conversion of STEP neutral document and database data.

Knowledge base mechanism. Knowledge base mechanism exerts complex restraint to the STEP model and deals with model and related data by artificial intelligence methods. In addition, it provides more advanced tools to implement STEP. The development goal of this layer is not only to complete the operations which all the traditional database management systems complete, but also have knowledge and rules-driver ability. Moreover, it makes the integrated database management system in an enterprise easier to manage. This layer is the product definition and development stage, which has not provided standard interface. The literature [15] takes rolling bearing as the object and takes the STEP standard as

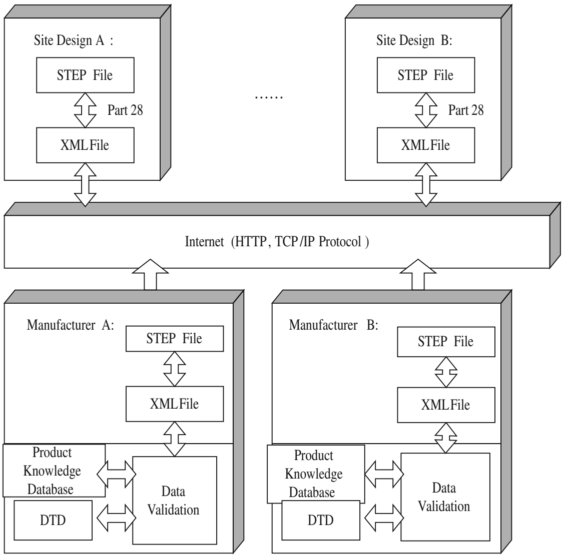


Fig. 8.10 The realization of product data sharing and exchange based on network

the foundation to establish the rolling bearing's EXPRESS information model. It proposed the three layers of product modeling and the characteristic description method of product model, and provided the foundation for the information integration of product model and the fast utilization of knowledge resources in design.

The above four kinds of realization mechanisms have their own characteristics. The four different kinds of access mechanisms meet the actual requirements on product data in manufacturing domain from different degrees.

2. The manufacturing resource information sharing based on network

As is shown in Fig. 8.10, the synchronizing manufacturing units, such as manufacturer A, registers and accesses product data through the internet. The design unit of network manufactures outputs product data in the form of XML. The data in the design site A shown in the figure must be transformed into the form of XML and saved in the network server. Each design unit uses its specific CAD system to cooperate mutually with different part's design unit of the same product.

Different CAD software outputs STEP document through AP203. The data transducer transforms these STEP documents to the form of XML. Meanwhile the data transformed must be effective. The CAx users in network manufacturing browses XML documents in the network and obtains product data which different design departments provide. They also request the design department to revise the product data to meet their special needs. The product data sharing and exchange process is shown in Fig. 8.11.

Through the use of STEP as an intermediate format to exchange different document forms of CAx systems, the collaborators in network manufacture

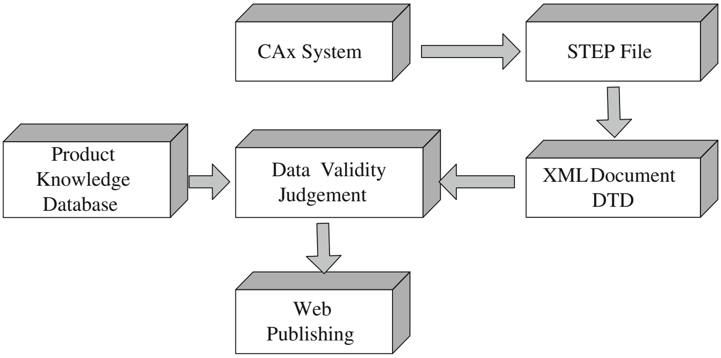


Fig. 8.11 The model of product data exchange process

quickly access the data through Internet. The EXPRESS language of STEP and the DTD of XML are the same. The newest STEP development is the mapping from the application agreement to XML. This new technology will be the best way to run synthetic data on Internet.

8.2.1.3 The Integration of Digital Manufacturing Resource

1. The product information integration base on XML

Because it is very difficult to meet the requirements of large number of heterogeneous information integrations in networking manufacturing system according to the information integration of hyper text markup language (HTML), the International Organization for Standardization W3C introduced an extendible markup language. It is a kind of tidy SGML language, which focuses on the common method of describing the content on web pages and processing web data directly to realize the sharing and interaction of information on Internet. The strategy of product information integration base on XML is shown in Fig. 8.12.

The integration strategy has the following characteristics:

The XML document mutual information is used either between the enterprise application systems, or between the enterprise application system and user, so we only need to establish the mapping from STEP to XML and need not establish other transformation, thus reducing system redundancy.

System information integration is bidirectional, that is to say, enterprise application system not only converts the product data expressed by STEP to HTML document for user queries, but also stores the product information which is converted from the XML document provided by user in the database to realize real information integration.

Because manufacturing domain describes manufacturing system integration information in accordance with unified markup language, and information interaction is realized based on XML document between different enterprises,

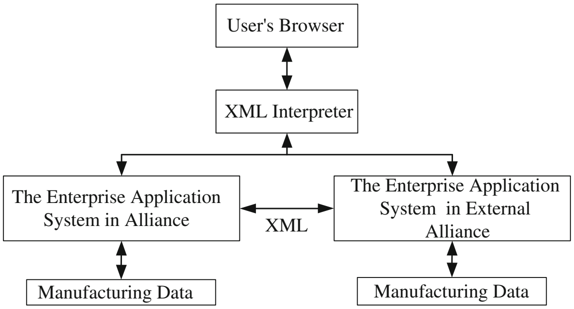


Fig. 8.12 The strategy of product information integration base on XML

enterprises within and outside the union realize the information integration based on XML conveniently to overcome the difficulty of system information integration between unions.

2. PDM system and its integration

In recent years, with the expansion and extension of PDM and ERP's function, PDM has exceeded the limit of product design departments. It supports the enterprise-wide business processing and the management of information, as well as document about product. At the same time, ERP has begun to support the engineering department. The ERP seller continues to develop ERP which includes PDM function, such as parts classification, configuration management, expanded parts information, document archiving, process workflow and procedure management which are all included in the ERP. So the two systems have extended and expanded the scope, and the superposition part presented. The biggest superposition part existed in the user statement of entries and the related data on BOM table. The possibility of conflicts will exist when the two independent systems try to protect the key data of their respective version. Therefore, the integration of the two has become an inevitable trend.

At present, the integration patterns between PDM and ERP mainly have the following three kinds:

The package integration of application system. The application tools access data document with corresponding format from PDM system, which is called encapsulation. However, we directly activate application program by document with corresponding format. We enhance PDM's scalability and the integration capability with ERP system or other application systems through CORBA standard instituted by OMG.

The two-way transmission of document. With the effort of PDM and ERP system's developer, nowadays the most advanced PDM system carries on seamless two-way transmission between product data and related document data as well as ERP system, which protected the intercourse of product data between the two systems. When we design new products or modify old products, the related data will be automatically transmitted to ERP system, and the related details in ERP system will be transmitted to PDM system in the consistent and latest form.

Through mode. It is very effective to integrate independent PDM and ERP system through file transfer, which contradicts the principle that data must be stored in the same location to keep all documents clear and avoid data inconsistency. Because the bottom layers of PDM and ERP systems are all relational databases, and the data about product is stored in each domain, the so-called through mode is that the two systems directly carry on operation to the data of database and exchange data.

The integration of PDM, ERP systems as well as workshop control system realized the information transmission from design department to production management department and manufacturing department, which ensured the continuity and integrity on the whole information of enterprise.

8.2.2 Manufacturing Grid: the Management and Scheduling of Resources

The global market competition and information technology as well as the rapid development of grid technology have fundamentally changed the manufacturing environment. The mode that enterprises only rely on internal resources to carry on production has been difficult to adapt to the existing development. Manufacturing grid is a kind of new effective way and solution produced in such environment. Enterprises in manufacturing grid environment use the M-Grid collaborative manufacturing platform to establish manufacturing network which faces the whole world and achieve the TQCSEF goal [16].

8.2.2.1 Manufacturing Grid

Manufacturing grid is a kind of specific materialized form of modern integrated manufacturing and agile manufacturing mode in global and networked economic environment, which is the supporting environment to realize the integrating and sharing on geographically dispersed and isomerous resources of individual enterprise and support resource optimization recombination and collaborative manufacture between enterprises. Its approach is to use grid technology, information technology and computer and advanced management technology, in order to overcome the obstacles which the distance in the space brings and achieves the connectivity of all of the geographically dispersed manufacturing resources through grid (the next generation grid). It provided all kinds of manufacturing services for users in a transparent way by the encapsulation and integration of various manufacturing resources and the shield of resources' isometry and geography distribution, which allow the users to use the resource services in manufacturing grid conveniently like using local resources. Its objective is, to the maximum extent possible, to achieve the integration and sharing on design, manufacture, information, technology, manpower, service, application system, calculation and other resources of enterprise and society, as well as the optimal operation of logistics, information flow and value flow in collaborative manufacturing process. The other objective is to provide the support environment for the complementary advantages cooperative enterprise with the basic characteristics of digitalization, flexibility, agility, distant service and visualization and realize various coordination (design collaboration, manufacturing collaboration and business collaboration), so that the enterprises group based on manufacturing grid running environment can produce the high-quality product which meets the need of market with the lowest cost, the shortest development cycle, the best service and the best flexibility [17].

8.2.2.2 The Architecture of Manufacturing Grid

The architecture of manufacturing grid is divided into the technological facility layer of manufacturing grid, the middleware layer of manufacturing grid and application layer of manufacturing grid, which is shown in Fig. 8.13.

The technological facility layer of manufacturing grid. It is the basic architecture of manufacturing grid, which supports all kinds of heterogeneous resources in product lifecycle, including designing resource, manufacturing resource, management resource, computing resource, storage resource, software resource, equipment resource and so on. All resources are connected to the manufacturing grid in accordance with the requirements of manufacturing grid interface.

The middleware layer of manufacturing grid. It manages the manufacturing grid resource and provides user interface in manufacturing grid, with the following modules:

The resource encapsulation and service operation management module. It encapsulates resource which is connected to manufacturing grid, provides the unified interface for upper layer and manages the service operation;

The service component module. It includes various management modules which are related to manufacturing characteristics, such as resource sharing control module, resource scheduling module, cooperative control module and integrated control module, in order to meet the requirements of manufacturing industry;

User support module. It includes user interface support and user programing support, which mainly tries to meet the calling requirements of application layer;

Safety management module. Various safety facilities in grid provide the security mechanism of manufacturing grid, such as functions of security authentication, multiple authentication of safety identity, communication encryption, protecting private key as well as safety commission and single sign-on.

The application layer of manufacturing grid. It includes all applications based on the product life cycle, such as material procurement, product design and manufacture, product assembly, logistic management, sales and service and so on. All of these applications have unified interface and transparently use the resource integrated on manufacturing grid. The middleware layer shielded the heterogeneous nature of resource, provided the unified application interface and completed the safety management.

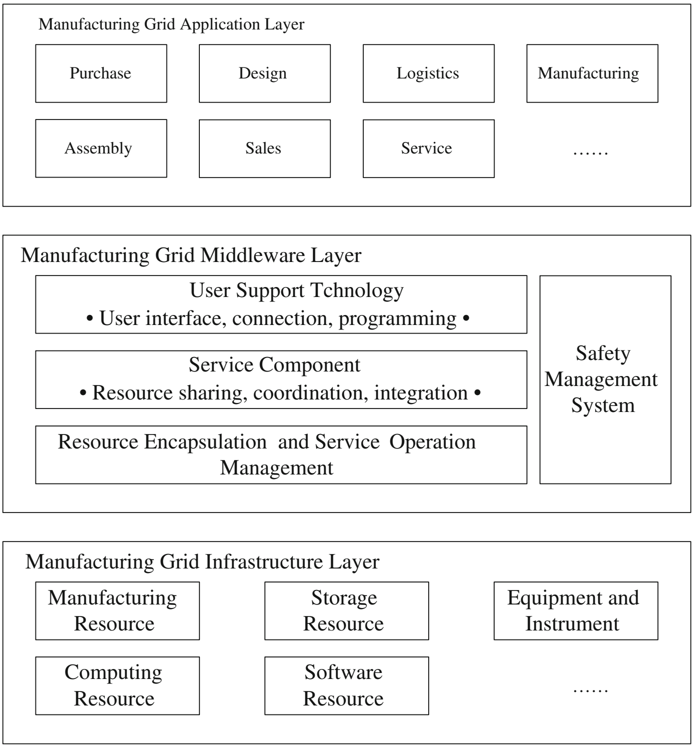


Fig. 8.13 The architecture of manufacturing grid

8.2.2.3 The Prototype System of Manufacturing Grid

The virtual enterprise organized by grid technology is fundamentally different from the existing virtual enterprise. The members of traditional virtual enterprise must have the enterprise nature, however, the members of virtual enterprise which use grid technology are not single actual enterprise or some department of enterprise, they are resource nodes such as specific computers and memory resources. These resource nodes may belong to a single enterprise, some research institution or even some private person [18].

Figure 8.14 shows the virtual enterprise I and virtual enterprise II based on grid, and the solid tissues which constitute the virtual enterprise—enterprises A, E and F (They are all manufacturing enterprises with manufacturing resources), enterprise B (with storage resources) and enterprise D (with equipment resources).

The resources of these enterprises are encapsulated in manufacturing grid nodes, the grid members visit the resource of each node. Each node in this manufacturing grid belongs to the computing resources of each enterprise (including high-performance computer, miniature PC and all kinds of matching

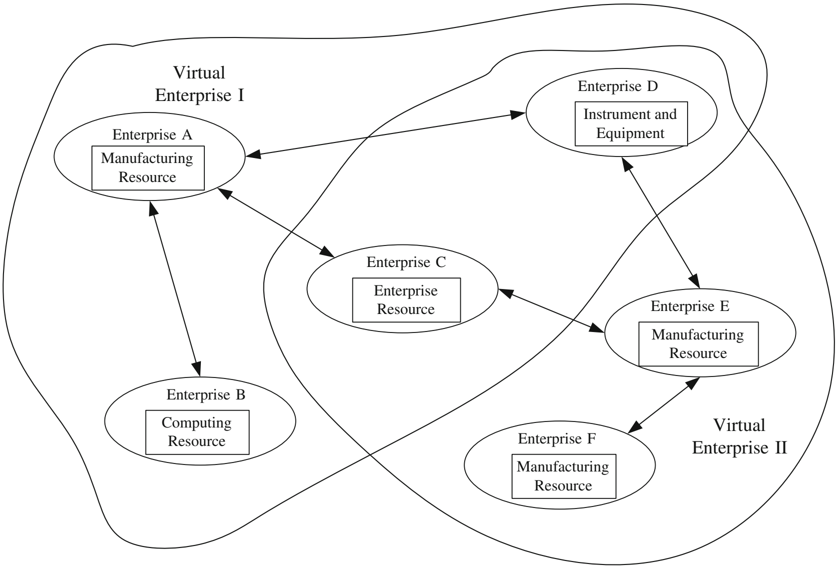


Fig. 8.14 Grid virtual enterprises

software), storage resource (storage devices, databases, etc.), equipment (all kinds of detecting instrument, emulation equipment, test equipment, etc.).

Enterprise E is an automobile manufacturing enterprise, whose main products are high-grade private cars. Because enterprise F has the more advanced production line, it is responsible for the main component production and manufacture; Enterprise C needs to provide storage capacity in order to save the design and manufacturing data of enterprise E; The test equipment of enterprise D takes an on-line reliable detection to enterprise E. Thus enterprises E, F, C and D constitute the virtual enterprise II, and each entity cooperates to complete the design and manufacture of automobile through grid-sharing resource.

It is noteworthy that the sharing of grid-sharing enterprise is no longer a simple exchange of documents, which includes computing resource, storage resource, manufacturing resource and the remote access, control and use of equipment resource.

8.2.3 Resource Service and Security Technology

8.2.3.1 The QoS Guarantee in Digital Manufacturing

The Conception of QoS (Quality of Service) is proposed early in information science domain. It refers to the quality engagement about information transmission between the service user and service provider as well as between the integrated service network of information transmission and them, which decides the comprehensive effect of service performance on user satisfactory degree. QoS includes two aspects of user request and network integration service provider. The user request refers to the service type which user requests and related service performance and quality, the behavior of integration service provider refers to the service performance and quality, which a certain class of service provides and achieves on internet [19].

In the actual digital manufacture production processing, the control content which runs through the entire production process mainly launches by the product's quality control, which nearly contains all requirements and control points of production. In addition, the constraints which manufacturing system and resource faces in service application have similarity with that in network service [20], for example: the constraints of resource, such as processing tool, work space, human resource, processing cost, delivery time and so on; the competition of multitask's use to the same resource; paradoxical coordination in the course of accomplishing multipurpose and the contradiction between low-resource consumption and the demand for high-performance service. Therefore, in the production process of digital manufacture, the corresponding QoS mechanism is needed to provide the performance guarantee for application service.

The manufacturing network in digital manufacturing environment is the virtual network which is constructed on the basis of internet environment, grid and other related technology facing the digital manufacture. The system's architecture presents multilayer structure. These layers are, respectively the user application layer, the middleware layer, the resource encapsulation layer the basic network layer and so on. In order to meet user demand for system performance, in every structure we must have the appropriate QoS mechanism to provide reliable service guarantee.

In order to provide the comprehensive digital manufacturing Qos guarantee, the strategy of integrating multi-layer QoS mechanism is proposed. It not only introduces QoS mechanism in end system like other architectures but also integrates QoS of the resource layer as well as QoS of the network layer, which upgrades system's overall performance with comprehensive QoS strategy.

Next we will discuss related QoS strategy in the following four levels: the application layer QoS, the middleware layer QoS, the resource layer QoS and the network layer QoS.

The application layer QoS mechanism. In the network manufacture facing service, two standards such as user satisfaction degree and application satisfaction degree must be reached by using related QoS [21]. We need to meet the two requirements because of the resources service existed in the manufacturing environment.

In the digital manufacturing activity based on network environment, users will face many complex applications in the manufacturing process. User satisfaction is related to that of how many requirements users would like to get from the application. So system provides the optimal services according to the user satisfaction in the manufacturing environment. For application satisfaction degree, a manufacturing application is usually composed of many sub-applications. Because each sub-application has its unique QoS demand, users in the application layer need to extract a unified QoS standard for application from these sub-applications [21].

The middleware layer QoS mechanism. The middleware layer is the core layer of structure. This layer not only defined the interactive interface with the service layer, but also provided a series of tools, services and agreements to shield the isomerism and distributed character of resource, which achieved the objective of effective sharing and coordination on resource.

In the digital manufacturing network service system, from the user's perspective, the services provided by application service provider consists of not only continuous and accurate data but also service delay. Aiming at this, corresponding QoS mechanism and strategy must be introduced into application service. There are two possible ways [22]: the first one is to integrate corresponding QoS mechanism in the middleware layer, the second one is to integrate in the application layer. Although both options have their merits, because of the factors of transparency and portability, the integration of corresponding QoS mechanism in the middleware layer to improve service delay is a better option.

In order to meet the QoS requirements of different manufacturing resources, some specific mechanisms also need to be considered by the middleware layer to be provided to resource management and scheduling. These specific relevant mechanisms of QoS include: the establishment of SLAs, the reservation and allocation of resource, service discovery, service scheduling, QoS monitoring and analyzing, as well as the abstraction and mapping of QoS.

The resource layer QoS mechanism. The resource layer is in the lower layer of the middleware layer, and all the resource nodes are also in this layer in the digital manufacturing environment. The manufacturing resources in this layer are divided into nine classes, including: human resources, equipment resources, material resources, application system resources, technology resources, public service resources, computing resources, user information resources and other resources. It provided the interface of the upper layer and manufacturing resources, which controls resources through network.

The network layer QoS mechanism. In the digital manufacture network environment, isomerous and dynamic resources are distributed on network (Internet/Intranet), which transfers communication and information through network. In this process, the control parameter and data in manufacturing application will carry on transmission and interaction based on network, in order to provide high reliability, visibility and diagnostic enzyme, as well as related performance, such as the cooperation of distributed control, diagnosis, security and equipment, workshop automatic scheduling, as well as control and diagnosis [23]. According to the above analysis, it is essential to provide good QoS control to network layer.

The QoS parameter standard facing network in manufacturing environment mainly includes [24]: the speed and bandwidth of network, the delay and jitter of data transmission, the stability and security of network architecture, and so on. Aiming at these QoS parameters, a number of important strategies with significant influence on network QoS will be adopted in this layer, such as congestion control and cohort shaping, bandwidth management and reservation, buffer management, routing stability and optimization, data encryption, and so on.

8.2.3.2 The Information Security Technology in Digital Manufacturing

The bottleneck problem of information resource sharing on digital manufacturing is the information security. Only with enough safety can resources be fully shared; only with adequate sharing of resources can trans-regional operation be really achieved. Therefore, the information security issues in manufacturing network are not ignored. It has become an increasingly important issue to use various effective security technologies and construct a reasonable and reliable security environment, in order to guarantee the security of digital manufacturing system.

In the construction of manufacturing resource platform, the entire enterprise relies so greatly on information. The use of this platform easily provides and produces a large number of decision-making data, so it is particularly important to ensure the security of information system. Therefore, we must solve the key problems, such as security, reliability, reality, anonymity, non-replay, non-repudiability and so on.

Security threats in digital manufacturing often have the below characteristics: eavesdropping, namely the attacker obtains sensitive information through monitoring network data; forgery, namely the attacker sends the imitative information to the recipient; tamper, namely the attacker modifies, deletes and inserts communication information between legal users, and then sends to the recipient; denial of service, namely the attacker makes the system response slow down or even become paralyzed through a certain method to prevent legal manufacturing users obtaining service; behavior denial, namely the communication entities deny the occurred behavior; unauthorization access, namely using the network or computer resources without prior consent.

With the prevalence of network technology, in order to ensure the safe, efficient and reliable operation of network, the common security technology includes: firewall technology, database encryption, key management technology, digital signature technology, etc.

8.2.3.3 The Property Right Protection of Network Manufacturing Product Based on Digital Watermarking Technology

With the popularization of network, multimedia information communication has achieved the unprecedented depth and the breadth. However, product infringement becomes easier and tamper becomes more convenient. As the protection of intellectual property right on manufacturing product is related to the vital interests of manufacturing companies, how to protect the property right has become the focus of attention.

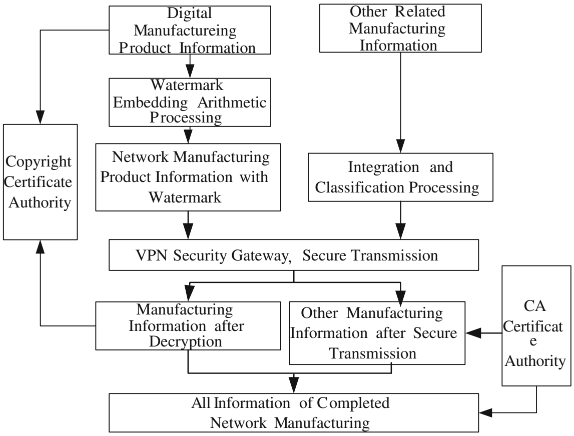
The digital watermarking technology is a kind of emerging technology which goes across multiple subjects such as signal processing, digital communication, cryptography, computer network and has tremendous potential application market, and the study on it has important academic and economic value. The digital watermarking as a new type of digital products copyright protection technology hides the specific information into digital products by the data-hiding technology to achieve the function of marking and protecting copyright. The digital watermarking technology which uniquely identifies the image source and predetermined user has aroused great interests in industrial circles and academic circles day by day, which lets the discrimination information to be embedded into the image data and difficult to remove, in order to achieve the purpose of copyright protection.

The digital watermarking technology should have the general characteristics of information-hiding technology as well as its inherent characteristics and research methods. For example, from the perspective of information security, although the hidden information is destroyed, the system is still regarded as a safe system because the secret information is not betrayed; however, in the digital watermarking system, if the hidden information loses, it will mean the loss of copyright information as well as the function of copyright protection. Therefore, the digital watermarking technology must have strong robustness, imperceptibility and vindicability. Among them, robustness is extremely important for watermarking technology; imperceptibility is also concealment, which refers to invisibility on visual sensation; vindicability means that a good watermarking algorithm should not only be able to provide copyright proof without any dispute but also be irreversible and asymmetric.

Based on the analysis and research on the business model of IMPRIMATUR online transactions [25, 26], we proposed the architecture of network manufacturing product property right protection and information security based on digital watermarking and VPN technology according to the relevant research results, which is shown in Fig. 8.15 [27]. A credible copyright authentication organization is introduced in this figure, which is responsible for maintaining the copyright database to verify the copyright ownership of digital products. When the owner of data wants to embed watermarking into his digital product in order to protect the property rights of the product, the owner will have to go to the copyright certification authority to register in order to get his legal title on the digital product after the identification of mechanism. On the assumption that company A transmits an important digital mechanical blueprint to company B, company A realizes the copyright protection of digital products and hiding of important information through the digital watermarking technology. Furthermore, in order to ensure that the relevant data and other manufacturing information will not be intercepted or stole, the architecture introduced VPN technology to achieve security tunnel communication.

It is shown in this figure that the entire architecture is composed of six parts. The first part is the information part of network manufacture, which includes manufacturing product information and other manufacturing information; the second part is the information processing part, which embed watermark into

Fig. 8.15 The architecture of property right protection and information security based on digital watermark and VPN technology



manufacturing product information and carry on integration and classification to other manufacturing information; the third part is VPN security gateway, whose function is to make all manufacturing information transmit safely and reliably; the fourth part is all manufacturing information after safe transmission; the fifth and sixth part are, respectively CA authentication center and copyright authentication organization, among them CA authentication center is used for exchanging digital certificate between the users as well as identity authentication while copyright authentication organization is responsible for the maintenance of copyright database to verify the ownership of digital products.

According to the relationship between various modules and the characteristic of information interaction in the architecture, we obtain the more detailed information flow chart of network manufacturing products, which is shown in Fig. 8.16 [27].

The concrete steps of network manufacturing product information's security policy are as follows:

Copyright registration. Company A proposes the copyright registration application to copyright certification center, the copyright certification center will give the copyright mark ID of the corresponding related products to company A, and this mark is the only mark of the products.

The generation of digital watermarking information. The watermarking information here includes two parts. One part is the copyright mark ID whose purpose is to protect the copyright of the product, while the partner company B goes to the copyright authentication organization to confirm the authenticity of the product they received based on the ID. The other part is to embed the important information of related product (such as key parameter, size and technical specification) into the product to be transmitted as watermark. The watermark is encrypted before it is embedded. Therefore, the watermark which is eventually embedded into products includes two parts of ID plaintext and ciphertext.

Embedding watermarking information. The digital watermarking information is embedded into the network manufacturing product to be transmitted.

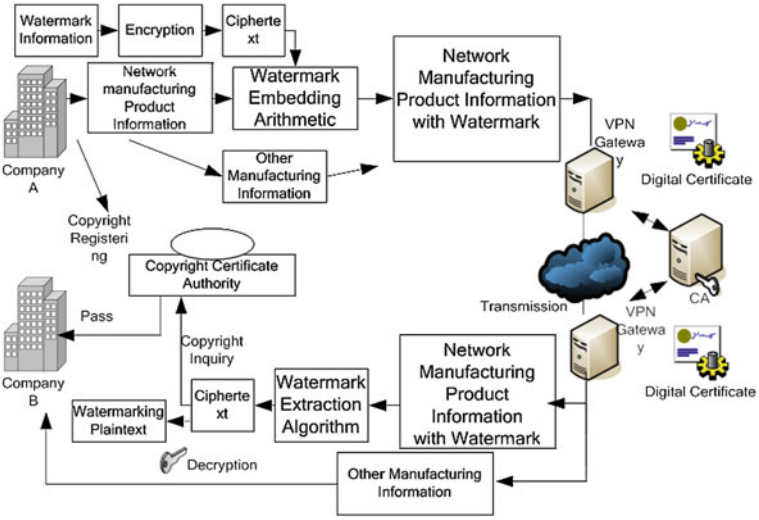


Fig. 8.16 The information flow chart of network manufacturing products based on digital watermark and VPN technology

The exchange of digital certificate. Companies A and B exchange digital certificate through CA and carry on identity authentication. After the successful authentication, data documents and related manufacturing information is safely transmitted through VPN tunnel in network.

The extraction of watermark. The recipient, namely company B extracts the watermark by using the watermarking extraction algorithm which company A provides. The watermarking information includes the ID mark of the product and a section of ciphertext. This ciphertext is the important information of the product.

Verification. Company B submits the extracted ID mark to a trusted third party to verify, and the third party is a copyright certificate authority. When verification is passed and the copyright of the product is confirmed to be owned by companies A, B and company A will continue to consult the extraction of ciphertext.

Secure transmission. When the two sides reach an agreement, company A will send the key to company B. When company B gets the key, it will decrypt the ciphertext to obtain the complete network manufacturing product information. The process information, control information and management information of the general manufacturing process will be directly and safely transmitted through VPN.

8.3 Management Technology in the Digital Manufacturing Process and System

Through the establishment and implementation on enterprise internal material requirements planning (MRP), according to the changing market information, from the overall situation and the long-term benefit, through the decision-making model, evaluating the production and management situation of enterprise, forecasting the future and operating condition of enterprise and deciding investment strategy and production task arrangement has formed the highest management information system (MIS) of manufacturing industry production system.

In order to support the management and production process of manufacturing business to rapidly reconstruct and integrate along with the market demand, there appeared the PDM system which covers the information in the life cycle of product's market demand, research and development, product design, engineering manufacture, sale, service and maintenance of the entire enterprise, thus achieving process integration which takes "the product" and "the supply and demand chain" as the core. At present, along with the widespread application of enterprise requirements planning (ERP), namely the modern management platform established on the basis of information technology, because it has information technology and advanced management technology, which integrates and synthesizes the logistics, information flow, capital flow and work flow in enterprise's management and management activity, forming the digital manufacturing concept which takes MRP/PDM/MIS as the core and is based on management [2, 28].

8.3.1 Digital Management in Digital Manufacturing

DM is generated with the generation of Internet. Internet completely changed the foundation, processing and transmission way of knowledge and information, which caused a social and economical transformation based on knowledge and information.

DM is to quantify object and management behavior with the use of computer, communication, Internet, artificial intelligence and other technology, to realize a series of management functions such as planning, organization, coordination, service and innovation, and to manage the marketing, finance, personnel and daily business with the help of network.

DM in the enterprise applications faces two major tasks. We firstly bring each information collection point of the entire production and business activities in enterprise into the enterprise information network; next we provide necessary application software tools to extract and process information timely and accurately.

The definition of DM contains two primary meanings. One is the enterprise management activities are realized on the basis of modern advanced computer networks and communication technology application, namely the knowledge resources, information resources and wealth of enterprises are digitized; the other is to use quantitative management technology to solve the enterprise's management problems, namely the computability of management.

The characteristics of DM mainly manifests in the following aspects:

Depending on computer and network technology, through database and the corresponding software application, to make management activities achieve digitalization and quantification.

The use of management means and tools of the high-tech technology, especially the use of artificial intelligence technology to simulate the human brain's information processing and thinking process, which makes the management activities of the enterprise be intelligent.

We consider the management of enterprises as a whole and use the thought and method of system theory to deal with various management activities of enterprises. With the function and technology of system, we integrate and combine the essence parts of various management methods and realize the integration of function and technology of management system, enabling each management function of enterprise to achieve systematization and integration.

The dynamic characteristic requires that in the DM process, we should constantly add and modify digital information input along with the change on the internal and external situation of enterprise, in order to make various management information in enterprise achieve dynamic real-time transformation, so that managers in enterprise will respond to the change on internal and external environment of enterprise in the shortest time.

We should give full play to the enthusiasm, initiative and creativity of enterprise staff and depend on collective wisdom and teamwork to gain competitive advantage. It embodies in the "people-oriented" of its management thought.

8.3.2 The Digital Management System in Digital Manufacturing

8.3.2.1 The Digital Resource Management System ERP in Digital Manufacturing

ERP is the most effective mode to realize the DM of enterprise. First of all ERP is a DM concept; secondly ERP is a practical management tool. Its effect is realized based on the following aspects in the enterprise manufacturing process.

Implementation of ERP system in enterprise, which realizes the essential conversion of production manufacturing management model in enterprise through implementation of advanced management modes such as MRP, JIT and PDM.

ERP supports hybrid-type manufacturing environment, which uses MRP model on multi-varieties and small-batch parts and establishes production task planning and purchase planning in advance; we use JIT and Kanban management model to the large number of flow production parts (or whole machine), in order to ensure JIT production.

ERP is the closed-loop feedback control system which takes plan as the center. It carries on decision-making support to the enterprise through the simulation and analysis of production capacity, the monitoring for boring resources and production processes and the timely mastery and quality feedback for sale data. The data collection methods in production process use handiwork, bar code and other methods.

We use CIMS thought to complete the integration through the CAD/CAM, CAPP, MAS (manufacturing automatic system), CAQ (computer-aided quality) of PDM (product data management) and TIS (technology information system), making the digital design of product integrate with digital manufacturing.

ERP embodies the "lean production mode": It emphasizes supply management integration, promotes preventive equipment maintenance and guarantees zero failure. It stresses timely production, inventory reduction and product reserving compression in production.

8.3.2.2 The Application of Digital Management System in Digital Manufacturing

The enterprise constructs project BOM at first to carry out trial production, research and analysis in the engineering design management of product. Once it completes, the project BOM will be quickly transformed into BOM of formal production. Sometimes we directly receive customer BOM, and this BOM has its own characteristics, which needs to be marked by the processing location and linked up with drawing document number.

The engineering department is responsible for the compilation of inventory, the establishment and modification of material consumption quota; the establishment and modification of process route and the determination of time quota; the establishment of coding, the determination of material attribute, the arrangement of material inventory data and fixed data.

We transform the customer BOM into production BOM or project BOM and establish the quota of BOM. The engineering department carries on controls such as management, design, maintenance and aggregation to project BOM or customer BOM and automatically enter of document drawing and data. Digital engineering management defines BOM in the form of graphical presentation and customization and carries on data link with design and development (such as CAD/CAE), digital manufacture(such as CAPP, CIMS, CAE) to exchange data, so that project BOM is timely and conveniently transformed into production BOM and delivery BOM for production. In the switching process, it is exchanged once and reaches the production BOM by stages according to the conditions and rules.

In the production, the DM processes production order, trace scheduling and management rework, carries on man-hour management, fed, tasking and so on. We also carry on the BOM amendments in management.

We manage the production capacity of workshop to exert its manufacturing productive efficiency. For the manufacturing industry, especially small and medium enterprises, the processing manufacturing material inventory BOM changes frequently, which easily causes manufacturing error and impeded procedure without timely communication. Workflow management tracks and controls the manufacturing procedure with the way of electronic document and e-mail and eliminates the problems of manufacturing errors and material anaplasty which may arise.

In the manufacturing process, enterprises need to purchase materials which include not only raw materials but also standardized parts or fittings. Purchasing management realizes the management to suppliers, price and purchasing order, punctually repurchases materials of manufacturing production with low cost, ensures that the digital manufacturing process is unblocked and eliminates the phenomenon of shutdown because of waiting for material.

For the manufacturing industry, specially the small and medium-sized enterprises, the manufacturing DM is the most basic one, enterprises use this system to integrate the material flow, information flow, capital flow and customer flow of enterprises, in order to form the expansion to digital enterprise and greet the challenge of global competition.

8.4 Control Technology in Digital Manufacture

8.4.1 Networked Control System

With the increasingly complicated control object and the rapid development of computer, communication and sensing technology, the structure of modern control system tends to be distributed. Recently the networked control system (NCS) has become one of the research focuses in academia and practitioners [28]. It has many advantages to integrate network into control system to replace the point-to-point connection in traditional computer control system, such as: the reduction of wiring cost, the reduction of cable weight, the simplification of installation process as well as the enhancement of reliability. Therefore, it is easy to realize system's diagnosis and maintenance to enhance system's flexibility. However, it also increased the complexity of analysis and design in control system when adding the communication network into feedback control loop. Therefore, one of the key issues which NCS must be handled with is how to ensure the real-time performance and stability of control system under the condition of limited bandwidth [29].

NCS is the system which realizes control loop on the serial networks, namely the elements such as controllers, sensors and actuators which in control system exchange the control and sensor signals through the serial networks. In NCS which is shown in Fig. 8.17, all of the controllers, sensors and actuators share the same serial network.

Control network is the core of NCS. Compared with the data network, it has the characteristics such as: the data frame is short, the data exchange is frequent and it has real-time constraints, etc. In the recent 20 years, the control network has obtained rapid development, especially the field bus technology as its mainstream has formed a series of international standards, such as CAN, FIP, FF, PROFIBUS and so on.

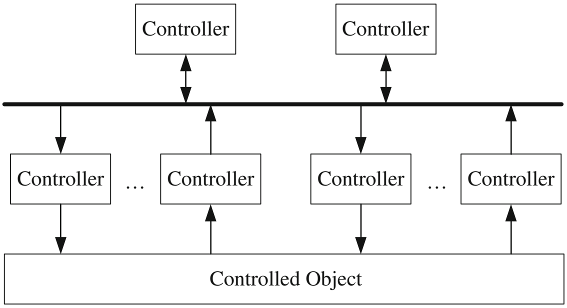


Fig. 8.17 Networked control system

At present, the NCS has obtained widespread applications in process automation, manufacturing automation, aerospace, wireless communication, robot, transportation system, intelligent building, defense and other fields [29, 30]. The NCS has the characteristics of interoperability, portability, interchangeability and reduction, which realizes the seamless integration with information network and achieves the integration of management and control, therefore it will substitute the traditional DCS and PLC system in process industry and manufacturing industry. In the automotive, aircraft control systems, network control structure with hard real-time performance and high reliability will become mainstream.

8.4.2 Virtual NC Technology

In recent years, the open architecture based on PC and the numerical control technology and system based on network have deeply changed the traditional concept and traditional structure of numerical control technology and system. The combination of virtual reality technology with numerical control technology and system creates the concept of virtual numerical control (VNC) [31–34].

Figure 8.18 shows the architecture of VNC system. The virtual simulation environment based on network provides the necessary human–machine interface and digital device as well as the corresponding hardware and software environment for users. The machine tool base, cutter and fixture base not only realize the assembling and operation of a single machine, but also provide a number of essential elements which constitute a complete machining cell, such as tools, fixtures, parts and machine tools, in order to provide the necessary support conditions for processing operation of numerical control system. The four basic platforms in this figure are the core of the architecture of VNC system.

From the architecture of VNC system, we see that the VNC system platform technology is the core of its development. The related technologies of four platforms involve modeling, simulating, interface, network, database and other related technologies, which are necessary and also pivotal for the research and development of VNC system. However, the development of VNC system will also depend on a

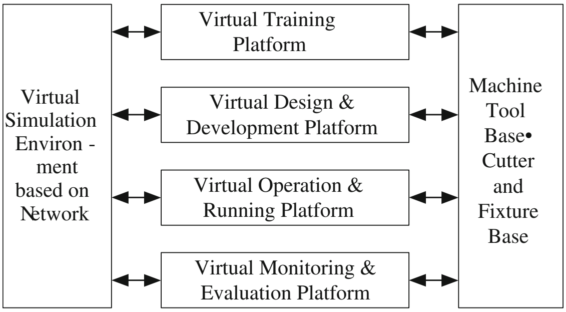


Fig. 8.18 The architecture of virtual numerical control system

number of other supporting technologies, and the research and development of VNC system will also promote the development of these supporting technologies, vice versa. As shown in Fig. 8.19, the network and virtual reality as well as the virtual machine tool, cutter and fixture base are the supporting technologies of VNC system as well as its necessary technology, while virtual design system, virtual instrument system and virtual motion controller are the important supporting technologies of it.

The VNC system is one of the key and basic technologies in virtual manufacture, which will provide the means to solve the bottleneck problem in the developing research process of numerical control system; to provide fast, safe and effective means without consumption of resources for numerical control talent training; to provide choice and basis for mechanical and electrical debugging, the best design of machinery electricity matching, system assessment, the optimization of processing, etc. The research and development of VNC system will certainly bring the research and development of numerical control system into a more brand-new stage.

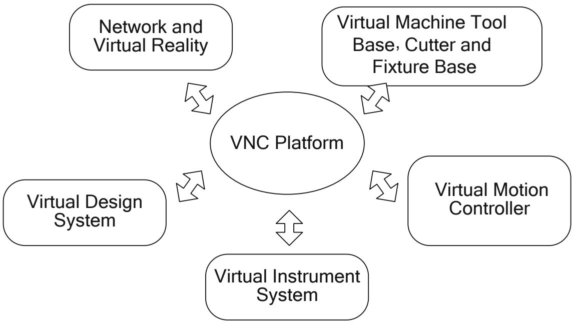
8.4.3 The Embedded Control Technology

8.4.3.1 The Digital Manufacture and Embedded Technology

The embedded control technology and digital manufacture are closely related, we even think that the embedded control technology and system is the core and key of the development of future digital manufacturing [35, 36]. The relationship between embedded control and digital manufacture is shown in the following aspects:

The intelligence and automation of digital equipment. The intelligence and automation degree of equipment product is the key factor to promote the quality of digital equipment product and enhance its market competitiveness. The embedded control technology not only improves the automation level of manufacturing equipment and enhances the independent innovation ability of digital equipment manufacture, but also creates conditions for speeding up the networking and intelligence of digital manufacturing equipment, so that the digital manufacturing product leaps to a new level and each digital manufacturing product becomes an Internet node by embedded technology.

Fig. 8.19 The diagram of virtual control supporting technologies



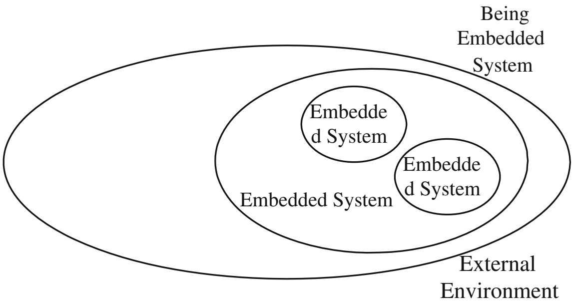
The intelligence and automation of digital enterprise. Embedded technology is one of the core technologies of the intelligence and informatization on advanced manufacturing enterprises. Embedded technology is the necessary manufacturing means of modern equipment manufacturing industry. The applications of embedded technology in the whole life cycle of manufacturing product such as design, manufacture and maintenance, management and market operation, greatly enhance the competitiveness of traditional enterprises and make it achieve the overall digitalization, intelligence and networking, in order to improve efficiency and really realize the intelligence and automation of digital enterprise.

8.4.3.2 The Model and Characteristic of Embedded System

Embedded technology and system provided abundant functions and outstanding performances with lower cost because of the full use of resources and compact system. Because embedded system can easily carry on function reduction of hardware and software and do not cause resources to be wasted, it provides the optimal cost performance for numerical control technology and system. Because embedded system has general serial interface and a variety of field bus interface and ethernet interface, it easily constitutes the grid needed by various digital manufacture. The use of embedded technology realized complete independent intellectual property, which build a good condition for developing the future new network digital control technology and system of independent intellectual property.

Embedded system model. Embedded system model is shown in Fig. 8.20. To understand from the physical level, the embedded computing system is regarded as a special electronic system, and this special electronic system is usually included in a more complex non-electronic system, which is the visual meaning of "embedded". A more complex non-electronic system is abstracted to the external environment of embedded system, which is called the being embedded system. The whole system usually contains a number of embedded systems, and the embedded system also directly communicates with the outside world.

Fig. 8.20 The model of embedded system



The embedded system provides a special service for the being embedded system. This service is a response to outside input directly from the outside world; it is also a response to the data of the being embedded system or the adjacent embedded system.

Modem electromechanical control system. In such a distributed system, each processing unit is connected by network, which constitutes the embedded system structure shown in Fig. 8.21 based on network. Here the network is a generalized conception, which is the loosely coupled architecture interconnected by some medium or the network on chips with the way of SoC, namely constituting NoC.

8.5 Digital Recognition and Integration Technology in Product

8.5.1 Radio-Frequency Identification Technology

The radio-frequency identification technology uses spatial electromagnetic inductive coupling or electromagnetic propagation coupling to communicate, in order to achieve the function of automatically recognizing the marked object. Its basic principle is to install RFID tags on the identified objects, to read the information contained in the label (such as identification tag and store data, etc.) through the RFID reader with the mode of wireless communication, and to complete the related decoding work. Finally, we transmit this information to remote computer to process, thus completing the entire work flow of RFID recognition.

The radio-frequency identification technology is widely applied in personal identification, supply chain, auto express-way toll collector, parking management and other fields. With the rapid development of RFID technology in recent years, its research in the manufacturing field has obtained great importance of people and wide applications. The literature [37] introduced a typical application of RFID technology used for tool recognizing in the field of numerical control machining.

In modern manufacturing industry, the tool is a more expensive resource consumed, which is composed of numerous parts such as tool shank, arbor and

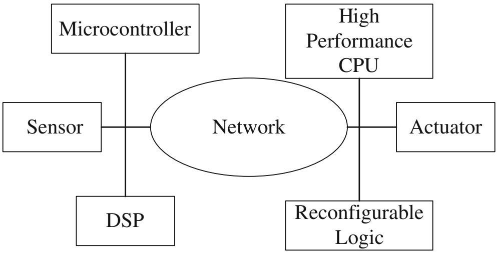


Fig. 8.21 The structure of embedded system based on network

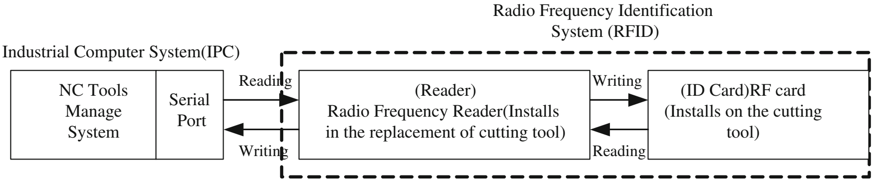


Fig. 8.22 The radio-frequency tool identification system [37]

knife head. In addition, as the species of NC processing equipment and parts continuously increase, the species and the corresponding resource information of tools, as well as their parts will be more miscellaneous. In manufacturing production and processing, a large number of tools frequently are always alternated and flowed between tool library and machine tool, as well as between machine tools, which make the traditional recording mode unable meet the needs of current production management. If we are unable to carry out effective information management for tools, it will result in a waste of resources and low-production efficiency. Furthermore, it will even cause too much deviation or process excursion of scale, thus resulting in product abandonment and causing the adverse effect to the production cycle. The application of the radio-frequency identification technology in the tool recognizing of numerical control processing field effectively solves the deficiencies and shortcomings in traditional management methods.

The basic structure of radio-frequency tool identification system is shown in Fig. 8.22 [37], which is composed of radio-frequency identification system and industrial computer system. The radio-frequency identification system mainly performs the function of tool identification and data exchange, and keeps the radio-frequency label with agreed format of electronic data attached to the surface of the tool which is to be identified. The reader reads the data information which is preserved in radio-frequency label in the way of non-contact, to complete automatic identification of the tool. Thereafter, the reader sends the acquired information to industrial computer system in the way of serial communication to carry on subsequent treatment. The management system in industrial computer system is specifically developed based on database in view of the requirements of numerical control tool management. This system receives data information from reader and gives off control instructions to actuator according to the data information and pre-programed function, thus achieving the corresponding tool management action.

8.5.2 Bar Code Recognition Technology

The bar code recognition technology is a recognition technology designed for the automatic scanning of information, in which the bar code is usually a strip and empty symbol regularly arranged according to certain rules. The strip and empty symbol with different width and reflectivity express the information which is composed of certain characters, numbers and symbols.

As the bar code recognition technology has advantages of low cost, high input speed, high reliability, large quantity of collecting information as well as flexible and practical, it has a broad application space. This technology has obtained wide applications in the field of digital manufacturing, such as manufacturing equipment management, logistic storage and distribution.

The literature [38] described a kind of manufacturing industry materials management system which combines material management with barcode tracking system, thus realizing real-time monitoring on each node in production manufacture. Through real-time acquisition of related production information, we obtain the situation of inventory and consumption, production progress and quality of each material in production manufacturing, in order to provide accurate and timely guidance data for the management optimization on distribution, inventory, logistic storage and transportation for MRPII. In this system, the three elements of essential goods, duration and quantity are printed on the label in the form of bar code, and each label contains the name and code of processing enterprise, purchase location and department, description of goods and specie code, delivery quantity, delivery time and cycle, as well as other enterprise product information. The label flows in enterprises as an information media, and the corresponding barcode information is scanned by bar code readers of each department and each process and is sent to various production sectors.

8.5.3 Electromechanical Integration Technology and the Light Mechanical and Electrical Integration Technology

8.5.3.1 The Electromechanical Integration Technology

The development of contemporary science and technology have emerged as the important trends of vertical differentiation and transverse comprehensive [39]. The electromechanical integration is the product on the reciprocal chiasmata, infiltration and comprehensive development of mechanical technology and electronic

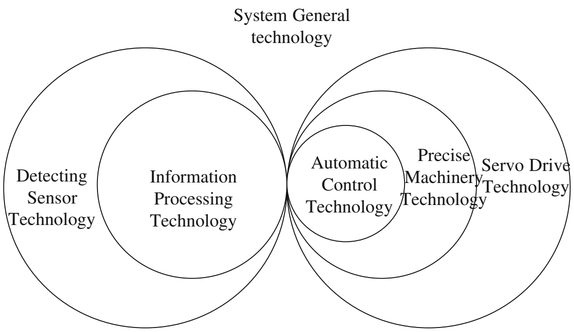


Fig. 8.23 The generality related technology of electromechanical integration

technology. On its composition, it involves mechanical technology, electronic technology, control technology, information technology, etc. In a sense, the electromechanical integration has already become the alias of interdisciplinary and comprehensive technology.

The generality related technologies of electromechanical integration are summarized in six aspects: testing-sensor technology, information processing technology, automatic control technology, precise machinery technology, servo-drive technology and system overall technology. The relationship between the various technologies is shown in Fig. 8.23.

The testing-sensor technology. The functional devices which detect all kinds of physical quantities and convert the various measured parameters into electric signal and transport them to information processing parts are called testing-sensor components or devices. The sensor is the core of detecting parts, which is equal to the human tactus. For example, in processing, the NC machine tool use force sensor or acoustic emission sensor to detect the wearing condition of tool and compare it to the given value. When the tool wear causes the load duration curve to increase and exceed the maximum allowable value, the manipulator will change automatically, which is the powerful guarantee of safe operation and improvement of processing quality.

The information processing technology. The information processing technology includes the technologies of information input, exchange, operation, storage and output, etc. It is achieved by microcomputer, microcontroller, single board computer, programmable controller, optoelectronic devices and other electronic devices. The Information processing part is equal to human brain, which directs the operation of the whole system. To improve the speed of information processing, such as the use of super-PC or super-LSI technique; to increase the reliability of system, such as the use of self-diagnosis, self-recovery and fault-tolerant technology; to enhance intelligence, such as the use of artificial intelligence technology and expert system, which are all the future development directions of information processing technology.

The automatic control technology. The automatic control technology includes the technologies of high-precision positioning control, speed control, adaptive control, self-diagnosis, correction, compensation, teaching and playback and retrieval. In the electromechanical integration technology, the automatic control mainly resolves several main aspects of the problems, such as how to improve the accuracy of products, the machining efficiency and the effective utilization of equipment. The key of its main technologies is the engineering and practicality of modern control theory in the electromechanical integration technology, the establishment of optimal control model, and the decision of boundary conditions.

The servo-drive technology. The servo-drive technology implements a number of technical problems in systems and institutions. The servo-drive includes various kinds of transmission devices, such as electric device, pneumatic device, hydraulic device and so on, the function of this part is equal to that of human hands and feet. It directly implements various related operations, having a direct impact on product quality.

The precise machinery technology. The mechanical part in electromechanical integration system should have higher accuracy and better reliability and maintenance than the general type of machinery, which should also have a newer structure. The parts should have modularization, standardization and normalization, that is to say, in electromechanical integration products, the mechanical body and mechanical technology itself have been provided with new demands. The core of this demand is precise machinery technology.

The system overall technology. The electromechanical integration technology is not the simple addition of several techniques; however, they are formed as an organic whole through the overall design of system. In order to solve the problem on the integration of multiple technologies, there are many new issues which are needed to be explored and studied.

The system overall technology is a kind of technical scheme which uses systematic viewpoints and methods from the overall objective, to decompose the whole into certain function units and find the technical scheme which completes various functions, thus combining each function and technical scheme into comprehensive application technology which is used to analyze, evaluate and optimize by scheme group. It ensures that it can economically, reliably and efficiently achieve its objectives in a given environment through the coordination of used technology.

8.5.3.2 The Light Mechanical and Electrical Integration Technology

Since the 1990s, the light, mechanical and electrical integration technology which is formed by introducing optical technology on the basis of the electromechanical integration technology has been causing a new technological revolution. In the light, mechanical and electrical integration technology, the optical technology not only simply joins in but also infiltrates into every part of the electromechanical integration technology. For example, in the part of sensors optical fiber sensor not only overcomes the inherent defects of the traditional mechanical and electrical sensors, but also adapts to extreme environmental conditions. Based on this, researchers have begun to introduce optical fiber sensing technology into the condition monitoring of large mechanical equipments; in the aspect of manufacturing technique, optical corrosion technology has become an effective manufacturing method of large scale integration.

Up to now the light, mechanical and electrical integration has not had an accurate definition. It is generally believed that the light, mechanical and electrical integration is the community technology which is composed of optics, mechanics, microelectronics, information processing and control, special software and other related technology. The light, mechanical and electrical integration system is a flexible automatic system with perfect function which is composed of mechanical structure, actuator, computer controller and sensor, and among them computer controller, sensor and computer software are important component elements of the light, mechanical and electrical integration technology [40, 41].

The characteristics of product technology in the light, mechanical and electrical integration technology mainly manifest in following four aspects [42]:

The integration of optical technology and all kinds of information processing technologies. The most direct and important function of optical technology in the light, mechanical and electrical integration product is to carry on photoelectric detection for various information, in order to provide foundation for the implementation on condition monitoring and intelligent control of equipment. Fiber bragg grating sensor is a new kind of optical measuring sensor. Since 1978 when it came out, it has become an important new branch of sensor technology after 20 years of development. Fiber bragg grating sensor has the following characteristics: small size, explosion-proof, electrical insulation, anti-electromagnetic interference, high accuracy, high reliability, the adaptability to environment is good, as well as many measuring gratings in view of different parameters are arranged on a single fiber to form the distributed sensor. Therefore, it has obtained wide applications in many industrial areas, particularly in the aspects of the safety monitoring of large bridge, dam and nuclear power engineering, and it has achieved significant social and economic benefits. With the rapid development of the fiber bragg grating sensor technology, all kinds of fiber bragg grating sensor products such as temperature, pressure, displacement, speed, acceleration and gas sensing have emerged, and its corollary use wavelength demodulator products have also formed the scale production, whose demodulation speed achieves 200–300 Hz generally, which basically meets the needs of structural engineering state and safety monitoring. With the extensive application of fiber bragg grating sensor technology, the demands for fiber bragg grating sensors with high precision and a wide scope of application become more and more prominent. Except the fiber bragg grating sensor, the charge couple device (CCD) sensor, CCD image sensor, and other sensors are used widely nowadays, and such sensors are widely used in the fields of image collect, image acquisition, scanner and industrial measurement and control, etc.

The combination of optical technology with a variety of instruments and devices. Many of the existing equipment and installations are formed by upgrading and updating on the basis of the original foundation after combining with optical technology, such as X-ray microscope, optoelectronic flat-printing device, photochemical vapor deposition device, 3D display, etc.

The combination of optical technology and micro-electro-mechanical system. On the basis of micro-electro-mechanical system (MEMS), we integrate optoelectronic device, microelectronics device and micro-mechanical device by microprocessing technology, causing the system to further miniaturize, which formed the micro optical electro mechanical system (MOMES).

The combination of optical technology and various processing technology. As early as the great development period of electromechanical integration, the laser processing technology has been quite mature. The current focus is the application research on optical processing technology in the MOMES and optical fiber communication.

Compared with these classic traditional subjects such as optics, mechanics and electronics, the light, mechanical and electrical integration technology is summarized as “The digitalization, intelligence, informatization and networking of electromechanical products and optical products”. Therefore, the light, mechanical and electrical integration technology is considered to be one of the key technologies in digital manufacture.

8.6 Summary

Modern manufacturing industry is gradually transforming from the partial quantification and partial experience-based learning, quantitative mode to the comprehensive digitalization, namely from macroscopic to microscopic. The digital manufacturing needs to not only process mass data and information of massive conventional engineering data, graphic information, as well as manufacturing process material flow, process flow and information flow, but also collect and process massive global manufacturing information and data involving management, decision, market, capital, manufacturing knowledge, and so on. The key technology of digital manufacture has provided a comprehensive technical support for the whole life cycle of digital manufacture. It is foreseen that the content of digital manufacturing technology will become more abundant and the application will become more extensive with the extension on concept and the deepness on theory of the digital manufacturing science.

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Chapter 9
Future Development of Digital Manufacturing Science

In recent years, some basic concepts and theories of digital manufacturing science have been proposed to research agenda, a growing number of research institutions and researchers in the world have plunged into the research field of digital manufacturing science, which launched some fruitful researches and obtained primary achievement. With the popularization of theory, the improvement of theoretical system, the breakthrough of key techniques and application platform and the implementation of principles and tools, digital manufacturing scientific system will certainly obtain more extensive development. And the precision, extremalization and environmental protection are the main directions in future research, which will further expand the connotation of digital manufacturing science and upgrade the technical level of digital manufacturing.

9.1 The Precision of Digital Manufacturing

9.1.1 The Micro Nano Electro Mechanical System and Digital Manufacturing

9.1.1.1 The Basic Principle of Micro Nano Electro Mechanical System (MEMS/NEMS)

In the 1960s, the micro electronic technology began to penetrate into each field of mechanical engineering and mutual promotion existed after combining with the traditional precise machining technology. Under this situation, the micro electro mechanical system (MEMS) was presented, which is the extension of the microelectronic technology in the mechanical field.

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The micro electro mechanical system (MEMS) was most early proposed in the theme report “Small Machines, Large Opportunities” in the symposium of IEEE Micro Robots and Teleoperators which was held in 1987. Subsequently, the micro electro mechanical system was the focus of research and correspondingly obtained rapid development. Since the technical level and emphasis of researchers on micro electromechanical system are not consistent, the forms of research are also different: American research mainly focuses on the technology based on semiconductor integrated circuit, so the system is called MEMS; European researchers stress to integrate multiple minisensors, actuators, signal processing and control circuit and other components to micro intelligent electronic mechanical system, so it is called Micro System; because Japan has traditional precision machining advantage, so it highlights the mechanical background. It uses large machine to produce small machine, in order to reuse small machine to produce micro machine, so it is described as Micro Machine. To summarize the characteristics and connotations of various names, we think that MEMS is the micro electronic mechanical system which includes micro mechanism, micro sensor, micro actuator, signal processing, control circuit, communication interface and power [1].

Micro electro mechanical system (MEMS) has the following three characteristics [2, 3]:

Miniaturization. Miniaturization is the basic characteristic, the shape or operation size of system not only ranges from centimeter to micrometer, but also enters into the tiny space to carry out micro manipulation and micro positioning.

Multiplicity. Multiplicity is the key of success, the actuator of system not only is parallelly created to form array, but also cooperatively completes the task that a single actuator cannot complete.

Microelectronics. Microelectronics integrate multiple functions effectively in order to enhance the signal-to-noise ratio, sensitivity and accuracy of system. In addition, it removes complex interface circuits to make the intelligence of system greatly improved.

The Nano Electromechanical System (NEMS) is a new concept which was proposed in the late 1990s, and it is a kind of subminiature electromechanical integration system which has the characteristics of nanotechnology in feature size and effect [4]. There is a simple concept to understand NEMS as the reappearance of MEMS in nanometer scale, namely the integration of mechanical actuating equipment, electronic device, computer and sensor in nanometer scale. However, the characteristics of microcosm lead to major differences between NEMS and MEMS [5, 6]: the NEMS device involves some characteristics and functions which the MEMS system cannot provide, such as ultrahigh frequency, low-energy consumption, high sensitivity, the control of surface integrity and adsorbability, as well as effective driving method in nanometer scale. Whereas, compared with MEMS, NEMS puts forward much higher requirements, namely the range of research materials should be broader and the spatial resolution of processing should also be higher.

MEMS and NEMS are the important components of micro/nano manufacturing technology, which has gradually been formed as a new technology field. Hitherto,

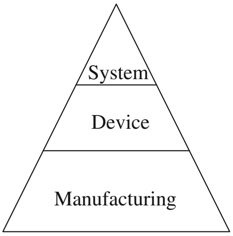

Fig. 9.1 The relationship between manufacturing technology, devices and systems [4]

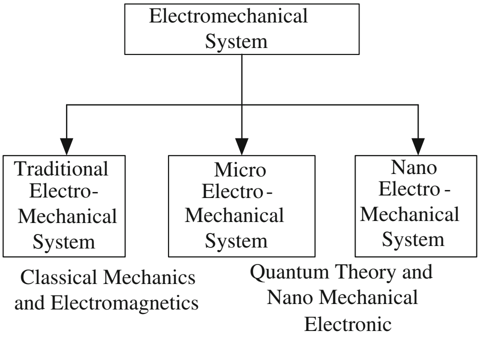

Fig. 9.2 The scale of electromechanical system and corresponding theoretical problems [4]

MEMS has obtained rapid development in the industrialization and achieved many significant achievements, but NEMS is still in the research stage.

MEMS/NEMS is the comprehensive technology which is formed by cross merging of multidisciplinary, and it has unique advantages in almost all the natural and engineering fields, especially in the machinery manufacturing field. According to the status and development trend of MEMS/NEMS, we summarize the following characteristics [4]:

Manufacturing technology and MEMS/NEMS. Figure 9.1 shows the relationship between manufacturing technology, devices and systems. We see that manufacturing is in the bottom of the structure and is the foundation of the system. So we say that manufacturing technology is the basis of MEMS/NEMS. In the development process of MEMS/NEMS, based on traditional IC manufacturing process, people have employed the characteristics of mechanical processing technology and systems to develop multiple micro-fabrication technologies, such as silicon micromachining technology, X-ray deep lithography technology, electroforming LIGA process and so on. At present, the characteristic scale of micromachining achieves nanometer.

The mechanism of MEMS/NEMS. Figure 9.2 describes the scale of electromechanical system and the corresponding theoretical issues. The reduction of scale to micro and nanometer will change some macroscopic properties of objects, thus leading to the emergence of some new properties. In MEMS, some classic physics laws are basically suitable. However, in the narrow space, the different kinds of substances (solid, liquid, heat, biological and chemical) will couple with each other, which makes some minor factors of macrocosm more important. New effects, such as quantum effect, interface effect and high performance of nano material created by nanometer structure in NEMS, must rely on quantum theory and nano mechanical electronic theory for analysis. And the research and analysis on generating new nature and effect is the key to the development of MEMS/NEMS.

9.1.1.2 MEMS/NEMS and Digital Manufacturing

Precise treatment is one of the main development directions of digital manufacturing, and MEMS/NEMS is the key point of the research in this direction [7–9]. The development of MEMS/NEMS in digital manufacturing has put forward new demands and challenges for the existing research methods and manufacturing technology.

Digital manufacturing model is an indispensable tool in the life cycle of digital manufacturing. We use appropriate modeling methods to abstractly express each object and process in the life cycle of digital manufacturing and complete analysis, integration, optimization and simulation through study on its structure and characteristics. The design of MEMS/NEMS in digital manufacturing needs to adopt a suitable model. The establishment of MEMS/NEMS model not only meets the requirements of conventional digital manufacturing modeling, but also ensures that the function principle of the built model accords with the physical principle in micro and nano manufacturing environment.

The modeling requirements of MEMS/NEMS in digital manufacturing are as follows [10]:

Correctness. The establishment of physical model must meet the basic principles of physics, such as the conservation law; the premise, assumption, simplification and approximation in the model are also compatible to all subsystems.

Visibility. The built physical model must have the ability to observe and explain physical quantities, which supports researchers to obtain the related objective state variables through the quantity of microscopic field or the average of field distribution.

The applicability of partition. When establishing model, we must restrict the number of dimensions which is produced by the state variables to be considered, in order to complete appropriate model for the determined question types.

Besides the modeling method, MEMS/NEMS also proposed new demands to digital manufacturing design technology which mainly manifests in CAD technology. The structure and manufacturing characteristics of MEMS/NEMS make CAD technology have the following characteristics [10]:

The structure size of micro nano causes the change of material nature and the working mechanism of system. When the size of system structure tends to be micro nanometer, the function and influence will obviously strengthen, which causes obvious differences between the structure work mechanism of MEMS/NEMS and the macroscopic machinery.

The influence of MEMS/NEMS manufacturing technology on CAD. The micromachining technology in MEMS/NEMS manufacturing technology pays more attention to the features and functions of object, which is a kind of micro/nano three-dimensional processing technology. In addition, CAD has an effective measuring ability for the simulation and various performances of three-dimensional structure.

Close contact with microelectronics. The electronic function and mechanical function in MEMS/NEMS products couple with each other, which constitute a complete and complex system together, so CAD needs to provide the appropriate support while resolving self-test circuit.

The research and application of MEMS/NEMS is the important content of precise development of digital manufacturing, which is the inevitable result of the multidisciplinary cross merging, involving mechanical manufacturing science, information science, micro fluid mechanism, microthermodynamics, chemistry, biology and other subjects. We believe that the further research on MEMS/NEMS will certainly make the technical contents of digital manufacturing richer and the application fields of digital manufacturing more extensive.

9.1.2 Micro Nano Equipment and System

Typical MEMS is composed of micromachine (actuator), microelectronics (controller) and micro sensor, which carries out energy supply, signal transmission and executive control outside by electricity, light, magnet or other untouchable ways. The restrictions on micro manufacturing technology and energy make MEMS disable to complete diversified movements and complex functions like macro machinery but able to have a tiny effect by a number of small and simple subsystems executing simple movements. MEMS relies on microelectronics to control several subsystems and make them work together, in order to finish a complex task. The typical applications of micro electro mechanical devices mainly include [11]:

The inertial detection and control. The accelerometer and micro-gyroscope based on inertial detection are the most typical micro electro mechanical devices in this application. The accelerometer outputs electrical signals by the non-contact inertial force produced by proof mass, and the entire system is encapsulated without disturbance from external environment. The micro-gyroscope is widely used in the traction and motion stability of mobile robots, vehicles, ships, etc.

The biomedical and physico-chemical research. In the research of biology and biochemistry because the scale of cells is usually in 1–10 μm, the thickness and length of biomacromolecule are, respectively nanometer and micron scale, the control and synthesis of cells or biological molecules must rely on micro electro mechanical devices to realize. Micro electro mechanical devices grasp and control these nanometer/micron cells or biological molecules to observe their behavior and effect. So far, people have successfully developed micro electro mechanical devices which are used in biomedical and physico-chemical field, such as micro-pump, micro-valve and micro-turbine.

Precision positioning and micro-position control. The most typical micro-position control application is the precision positioning of magnetic head on disk. With the rapid development of information technology and the increase of magnetic storage density year by year, the location accuracy of current track is less than 0.1 μm, it is expected that the position accuracy of the current track will be less than 0.025 μm [12]. Such a high-position accuracy makes the existing technology difficult to achieve precise positioning and thus must rely on micro actuator to modulate based on deviation errors by circuit control.

Optical signal processing and display. The digital micro microscope optical display device is a major breakthrough in the field of MEMS application. Because optical signal is non-contact information without quality, it is applicable for the processing of microsystem, and it obtains effective application in high-speed modulator of optical communication, fiber control, micro optical switch, etc.

Magnetic signal processing and transmission. Magnetic signal is also a non-contact signal without quality, the mechanical structure and control circuit within package communicate and transmit with outside by magnetic signal to carry out mechanical action. Typical micro electromechanical devices have magnetic printer head, and so on.

Although, the research of NEMS is still in its starting stage, NEMS has more significant advantages than MEMS in high sensitivity, small size, low power consumption, etc. The typical applications of nano electro mechanical equipment mainly include [11]: nano biological equipment, nano sensor equipment, nano information equipment and nano fluid equipment, etc.

The research field of MEMS/NEMS is constantly advancing and expanding, especially in the mechanical manufacturing field it has been widely used. The future research trend is to research from single MEMS/NEMS device which gradually develops into making MEMS/NEMS devices as the components of embedded system, in order to enhance the overall performance and added value of system.

9.1.3 Digital Manufacturing Technology in Micro-Nano Manufacturing

The rapid progress of microelectronic and silicon manufacturing technology in the past 20 years and the rapid development of its related application laid the solid foundation for developing micro-nano manufacturing system in microelectronic. However, the research on the micro-nano manufacturing started relatively late, the research of the current micro-nano electromechanical system also exists many key issues to be resolved. These existing key issues have become the bottleneck in complementation of the micro system.

The development of digital manufacturing from the generation of this concept up to today has gradually developed into a generalized digital manufacturing connotation, which includes the product life cycle and its environment of supportive operation derived from the simple product digital production manufacture. In the product life cycle of micro-nano manufacturing, it has taken the development trend of digital manufacturing, and the application of digital manufacturing technology has provided an effective way for the breakthrough of the application bottleneck in micro-nano manufacturing [11, 13].

The digital modeling theory of micro-nano manufacturing system. Digital manufacturing uses virtual reality technology, rapid prototyping technology, database technology, network technology and multimedia technology, combines with computer integrated manufacturing, collects resource information rapidly according to user requirements, and carries on analysis, planning and recombination for product information, process information and resource information with the support of advanced decision system, in order to realize rapidly the simulation and prototyping manufacture of the design, function and production of products which meet user's demands. Therefore, we use digital manufacturing technology in micro-nano manufacturing system, and complete product manufacture in digital space established by the exact quantitative and digitized descriptions, which have a statistical significance on improving the precision of micro-nano manufacturing, shortening the cycle of production and promoting efficiency of production. The digital modeling method describes the input and output as well as each structure parameter of micro-nano manufacturing system clearly within proper mathematical model, thus it can realize the optimization of decision, simulation, and predicable recognition in abnormal states, motion control, etc. Among them, the digital modeling objects of micro-nano manufacturing system involve the whole generalized manufacturing process, including equipment modeling, machine process modeling and information modeling.

The digital design theory of micro-nano machinery. Compared with traditional machinery, the micro-nano machinery dose not just apply the single micro-nano on geometric size of mechanical parts but to use a new device which is constructed by new thoughts and methods. Because the relationship between surface area and volume surface areas and volumes of mechanical parts will dramatically change after constructed by the micro-nano mechanical structure, and the influences of scale and surface on mechanical performance of components will be also very obvious, which makes the micro-nano manufacturing different from the traditional machinery manufacturing in scale, structure, materials, manufacturing methods and work principles, etc. Some principles and methods of traditional machinery manufacturing are no longer suitable for the micro-nano manufacturing. The digital manufacturing establishes the digital models of product and gives the digital definitions of the whole life cycle of product which computers understand. This method digitizes the geometric information of product in micro-nano manufacturing and expresses it in the form which computer can deal with, in order to provide effective approaches for enhancing the accuracy of system and decreasing the effects of scale and surface on product design in micro-nano manufacturing.

The digital manufacturing technology of micro-nano mechanical structure. In the current micro-nano manufacturing, the restriction of manufacturing specification makes the micro-nano mechanical components mostly into a simple two-dimensional shape. We usually use multilayer structure method to constitute the three-dimensional mechanical construction. However, the mechanical construction will make micro-nano machinery limited to linear motion or reciprocating motion states and not easy to realize rotary motion, and will affect the movements and motor functions of micro-nano machinery seriously. In certain applications, the advantages of rotary movement will be very evident. Therefore, we say that the two-dimensional structure of micro-nano components has greatly restricted the functional display of micro-nano machinery. The CAx and CAx integration technology in digital manufacturing accurately describes objects in the two-dimensional and three-dimensional space, which improves the ability and productivity to describe product in the production process effectively. Such a digital manufacturing technology will be of great benefit to production of micro-nano in three-dimensional structure with low cost and the promotion of the practical process of micro-nano electromechanical system.

The digital machining technology of micro-nano machinery. Micro-nano mechanical machining technology is a very important research direction in micro-nano manufacturing system. Micro mechanical machining technology is the machining technology which is developed on the basis of silicon plane technique to produce micro mechanical parts and structures for sensors, micro actuators and the micro electro mechanical system, which includes micromachining technology, surface micromachining technology, metal micromachining technology and compound micromachining technology, etc. [14]. With the improvement of micro-machining in manufacturing machinery, the scale of machining is extending to nanometer. Nanofabrication has put forward higher requirements for processing methods and accuracy. The digital machining technology in micro-nano manufacturing describes the change on micro status of processing objects in digital form, such as the changes of objects in geometric shape and size, and the changes of location, direction and physical parameters. It also realizes the digital process of micro-nano machinery to meet the machining-accuracy allowances of product in micro-nano manufacturing.

9.2 The Extremalization of Digital Manufacturing

9.2.1 Extreme Manufacturing

Extreme manufacturing [15, 16] generally refers to the insurmountable front of manufacturing in science and technology, whose connotations change along with the development of science and technology. In the contemporary era, extreme manufacturing refers to an extreme size or device or a system with extreme functions in extreme conditions, in order to work in an extremely harsh service environment. Extreme manufacturing has become the development trend of digital manufacturing technology, and the digitalization of extreme manufacturing has reflected more attractive prospects and has penetrated into various manufacturing fields such as basic industry, electronic information, aviation delivery, military equipment, and so on.

In various extreme circumstances, to manufacture devices and systems with extreme size or high performance is the key characteristic of contemporary extreme manufacturing, which mainly displays within the following three aspects:

Micro-nano manufacturing. Micro-nano manufacturing includes products with an extremely small size and a high precision, such as micro-nano electronic device, micro-nano photoelectric system, molecular device, quantum device and so on. The related concrete contents have been introduced and described in 9.1. Micro-nano manufacturing is the combination of various extreme manufacturing technologies, which has become the most influential industry in the world.

Giant system manufacturing. It produces the key equipments with a great size, extremely complex systems and powerful functions, such as aerospace vehicles, energy dynamic equipments with a super power and super-large metallurgical petroleum chemical equipments.

Strong-field manufacturing. We put substances into various extreme strengthening energy fields and movement environments, leading to realize multiple-scale evolution of geometry and physical properties and integrate enabling system with powerful function which works in various extreme conditions in accordance with the precise physical laws, which forms the strong-field manufacturing.

At present, the key problems of breakthrough of "extreme manufacturing" which exist in the basic theoretical research and key technologies mainly display within the following aspects:

The multi-dimensional and multi-scale evolution of the strong-field manufacturing. In the strong-field manufacturing, the applications of energy are constantly breaking the limitation. Many kinds of energy forms which transcend traditional field, such as electro-magnetic energy, microwave, and chemical energy, etc., are introduced to the strong-field manufacturing, which makes the strong energy field integrate, transmit, absorb and disperse on manufacturing interface. In this domain, we mainly study the contents of energy transmission and transformation as well as material transport process between a super strong processing energy field, giant processed parts and a giant logistic system, in order to explore the multi-scale evolution mechanism of material induced by a super strong energy field and to seek the formation of a super strong physical field on manufacturing interface and the new principles and methods of realizing manufacturing process.

Micro-structure precision forming and selective performance evolution. Micro-forming refers to the manufacture of micro-structure with three-dimensional geometric features, and the micro-modification refers to the modification of the multi-energy bands to the material in micro-manufacturing process. The research contents in this field mainly include: the physical and chemical effects on manufacturing interface such as micro-removal, micro-growth, micro-forming and micro-modification; the transport law of high-density energies and micro-scale materials; the quantum and scale of micro-structure volume and interface;

the mechanism and evolution laws of different energy forms corresponding to material selectivity; the new theory of micro-structure geometry, topology metastasis and performance evolution and the precise expression and measurement of micro-structure geometric shape.

Micro system assembly and function formation. Microintegation makes the micro-structure become the micro-system with specific functions. The research contents in this field mainly contain: the unknown effects and behavior laws of quantum mechanics, dynamics, thermodynamics and micro tribology in the process of micro-driving, micro-manipulation, micro-jointing, micro-assembly in microintegation; the medium metastasis and energy transportation of micro-channel, micro-gap and micro-interface in micro system; the new theories of micro system function and the dynamic formation laws of micro-nano accuracy and the foundation of micro-structure precise manufacturing and micro-nano scale engineering metrology.

The creation of complex function system and the certainty of function state. The research contents of this field mainly include: the morphological evolution from function units to the energies in the complex function system; the state evolution of movement and the schema evolution of functions; the related mechanisms of uncertainty factors; the nonlinear transmission and function certainty in a giant system; and the correlation and interference of various micro-effects on functions in micro system, the purpose of which is to study the system laws created by the functions of giant and micro systems.

The multi-field coupling, random disturbances and stability in the extreme manufacturing environment. Extreme manufacturing system is usually integrated by multi strong fields such as light, machine, electricity, fluid, magnetism and heat. And the existing multi-field coupling and random disturbance may lead to movement distortion, instability and defunctionalization. Therefore, this field mainly studies the transmission and evolution laws of complex coupling behaviors, the aggregation and divergence of energy transfer, the random fluctuated disturbances between manufacturing carriers and receptors in the extreme manufacturing system and explores the formation and control of interactive, high stable, and high accuracy manufacturing processes in regulatory quick-changing process and leading slow-varying process respectively.

9.2.2 Complex Mechanical and Electrical System Modeling

Complex mechanical and electrical system is a “complex system” which is mutually permeated and integrated by multidisciplinary technologies such as machinery, electron, hydraulic pressure and aerodynamic, whose main attached parts are composed of mechanical part, electric control part and liquid pressure, pneumatic and other parts.

Complex mechanical system is a reflection of extreme digital manufacturing. Because various parts are coupled with each other through certain physical relationships, and various parts consist of subsystems through the certain physical relationships. The staggered coupling relationships between various systems and their subsystems make the complex electrical and mechanical system have high dimensions, a large number of units and a complex interprocedural coupling relationship. The above extreme conditions cause essential differences between complex electrical and mechanical systems and general systems in the aspects of structure, function, behavior and others.

The coupling functions which mainly exist in the complex mechanical and electrical system are presented as follows [17]:

Electromechanical coupling. The electrical parameters which originate from the two subsystems of drive and control in an electrical system constitute the complex mechanical and electrical system coupling with the mechanical parameters in a mechanical system through the correlation and integration between subsystems, thus it affects the dynamic and response of the whole system.

Interface coupling. As the whole complex mechanical and electrical system is integrated by the interfaces of various physical processes or structure modules, the existing interface coupling ways are various, and the interface coupling mechanisms and characteristics of different systems are diverse too. The interface coupling is also the interface constraint, whose stability is the condition for the normal operation of this system, so interface constraint has increasingly become the key problem concerned in this research field.

Besides the above coupling functions, there are many coupling factors whose influence on system can not be explained by a single coupling function or their simple addition, and these multiple coupling factors are easy to form complex unknown mechanisms, so as to produce harmful effects on the whole system. Facing the existing coupling functions and complex multiple coupling factors, we must use the integrated modeling method oriented to complex electromechanical system and carry out further researches and discussions on its dynamic coupling mechanism, in order to realize the optimization of performance in the whole system [18].

The complex mechanical and electrical system is integrated by global multi-process coupling in network. We need to use the appropriate mathematical methods to describe the topologic relationship in global multiple coupling while establishing the coupling model of physical processes, which is shown in Fig. 9.3 [17].

The coupling factors extraction refers to using engineering practices and experiments to get the basic features about coupling problems such as the levels, types and carriers of coupling and coupling parameters, which are the basic premise for analysis.

The local coupling question of modeling is to decouple local coupling factors from global coupling and decompose their related coupling parameters, so as to establish the mathematical model of complex mechanical and electrical system by theoretical and experimental modeling methods. Local coupling mathematical models are divided into an analytical models and a statistical model.

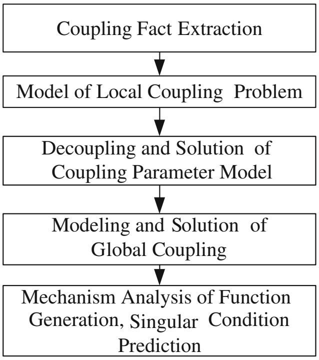

Fig. 9.3 The global coupling analysis diagram [17]

Through decoupling and solution to coupling parameter model, we carry out analysis, modeling and solution to the global coupling structure system based on the basic law of coupling parameters, thus it is important to seek a dynamic synthesis method that is suitable for global coupling. The basic purpose of analyzing global coupling model in complex electrical and mechanical systems is the further study of organization rules created by system functions, which will obtain the prediction and trouble-precontrol on a singular condition by exploring and analyzing the restraint mechanisms of coupling on movement and the relevant mechanisms between coupling parameters with the main movement and functions of system.

The literature [19] has proposed a kind of global modeling method of complex electrical and mechanical system through recursive group collection method. This modeling method establishes the monomer dynamics model of mechanical system on the basis of the topology and Jordan variational principle of complex electrical and mechanical system, and use the recursive group collection technology to establish the dynamics model for the tree-type complex electrical and mechanical system. In addition, this method also uses the modeling method of tree-type system to establish the dynamics model of non-tree-type system. Based on this, through the establishment of mechanical and electrical coupling constraint function, we uses the constraint function and electromechanical system equation, finally to establish the global model of complex electrical and mechanical system. The global research of the complex electrical and mechanical system has provided a common and simple global modeling method.

9.2.3 *The Theory and Technology of Electrical and Mechanical Systems in Extreme Environments*

In extreme manufacturing, electrical and mechanical systems often work in an extreme atrocious service environment. Extreme environmental conditions such as high-temperature, high-pressure and high-speed, as well as temperature field, pressure field, electromagnetic field and multi-source incentives make no small challenge for ensuring the efficient, reliable and safe operation of electrical and mechanical devices.

With the continuous development of modernized great production and the continuous progress of science and technology, the electrical and mechanical devices are moving toward the direction of large-scale, high-speed, precision and continuous operation, as well as the complex integration of light, machine, electricity, fluid, meter and computer, which make the scale of production system bigger and bigger, the structures become more and more complex, the functions becomes greater, the performance index becomes higher, the work intensity becomes heavier and the mutual function and coupling become stronger [20]. In the extreme condition from exterior and their own, the possibility of failure on electrical and mechanical devices will increase, and the appeared mode will be more complicate. If the failure caused by the extreme work environment cannot be detected or removed, it may cause the failure and paralysis of the whole system or even results in major disastrous consequences. Therefore, the monitoring and diagnosis of electrical and mechanical devices in extreme work environment, particularly digital monitoring and remote diagnosis, have become the highlight and difficulty of mechanical and electrical system theoretically and technologically in the current extreme circumstances [21].

Failure diagnosis technology was born in the 1960s, which was applied to the key parts of devices and single small devices at first. The traditional failure diagnosis technology used the technologies such as oil analysis, acoustic emission analysis and vibration signal analysis, which established various rotating, reciprocating machinery monitoring the failure diagnosis systems, and proposed observer/filter, parameter estimation, analytical redundant, evidence theory, pattern recognition and so on [22]. However, the object devices in these methods are relatively simple, neglecting the influence of environmental factors and human factors on devices, and no considering about the coupling relationship between various devices, it cannot be directly applicable in the monitoring and diagnosis of electrical and mechanical devices in extreme environment. In addition, the extreme environmental factors will also make some traditional sensing equipments disable, such as strain gauge and piezoelectric conventional electric measurement sensors.

As the multi-field coupling and random disturbances in the extreme environments may mutate to movement distortion, instability and defunctionalization of electrical and mechanical devices, and the applications of traditional sensing equipment in certain extreme environments also exist limitation, which causes many difficulties in the monitoring and diagnosis of electrical and mechanical devices in extreme environments, and there is no integrative theories and methods at present.

The large rotating machineries which work in extreme conditions such as aviation engines, compressors, hydraulic and steam turbine, electric motors, blowers and large-scale water pumps, are the main mechanical devices in the industries such as aerospace, petrochemical industry, electricity, metallurgy, coal, nuclear and so on. These large rotating machineries usually operate in extreme conditions, so the “health” status of their operation states directly affects the production and security of major projects.

The main features of the condition monitoring system in early large rotating machinery are: the adopted sensors are mainly electrical measuring sensors, such as the eddy current sensor which is used in rotor measurement of large rotating machineries; measuring signals are mainly the vibration, noise and strain of large rotating machineries; signal transmission mainly uses the field bus technology; signal analysis and processing uses the digital optimal calculation, artificial intelligence and other advanced methods. However, because the singleness and anti-interference ability of points and parameters in electrical measuring sensors are weak, it makes the on-line condition monitoring of multi-parameter distribution hard to achieve, as the influence of size, quality, and other factors of electrical measuring sensors makes it hard to carry out effective on-line condition monitoring in some key positions in some large rotating machineries. In fact, with the development of industrial technology, large rotating machineries express the high-speed developing trend under a high pressure and a high temperature, which makes the change of temperature, pressure, stress and strain and vibration in large rotating machineries display diversity, nonlinearity, coupling and time variation. Obviously, for this developing trend of large rotating machineries, the use of strain gauge, piezoelectric and other conventional electrical measuring sensor technology is hard or even impossible to carry out the on-line condition monitoring of multi-parameter distribution. Therefore, it is hard to accurately monitor and clearly understand the state change and their influencing factors of various large rotating machineries, which severely restricts the optimization of design as well as their manufacture and operation maintenance.

Fiber bragg grating sensor is a new kind of optical measuring sensor. Since 1978 when it came out, it has become an important new branch of sensor technology after 20 years of development. Fiber bragg grating sensor has the following characteristics: small size, explosion-proof, electrical insulation, anti-electromagnetic interference, high accuracy, high reliability, the good adaptability to environment, as well as many measuring gratings in view of different parameters are arranged on a single fiber to form the distributed sensor. Therefore, the advantages of fiber bragg grating sensors make it replace electrical measuring sensor and be applied to condition monitoring systems of large rotating machineries.

With the research and development of digital manufacturing, a kind of new digital detection method has been presented and brought new hope for the online, real-time, dynamic, distributed monitoring of manufacturing devices in extreme conditions, which is fiber bragg grating sensor. Fiber bragg grating sensor is used in dynamic detection of large rotating machineries, which will bring about a revolution and new scientific challenges for mechanical equipments in extreme service conditions.

On the basis of fiber bragg grating sensors, wavelength demodulation is proposed with features of embedded, wide-band and high-speed. Wavelength “demodulation” is the key link of signal decoding in fiber bragg grating sensing system. Various wavelength demodulation theories, methods and technologies such as "interferometry", "scanning filtering method", "matching filter method" and "edge filtering method" have also the technical problems of another theoretical science in this research. The current theories and methods are based on the scanning filtering method of "Fabry–Perot" filter, and this method has been widely applied in "static" or "quasi-static" fiber bragg grating sensing system. However, due to the restriction of demodulation velocity, the theory and technology can not be applied to high-speed changing dynamic monitoring systems and particularly the multi-parameter, high-capacity and distributed on-line monitoring systems. Besides, for the real-time on-line monitor of the large rotating machinery, it also needs the miniaturization of monitoring system, so the research on embedded high-speed demodulation system is a key scientific and technical issue in this field.

Large rotating machinery usually exists in high-temperature, high-pressure, high-speed and extreme work conditions, and its conditions varies complicatedly, the influencing factors couple with each other. Therefore, the key problems of carrying out on-line state monitoring are the coupling mechanism of various factors, the adaptation properties of dynamic monitoring systems and the design method of monitoring network. The main problems include: the running state of large rotating machinery; the effects of coupling matching and mechanisms of monitoring system; the principles and ranges of influencing factors and their coupling effects of multi-parameter distributed state monitoring systems; the multi-parameter distributed state monitoring network model based on fiber bragg grating sensors and compensation theories and methods.

The transmission and processing of multi-sensor data from optical fibers are in high-speed, high-temperature and high-pressure environment. For the state monitoring system of large rotating machinery within the restriction of space position, we need to resolve the scientific issues such as fast and effective transmission of multi-parameter large-capacity distributed data in high-speed, high-temperature and high-pressure conditions. The main issues include: the attenuation mechanism and compensation of transmission by multi-sensor data from optical fibers, as well as the anti-interference source-channel joint-coding method; the synchronization principle, method and the assessment of synchronization precision on multi-parameter large-capacity distributed data; the space, time model and its real-time processing method of fiber transmission data, which include data fast registration principle, feature extraction and fusion algorithm of multi-sensor heterogeneous information in space domain.

The integration and implementation of online state monitoring system are based on multi-parameter distributed sensor network. According to the practical problems on on-line condition monitoring of large rotating machinery such as aeroengine, we study the model and design of multi-parameter distributed on-line state monitoring systems based on fiber bragg grating sensors, which includes data calculation and processing, characteristic information recognition, human–machine interface and visualization. We make it feasible and effective by the application and analysis of practical on-line monitoring.

The breakthrough of the above scientific challenges and technical difficulties not only provides scientific and technical supports for the design manufacture and operation maintenance of large rotating machinery in extreme atrocious service conditions and extreme conditions, but also has great scientific and practical significance to enrich and develop modern testing science and technology in extreme environments and enhance the level of digital technology in extreme manufacturing.

9.3 The Environmental Protection of Digital Manufacturing

9.3.1 The Implementation on Environmental Protection for Environmental Protection

The manufacturing industry has made great contributions for the prosperity of human, and has produced nearly 5.5 billion tons of harmless waste products as well as 700 million tons of harmful waste products. In the past, people paid attention to how to deal with and eliminate the harmful and harmless waste products of industry, unfortunately it is not effective in preventing environmental pollution. Therefore, in order to effectively protect the environment, we must carry out pollution control in various stages of manufacture. Products have effects on the environment in various stages of its effective survival, so it is necessary to evaluate how products influence environment in various stages so as to support the design and manufacture, which is a kind of advanced manufacturing technology with environmental protection consciousness—environmentally conscious design and manufacturing (ECDM) [7].

The benefits of ECDM are to make the production manufacturing process safe and clean, to protect the environment and keep workers healthy, to enhance the quality of products with the lowest cost, and to improve the public image and productivity. The practice of ECDM will allow manufacturers to minimize pollution, and change waste products into useful products.

ECDM refers to a reduction of the impacts on industrial activities without sacrificing quality, cost, reliability performance or energy utilization efficiency. ECDM emphasizes that extracting useful products from raw materials, avoiding the waste of production resources and using waste products to manufacture other products. It is a kind of manufacturing which includes the design, integration, processing and use of continuous or separated manufacturing products in the aspects of society and technology. It is different from the traditional method which uses packing to control pollution, ECDM takes measures in advance to minimize the pollution of products on environment, which will enhance the competitiveness of products in markets of environmental protection consciousness.

Zero-waste lifecycle. ECDM reduces the influence of products on environment to zero in the validity of products. The key of this method is to create a continuous product cycle as far as possible, and the sustainable products refer that products are

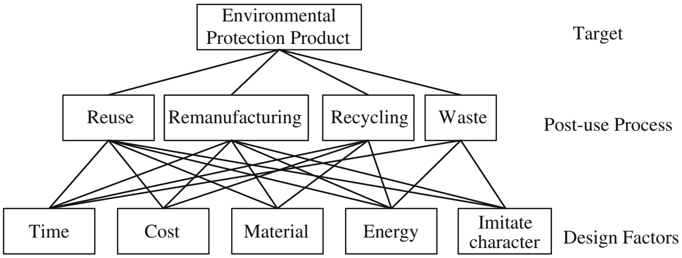

Fig. 9.4 The grading system of environmentally conscious design and manufacturing

designed, manufactured, sold, used and processed, in order to make these products have the least impact or no impact on environment and health and use the least resources. The sustainability of system refers that the system maintains and extends its existing capacities.

The control on life period of waste products. Using the hypothesis that there are certain negative influences on the current production cycle as the premise, these harmful effects are reduced or eliminated by some advanced technological means and methods which are controlled by waste products life cycle. The essence of this approach is to reduce the harmful effects of harmful substance by clean technology.

The grading system of environmentally conscious design and manufacturing. The grading system of environmentally conscious design and manufacturing is shown in Fig. 9.4. The grading system of environmentally conscious design and manufacturing mainly has three layers: the first layer carries out comprehensive consideration, taking the creation of environmental protection products for purpose; the second layer expresses as the process used for realizing the target; the third layer is composed of five design factors which are beneficial to the process of follow-up use as well as the realization of the whole objective. The grading system shows the method for dealing with waste products, and designers abandon or reuse products, or recycle partial or the whole products.

9.3.2 Environmentally Conscious Manufacturing

9.3.2.1 The Concept and Connotation of Environmentally Conscious Manufacturing

The influence of digital manufacturing on environment acts in each stage of product lifecycle, which includes the development, manufacture, use and final disposal of products. In the process of transforming manufacturing resources into products, as well as use and waste disposal of products, it will not only consume a large number of limited resources, but also causes environmental pollution. So the concept of "environmentally conscious manufacturing" is proposed [23], in order to solve the existing problems in this field.

As the concepts and connotations of environmentally conscious manufacturing are still in incessant development and perfection, there is no uniform definition at present. For environmentally conscious manufacturing, a relatively comprehensive definition is as follows [24]:

Environmentally conscious manufacturing is a modern manufacturing model which comprehensively considers environmental impact and resource efficiency, whose goal is to make the impact (negative effect) of products on environment become zero or very small, resource consumption becomes almost least in product lifecycle from the beginning of design, manufacturing, packaging, transportation, uses to scrap disposal, and the economic and social benefits of enterprises co-ordinatively optimize.

From the above definition, the environmentally conscious manufacturing has profound meaning, which mainly manifests in [25]:

Environmentally conscious manufacturing mainly involves the questions of manufacture, environmental impact and resource optimization, which are the cross and integration of these three parts;

The “manufacturing” in environmentally conscious manufacturing involves the product lifecycle process and embodies the characteristics of modern manufacturing science which has “large scale, a lot of processes, interdisiplinarity”;

The contents which are covered by environmentally conscious manufacturing are wide, green design, green planning, clean production and green package, which are proposed in recent years and may become integral parts.

Environmentally conscious manufacturing is a modern manufacturing model which fully takes resources and environment problems into considerations.

Environmentally conscious manufacturing is the embody of the implementation of global sustainable development strategy of human society in modern manufacturing industry.

9.3.2.2 The System of Research Content of Environmentally Conscious Manufacturing

The system of environmentally conscious manufacturing is shown in Fig. 9.5 [26], which includes the theoretical system and general technology of environmentally conscious manufacturing, the special technology of environmentally conscious manufacturing and the supporting technology of environmentally conscious manufacturing.

The theoretical system and general technology of environmentally conscious manufacturing. From the global and integrated perspective, different systems have their own components and highlights, the researches on the theoretical system involve resources attribute, modeling theory, operation characteristics, sustainable development strategy, system characteristics and integration characteristics; the system structure and multiple lifecycle engineering of environmentally conscious manufacturing, consists of target system, functional system, process system, information structure, operation mode and so on; the system running pattern of

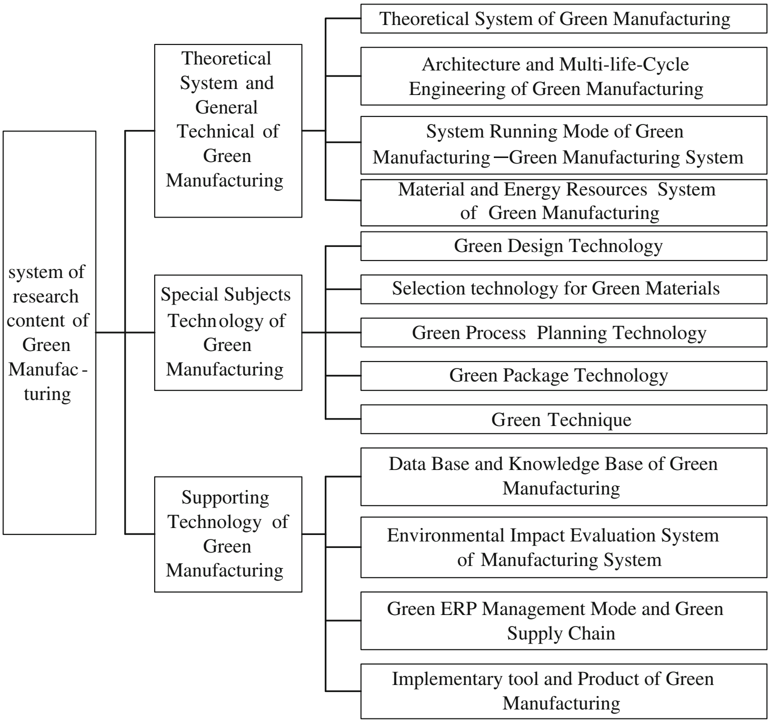

Fig. 9.5 The system frame of research content of environmentally conscious manufacturing [26]

environmentally conscious manufacturing (namely environmentally conscious manufacturing system) is composed of environmentally conscious design, product lifecycle and its logistical process, the extension of product lifecycle and its related environment, etc.; the material and energy resource system of environmentally conscious manufacturing mainly studies the problems such as the resource consumption law of manufacturing system and its optimization technology, the environment-oriented product material selection and the management and control of logistics and energy based on product lifecycle.

The special technologies of environmentally conscious manufacturing mainly include green design, choosing green material, green process planning, green package and green treatment.

Green design technology means that in the design of product, we fully consider the function, quality, development cycle and cost, and optimize the relevant design factors, in order to minimize the overall impact of product and its manufacturing process on the consumption of resource and environment.

While choosing materials, it is essential to consider not only the green attributes of materials, but also the requirements of products on materials in function, quality, cost and so on.

Green planning technology is to plan and use the route which has less materials and energy consumption, less wastes and less environmental pollutions.

Green packaging technology is to optimize the packaging methods products from the perspective of environmental protection, in order to make the resource consumption and waste production become the least.

Green treatment technology mainly pays close attention to the recovery issues of the environment-oriented products. It is a systematic project, so we must fully consider these issues from the beginning stage of product design and make further systematic classification.

The supporting technology of environmentally conscious manufacturing. The database and knowledge of environmentally conscious manufacturing mainly provide the supports of data and knowledge for green design, selection of green material, green planning and recovery scheme.

Environmental impact assessment system of manufacturing system mainly evaluates the resource consumption and environmental impact in each link of the product lifecycle, such as the consumption status of material resource in manufacturing process and energy in manufacturing process, the pollution status of manufacturing process and products application on environment and the pollution status on environment after the end of lifecycle, and so on.

In the environmentally conscious manufacturing of enterprise, we must think about the resources consumption and environmental effects as well as its corresponding the costs of resource and environmental protection, in order to improve the economic and environmental benefits of enterprises. In this field, the green ERP management mode and green supply chain will be a research emphasis in the future.

The implementation tools and products of environmentally conscious manufacturing mainly contain computer-aided green design system, green planning system, the decision support system of environmentally conscious manufacturing and the support system of ISO international certification.

9.3.2.3 Digital Green Manufacturing System

In environmentally conscious manufacturing, the support of CAD/CAE/CAM technologies is also of the essence [27]. Therefore, the digital technology with advanced manufacturing means is applied to the research and application of environmentally conscious manufacturing, and provides technical support for its development. Figure 9.6 shows the relationship between the manufacturing digitalization and manufacturing green revolution. These two groups are the innovations of manufacturing system at different levels and angles, which are supplementary to each other. Manufacturing digitalization has provided a series of technical supportive tools for manufacturing green revolution, while manufacturing green revolution has further expanded the connotation and application of manufacturing digitalization.

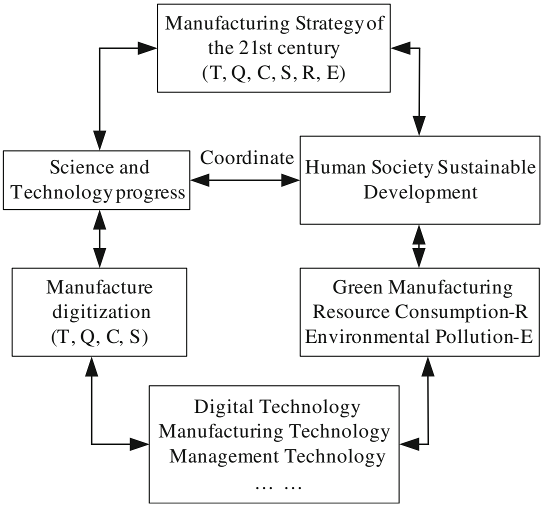

Fig. 9.6 Manufacturing digitalization and green revolution [27]

Digital green manufacturing system (DGMS) [27] is the organic combination of manufacturing digitalization and manufacturing green revolution, which has provided an effective model for solving the design and manufacturing of digital green manufacturing and becomes an important method to break through the bottleneck of green manufacturing. It comprehensively uses the modern manufacturing technology, information technology, digital technology, management technology, control technology and environmental technology to effectively make use of various resources, as well as information flow, material flow, energy flow and capital flow, in order to realize the global optimization of enterprises and ecological environments.

The architecture of digital green manufacturing system is shown in Fig. 9.7, which is composed of management decision layer, product decision layer and production decision. The three layers cooperatively work in integrative hardware-software supporting environment, leading to the global optimal decision. The function modules of the system include product design module, material selection module, process planning module and monitoring module, which realize the these functions on products, such as digital management, product digital design, manufacturing, packaging, demolition, recycling, green assessment and so on.

Sustainable development is the development theme of the current manufacturing industry, while green manufacturing is the future trend of digital manufacturing science. With the development of digital manufacturing science and the breakthrough of its key technologies, digital green manufacturing that completes the digital green manufacturing, and develops digital green products will become the important way to enhance the market competitiveness of enterprise products and have great significances for the sustainable development of human society.

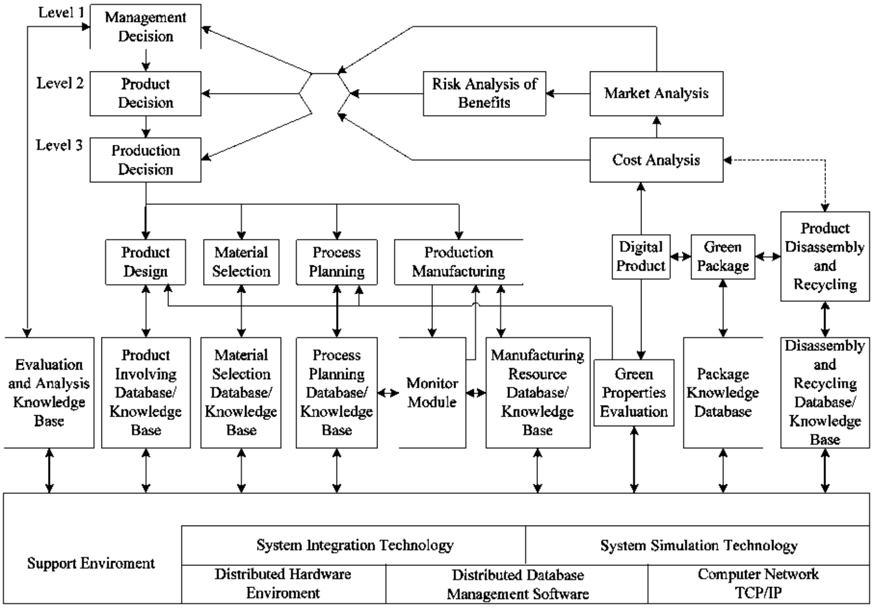

Fig. 9.7 The architecture of digital green manufacturing system [27]

9.3.3 Remanufacturing Engineering

9.3.3.1 The Concept and Connotation of Remanufacturing Engineering

Remanufacturing engineering is the term that takes the lifecycle design and management of electromechanical products as the guidance, considers the realization on the performance leap-type promotion of waste electromechanical products as target, looks the high quality, high efficiency, energy saving, environmental protection as the criteria, seems the advanced technology and industrial production as the methods, as well as repairs and changes a series of technical measures or engineering activities [28–30].

There are some essential differences between remanufacture, maintenance and recycling [28]:

Maintenance is to keep good operation status of produces by technical measurements. However, the maintenance are often difficult to reach new levels.

The recycling takes remelting as the basic way. When the products are melts down, the original energy value, labor value and other additional value will be completely lost, and we will only use raw materials. In addition, more energies will be consumed in remelting and its subsequent forming process.

Remanufacturing disassembles a large number of congeneric scrap of products firstly, then collects and detects those pieces according to the types, and the batch

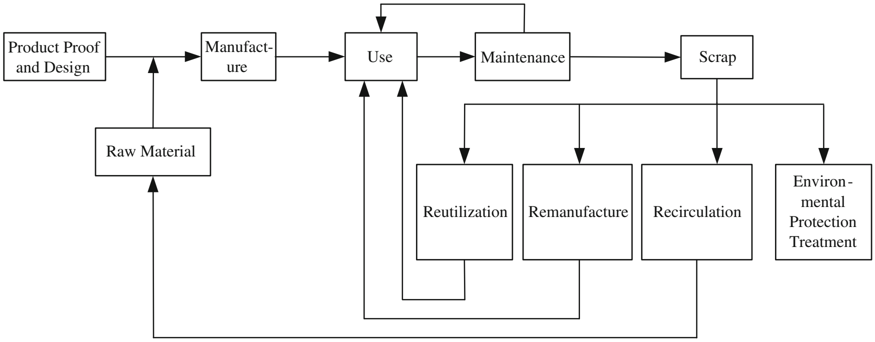

Fig. 9.8 The position of remanufacturing in product lifecycle [30]

repair and function upgrading are carried out on the scrap parts through high technologies, at last, the remanufacturing products reach a new level in technical performance and quality.

The position of remanufacturing in product lifecycle is shown in Fig. 9.8, and we can see the difference between manufacture, maintenance and recycle. After products reach service life, a lot of the components are reused directly, and the others need to use the processing or transformation of remanufacturing technology for continuous usage. Due to the restriction of technical condition or poor remanufacturing economy, a number of components need to be changed into raw materials to continue to use through recycling method. We must carry out environmental protection for the remaining components which cannot be repaired, remanufactured or recycled.

9.3.3.2 The Key Technology of Remanufacturing Engineering

Remanufacturing engineering technology is an important part of remanufacturing engineering. The remanufacturing of waste products is realized by combining various current high technologies, and many of these technologies are the key technologies formed by the timely absorption of current scientific and technological achievements. The key technologies of remanufacturing engineering mainly include [31]:

Advanced surface technology. In some harsh conditions, the single surface technology is hard to meet the requirements of product performance, so we must compound it with other surface technologies to form multi-element multi-layer complex coating layer with different functionalities on products, so as to improve product performance and meet the needs of users.

Remanufacturing blank rapid prototyping technology. This technology uses waste parts as its blanks of remanufacturing parts, collects the geometric information of products extracted from CAD model, and relies on integral principles and laser coaxial scanning technology to carry out fused deposition on metals, thus completes the rapid prototyping of remanufacturing parts.

Nano-coating and nano antifriction self-repairing technology. This technology is based on nano-powder materials, and uses special processes to strengthen, modify and give new features to solid surface, or carries out self-repairing to damaged surface.

Restoration heat treatment technology. In the long-term large equipment, some important components (such as turbine blade, superheated boiler tube, various rotors, engine crankshaft and so on) often have manufacturing process with great capital outlay, and are all expensive, but they are only recycled as steelmaking waste after the failure, which causes serious wastes. In view of such problems, restoration heat treatment technology restores the whole service performance of components through reestablishing internal microstructure under the limitation of permissible thermal deformation range.

9.3.3.3 Digital Manufacturing Technology in Remanufacturing Engineering

Digital manufacturing technology attaches great importance to the technology of reducing production resources waste and decreasing environmental pollution. Through the analysis on the lifecycle cost of products, we see that the cost consumed by the usage and maintenance of equipments is usually several times of the total cost consumed by development, design and manufacture. With the development of digital manufacturing technology, manufacture and maintenance will become more and more integrative, and maintenance technology will completely penetrate into the manufacturing process of product lifecycle. Remanufacturing technology meets the requirements of saving energy and material and reducing environmental pollution, which not only carries out incessant technical transformation to equipment product and decreases subsequent cost, but also extends the connotation in the lifecycle of equipments and effectively prolongs the service life of equipments, thus it is able to obtain more profits [32]. Generally, it is said that remanufacturing engineering is the important development direction of digital manufacturing science.

At present, some digital manufacturing technologies have been effectively applied in remanufacturing engineering and a great reform happens in this field, which provides an effective way to promote the remanufacturing efficiency of products. The literature [33] described a kind of equipment remanufacturing digital platform based on knowledge, and the platform is based on the corresponding theoretical basis, such as virtual simulation foundation, KEB definition and its foundation, and is assisted by three-dimensional digital software and simulation software, which provided possibility for the generalization, seriation and intelligence of remanufacturing equipment.

In remanufacturing engineering, the objects of equipment remanufacturing are no longer raw materials but discarded equipments. Based on this, we use digital modeling technology to create the model in original equipment under normal circumstances and the model after remanufacture. These models have the information of the shape, feature and function of equipment, which facilitate the appropriate analysis, treatment and processing to equipments.

We also virtually realize the remanufacture of equipment on computers through digital technologies. Some new studies have combined the virtual manufacturing with the remanufacturing engineering and proposed the concept of virtual remanufacturing [34]. In remanufacturing digital platform, we virtually realize the remanufacturing scheme of products through computers and carry out analysis and evaluation as well as optimum design decision on it. This platform also has virtual remanufacturing processing functions, which realizes the virtual processing of equipments through establishing the virtual simulation of equipment remanufacturing and provides scientific basis for the actual decision of equipments.

Product quality is the standard to measure the remanufacturing industrial value of equipment and dynamically monitor the geometric parameters and mechanical parameters of products in remanufacturing process, in order to ensure the remanufacturing quality of equipments.

To sum up, the combination of digital technology and remanufacturing engineering effectively achieves the virtual simulation of products from the selection of optimization scheme, virtual remanufacturing processing to the quality control of remanufacturing product, and subsequently provides a scientific and reliable basis for the actual remanufacture of equipments and products, which is the effective way to enhance the remanufacturing engineering technology and equipment performance.

9.4 Summary

This chapter emphatically introduces the research contents and status of precision, extremalization and environmental protection of digital manufacturing, all of which constitute the key research direction of the future development in the digital manufacturing science. With the deepen researches on above problems, it will certainly promote the rapid development and improvement of the theories and technological systems in the digital manufacturing science and lead the whole human society into digital manufacturing era.

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