

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

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

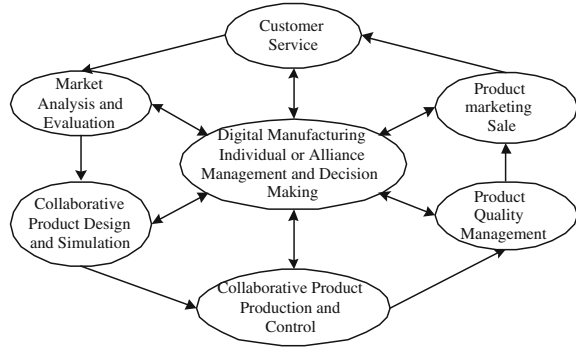
The basic process of the digital manufacturing means that the design, simulation and production of a product are completed in a digital environment. That is to say, after receiving orders, a conceptual design and general design are first carried out, followed by a computer simulation or rapid prototyping 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.

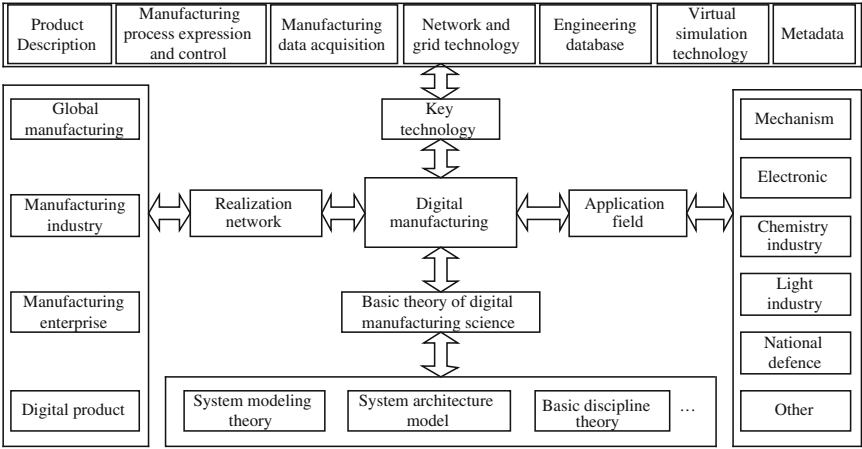


Fig. 2.2 Architecture of digital manufacturing system

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 byumbaugh. 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.

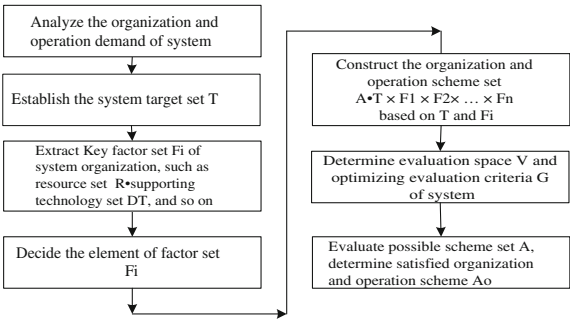
Second step: Synthesis. In this step, the analysis results should be synthesized, and it is important to determine the solving scheme and evaluating method.

(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 ($i = 1, 2, \dots, n$) 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.

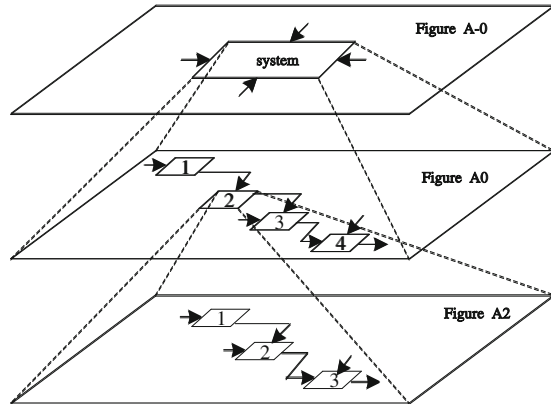
The obtained system model S reflects the relationship of the key elements that make up the system, and any constitutive relationship is on behalf of a state of system constitution. The satisfied relation getting through the evaluation is a selected organization structure, the necessary and sufficient 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.

IDEFIX 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.

IDEFIX 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 IDEFIX 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 IDEFIX 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

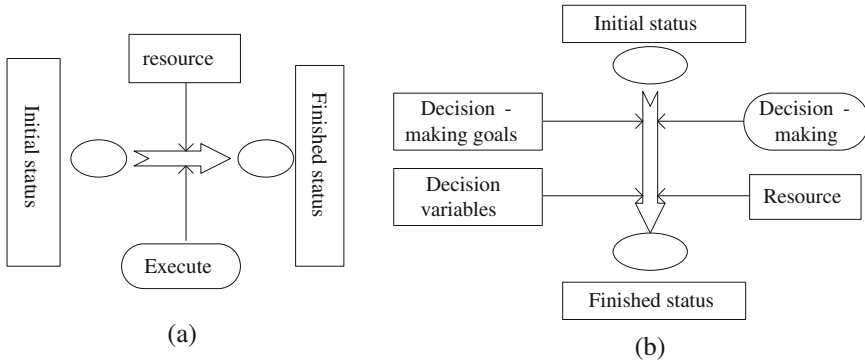


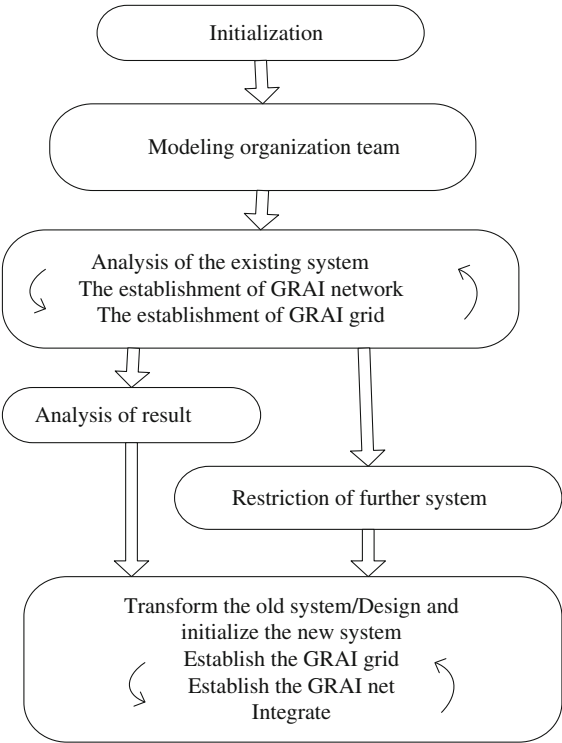
Fig. 2.5 The expressing method of GRAI network activities. (a) Executive activities; (b) decision-making activities

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

Transition set $T : T(T_1, T_2, \dots, T_m)$ 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 $\mu : \mu(P_1, P_2, \dots, P_n)$ 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 “ $\rightarrow$ ” for connection of location and transition, marked by a black point, thus “ $\odot$ ”.

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

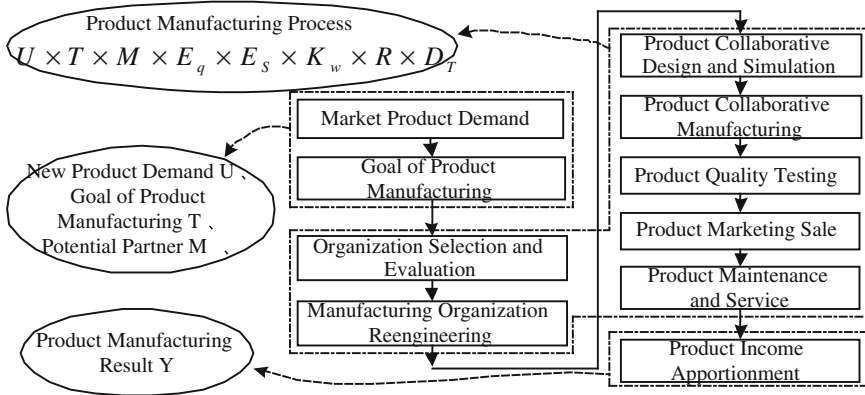
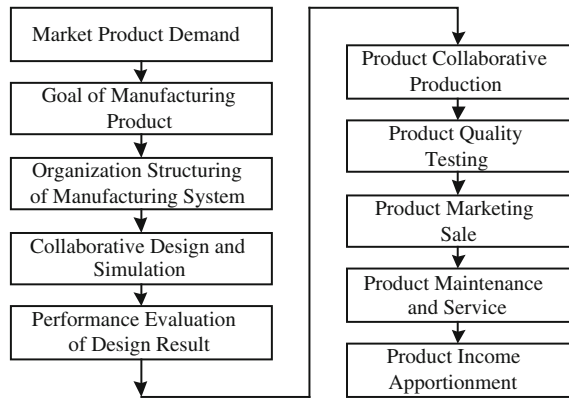
of the digital manufacturing system is obtained by using the modeling method of a generalized model. Secondly, according to the definition of the digital manufacturing system and the requirement of a system operation reference mode, the organization model of the digital manufacturing system is constructed 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 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 composite 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:

$$\text{DMS} = \langle U, M, T, E_q, E_S, K_w, R_E, D_T, P, G \rangle$$

The generalized model is:

$$\left. \begin{aligned} P &: U \times M \times T \times E_q \times E_S \times K_w \times R_E \times D_T \rightarrow Y \\ G &: U \times M \times T \times E_q \times E_S \times R_E \times K_w \times D_T \times Y \rightarrow V \\ S &= ((U, M, T, E_q, E_S, K_w, D_T, R_E, Y), P) \end{aligned} \right\} \quad (2.1)$$

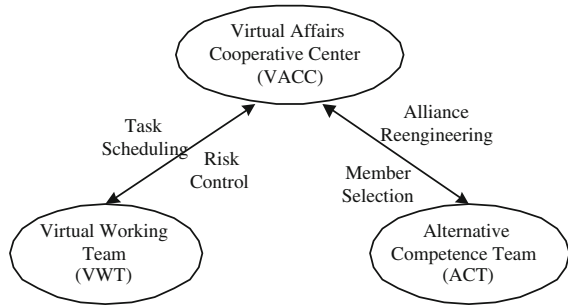
In this equation, S represents the digital manufacturing system.

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.

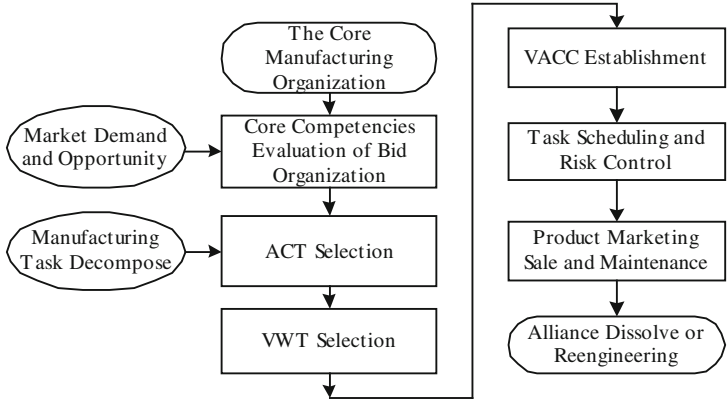


Fig. 2.10 Operation process of virtual manufacturing alliance organization

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

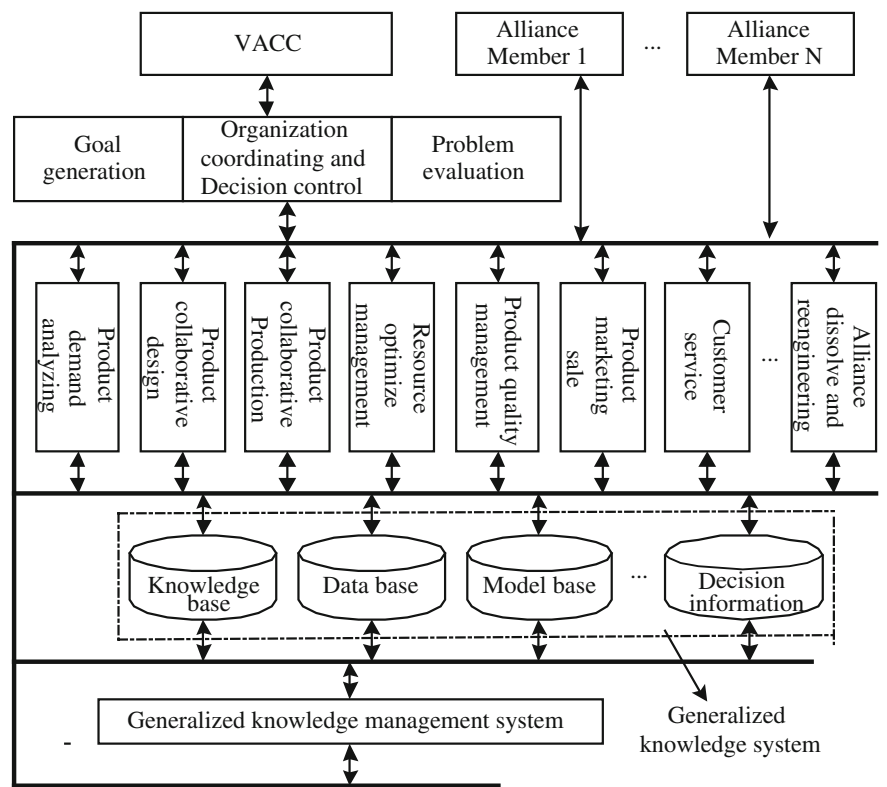


Fig. 2.11 The general function structure model of digital manufacturing system

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.

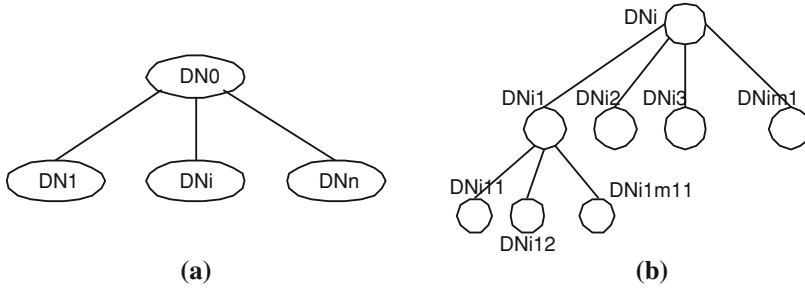


Fig. 2.12 Information structure model of digital manufacturing system. (a) The inter-domain information structure; (b) the intra-domain information structure

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 (DN_0) and the members domain node ($DN_1 \dots DN_n$). 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 $DN_{i1} \dots DN_{im_1}$ 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 composite 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

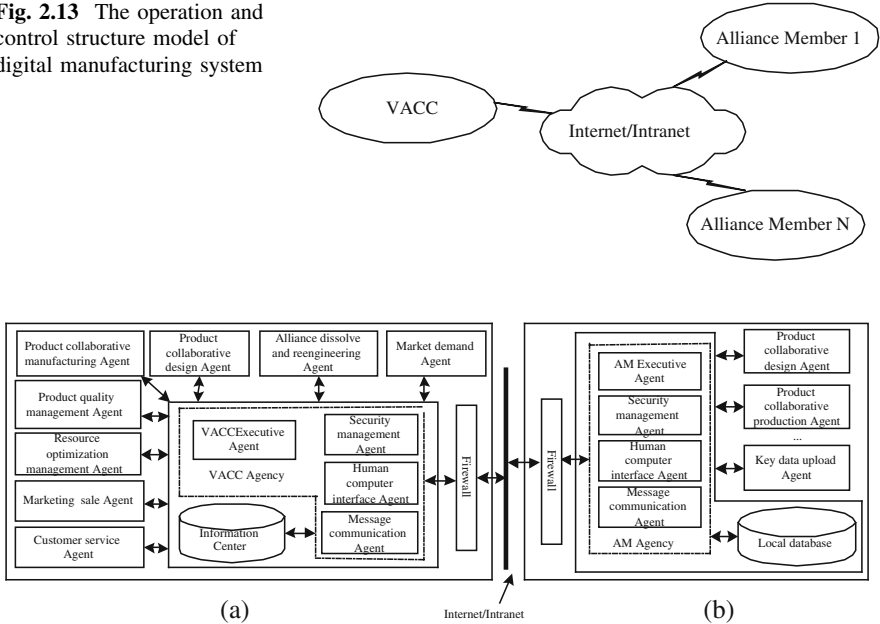


Fig. 2.14 Operation and control structure of Agent-based digital manufacturing system. (a) Agent-based VACC; (b) Agent-based alliance member

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 multi-disciplines 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

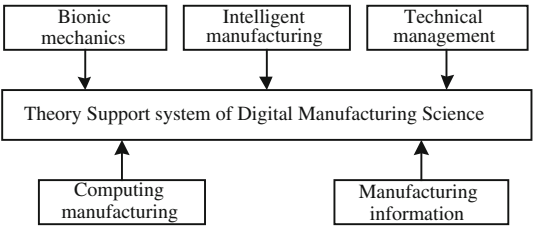
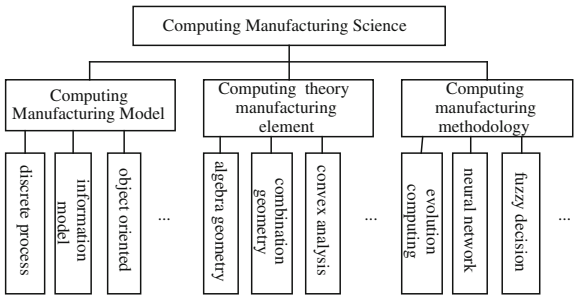


Fig. 2.16 The connotation of computing manufacturing theory



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.

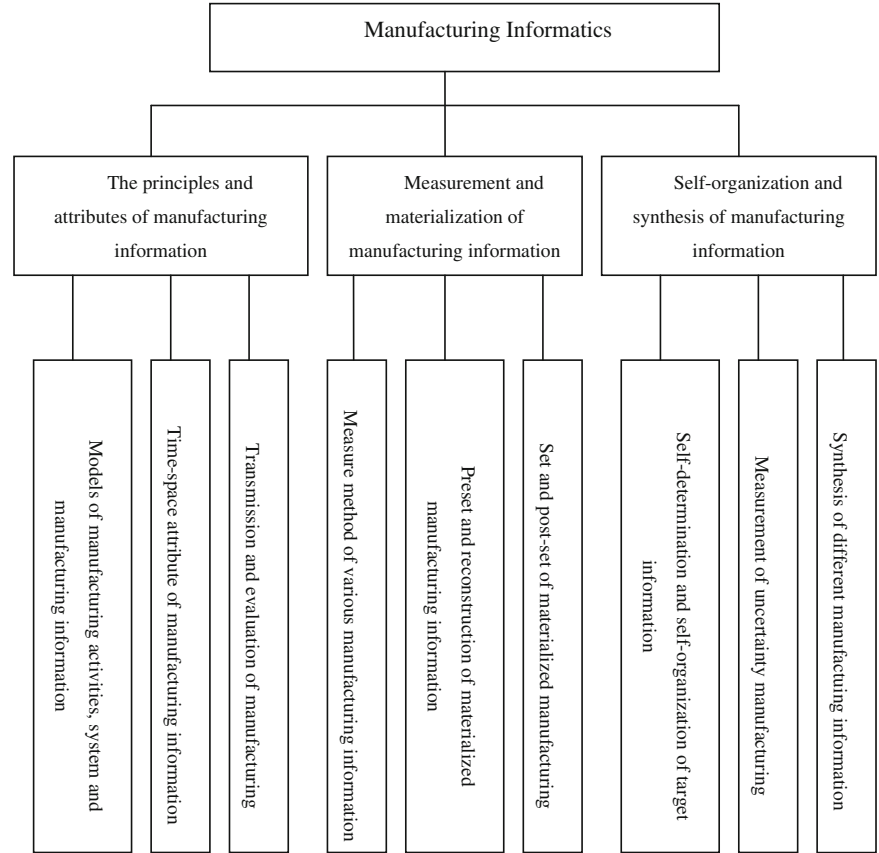


Fig. 2.17 The basic connotation of manufacturing informatics

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 as 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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<http://www.springer.com/978-0-85729-563-7>

Fundamentals of Digital Manufacturing Science

Zhou, Z.; Xie, S.; Chen, D.

2012, XIV, 366 p., Hardcover

ISBN: 978-0-85729-563-7