CHAPTER 15

COMPUTER INTEGRATED MANUFACTURING

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1. INTRODUCTION

Joseph Harrington introduced the concept of computer integrated manufacturing (CIM) in 1979 (Harrington 1979). Not until about 1984 did the potential benefits the concept promised begin to be appreciated. Since 1984, thousands of articles have been published on the subject. Thanks to the contributions of researchers and practitioners from industries, CIM has become a very challenging and fruitful research area. Researchers from different disciplines have contributed their own perspectives on CIM. They have used their knowledge to solve different problems in industry practice and contributed to the development of CIM methodologies and theories.

2. CIM DEFINITIONS AND CONCEPTS

2.1. Manufacturing Environment

From the name ‘‘computer integrated manufacturing,’’ it can be seen that the application area of CIM is manufacturing. Manufacturing companies today face intense market competition, and are experiencing major changes with respect to resources, markets, manufacturing processes, and product strategies. Manufacturing companies must respond to the rapidly changing market and the new technologies being implemented by their competitors. Furthermore, manufacturing, which has been treated as an outcast by corporate planning and strategy, must become directly involved in these critical long-range decisions. Manufacturing can indeed be a formidable competitive weapon, but only if we plan for it and provide the necessary tools and technologies (Buffa 1984).

Besides the traditional competitive requirements of low cost and high quality, competitive pressure for today’s manufacturing companies means more complex products, shorter product life cycles, shorter delivery time, more customized products, and fewer skilled workers. The importance of these elements varies among industries and even among companies in the same industry, depending on each company’s strategy.

Today’s products are becoming much more complex and difficult to design and manufacture. One example is the automobile, which is becoming more complex, with computer-controlled ignition, braking, and maintenance systems. To avoid long design times for the more complex products, companies should develop tools and use new technologies, such as concurrent engineering, and at the same time improve their design and manufacturing processes.

Higher quality is the basic demand of customers, who want their money’s worth for the products they buy. This applies to both consumers and industrial customers. Improved quality can be achieved through better design and better quality control in the manufacturing operation. Besides demanding higher quality, customers are not satisfied with the basic products with no options. There is a competitive advantage in having a broad product line with many versions, or a few basic models that can be customized. A brand new concept in manufacturing is to involve users in the product design. With the aid of design tools or a modeling box, the company allows the users to design the products in their own favor.

In the past, once a product was designed, it had a long life over which to recover its development costs. Today many products, especially high-technology products, have a relatively short life cycle. This change has two implications. First, companies must design products and get them to the market faster. Second, a shorter product life provides less time over which to recover the development costs. Companies should therefore use new technologies to reduce both time and cost in product design. Concurrent engineering is one method for improving product design efficiency and reducing product costs. Another new paradigm is represented by agile manufacturing, in which the cost and risks of new product development are distributed to partners and benefits are shared among the partners. This requires changes to or reengineering of traditional organization structures.

Several demographic trends are seriously affecting manufacturing employment. The education level and expectations of people are changing. Fewer new workers are interested in manufacturing jobs, especially the unskilled and semiskilled ones. The lack of new employees for the skilled jobs that are essential for a factory is even more critical. On the other hand, many people may not have sufficient education to be qualified for these jobs (Bray 1988).

To win in the global market, manufacturing companies should improve their competitive ability. Key elements include creative new products, higher quality, better service, greater agility, and low environmental pollution. Creative new products are of vital importance to companies in the current "knowledge economy."

Figure 1 presents a market change graph. From this figure, it can be seen that the numbers for lot size and repetitive order are decreasing, product life cycle is shortening, and product variety is increasing rapidly.

End users or customers always need new products with advancements in function, operation, and energy consumption. The company can receive greater benefits through new products. A manufacturing company without new products has little chance of surviving in the future market. Better services are needed by any kind of company. However, for manufacturing companies, better service means delivering products fast, making products easy to use, and satisfying customer needs with low prices and rapid response to customer maintenance requests.

2.2. Features of a General Manufacturing System

The manufacturing company is a complex, dynamic, and stochastic entity consisting of a number of semi-independent subsystems interacting and intercommunicating in an attempt to make the overall system function profitably. The complexity comes from the heterogeneous environment (both hardware and software), huge quantity of data, and the uncertain external environment. The complex structure of the system and the complex relationships between the interacting semi-autonomous subsystems are also factors making the system more complicated.

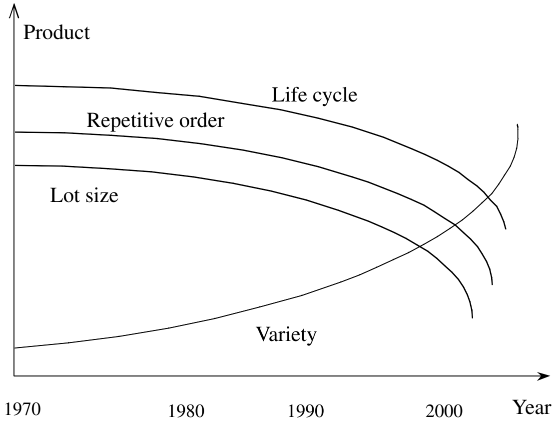


Figure 1 Market Change.

A simple model of a manufacturing system can be a black box that takes as input materials, energy, and information and gives as output products. The internal details of the manufacturing system depend on the particular industry involved, but the key feature common to all manufacturing organizations is that the system processes both materials and information. General manufacturing systems can be decomposed into seven levels of decision hierarchies (Rogers et al. 1992) (Figure 2). Decisions at the upper levels are made at less frequent intervals (but have implications for longer periods into the future) and are made on the basis of more abstract (and slower to change) information on the state of the system. Decisions at the lower levels are made more frequently using much more detailed information on the state of the system.

Three kinds of decisions should be made for any manufacturing company: (1) what kinds of products to make, (2) what resources will be needed to make the products, and (3) how to control the manufacturing systems. These decisions cannot be made separately. If the company wishes to make a decision at a certain level, such as at the business level, it should also get access to the information at other levels. In the whole process of decision making, the core concept is integration. This is the fundamental requirement for the research and development of computer integrated manufacturing.

2.3. CIM Definitions

There are many definitions for CIM, emphasizing different aspects of it as a philosophy, a strategic tool, a process, an organizational structure, a network of computer systems, or a stepwise integration of subsystems. These different definitions have been proposed by researchers working in different areas at different times from different viewpoints. Since the concept of CIM was put forward in 1973, it has been enriched by the contributions of many researchers and practitioners. One earlier definition of CIM is "the concept of a totally automated factory in which all manufacturing processes are integrated and controlled by a CAD/CAM system. CIM enables production planners and schedules, shopfloor foremen, and accountants to use the same database as product designers and engineers" (Kochan and Cowan 1986). This definition does not put much emphasis on the role of information.

Another definition is given by Digital Equipment Corporation (DEC): "CIM is the application of computer science technology to the enterprise of manufacturing in order to provide the right information to the right place at the right time, which enables the achievement of its product, process and business goals" (Ayres 1991). This definition points out the importance of information in manufacturing enterprise, but unfortunately it does not give much emphasis to the very important concept of integration.

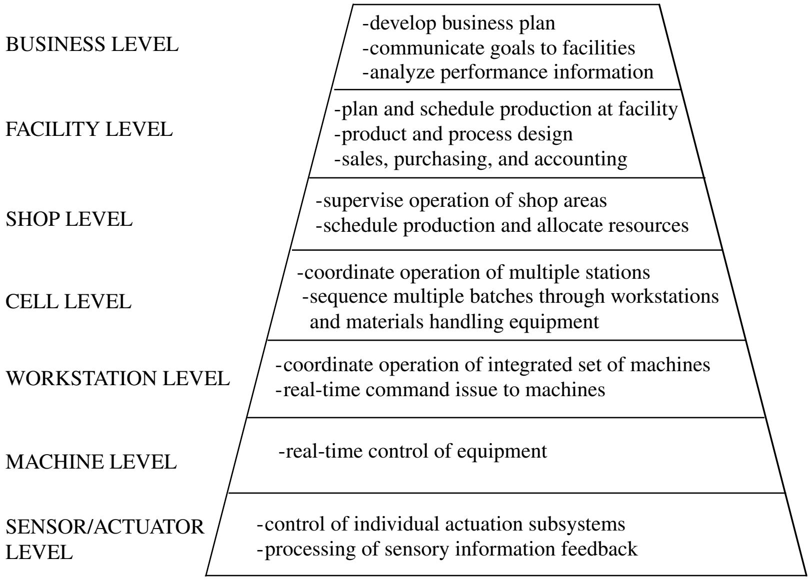


Figure 2 A Seven-Level Manufacturing Hierarchy. (From Rogers et al. 1992)

Other definitions have pointed out that CIM is a philosophy in operating a manufacturing company. For example: "CIM is an operating philosophy aiming at greater efficiency across the whole cycle of product design, manufacturing, and marketing, thereby improving quality, productivity, and competitiveness" (Greenwood 1989).

To stress the importance of integration, the Computer and Automation Systems Association of the Society of Manufacturing Engineers gives the following definition: "CIM is the integration of the total manufacturing enterprise through the use of integrated systems and data communications coupled with new managerial philosophies that improve organizational and personnel efficiency" (Singh 1996).

CIM does not mean replacing people with machines or computers so as to create a totally automatic business and manufacturing processes. It is not necessary to build a fully automatic factory in order to implement a CIM system. It is especially unwise to put a huge investment into purchasing highly automation-flexible manufacturing systems to improve manufacturing standards if the bottleneck in the company's competitiveness is not in this area. In the current situation, the design standards for creative and customized products are more important than production ability in winning the market competition.

The importance of human factors should be emphasized. Humans play a very important role in CIM design, implementation, and operation. Although computer applications and artificial intelligence technologies have made much progress, even in the future, computers will not replace people. To stress the importance of the role of humans, the idea of human-centered CIM has been proposed.

Two views of CIM can be drawn from these definitions: the system view and the information view. The system view looks at all the activities of a company. The different functions and activities cannot be analyzed and improved separately. The company can operate in an efficient and profitable way only if these different functions and activities are running in an integrated and coordinated environment and are optimized in a global system range. The SME CIM wheel (Figure 3) provides a clear portrayal of relationships among all parts of an enterprise. It illustrates a three-layered integration structure of an enterprise.

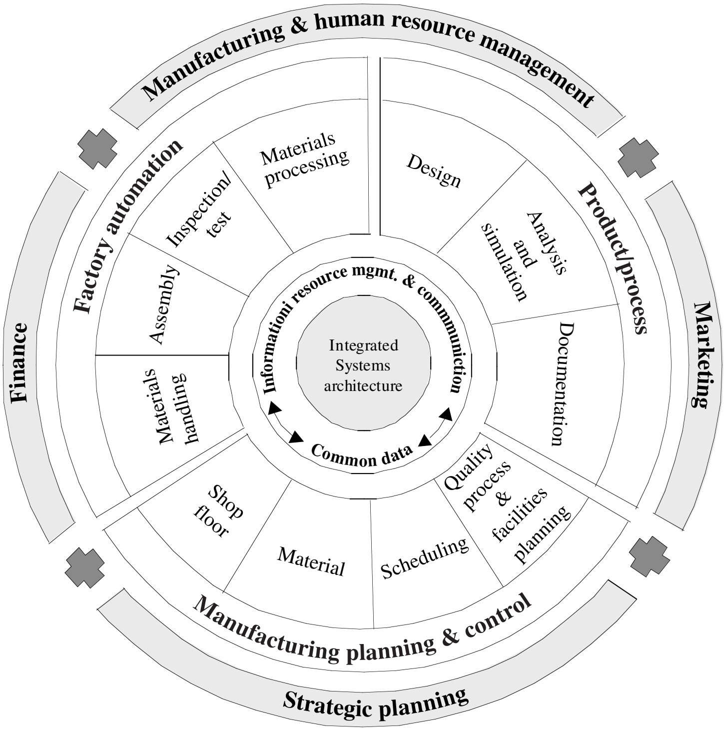


Figure 3 The SME CIM Wheel. (From *Systems Approach to Computer-Integrated Design and Manufacturing,* by N. Singh, copyright 1996 by John Wiley and Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

The outer layer represents general management and human resources management. The middle layer has three process segments: product and process definition, manufacturing planning and control, and factory automation. These segments represent all the activities in the design and manufacturing phases of a product life cycle, from concept to assembly. The center of the wheel represents the third layer, which includes information resources management and the common database.

The other view of CIM is the information view. As stated in the definition given by Digital Equipment Corporation, the objective of CIM implementation is to enable the right information to be sent to the right person at the right time. The information system plays a vital role in the operation of CIM. Although many kinds of activities are involved in managing a manufacturing company, each activity has a different function in business management and production control. The associated function unit for the information system of CIM normally can be classified into three kinds of tasks: information collection, information processing, and information transfer.

Information collection is the basic function of an information system. The information collected forms the basis of decision making at different levels from business management to device control. There are many methods of information collection, depending on the information sources and technologies used. Device sensors may provide data regarding device status; barcode scanners may provide data about the production status of online products; and form scanners and database table view interfaces may provide data about order, raw material purchasing, and user requirements. Some data may also come from e-mail systems. The data collected can be stored in different data formats and different repositories.

Information processing is closely related to the business functions of a company. Business functions range from strategy planning, process planning, product design, warehouse management, and material supply to production management and control. The upper-stream process data are processed by algorithms or human intervention and the instructions produced are used for the downstream process. In data processing, different decisions will be made. The decisions can be used to optimize the production processes or satisfy user requirements such as delivery time and quality requirements.

Information transfer between different function units has three main functions: data output from application software in a certain data format to a certain kind of data repository; data format transformation, and data transfer from one application to another application within the same computer or in a network environment.

2.4. Integration: The Core of CIM

The core of CIM is usually seen to be integration. In our opinion, computer technology is the basis of CIM, manufacturing is the aim, and integration is the key technology. Why should integration be considered the core of CIM? This can be seen from different aspects. The system view of CIM was described above. *System* means the whole company, including people, business, and technology. In order to form a coordinated system, these elements must be integrated. Material flow, information flow, and capital flow must also be integrated. Although those aims seem clear, the technology for realizing this integration is far from mature.

CIMOSA (Esprit Consortium AMICE 1993) identifies enterprise integration as an ongoing process. Enterprises will evolve over time according to both internal needs and external challenges and opportunities. The level of integration should remain a managerial decision and should be open to change over a period of time. Hence, one may find a set of tightly coupled systems in one part of a CIM enterprise and in another a set of loosely coupled systems according to choices made by the enterprise. The implementation of multivendor systems in terms of both hardware and software and easy reconfiguration requires the provision of standard interfaces. To solve the many problems of the industry, integration has to proceed on more than one operational aspect. The AMICE (European Computer Integrated Manufacturing Architecture) project identifies three levels of integration covering physical systems, application and business integration (see Figure 4).

Business integration is concerned with the integration of those functions that manage, control, and monitor business processes. It provides supervisory control of the operational processes and coordinates the day-to-day execution of activities at the application level.

Application integration is concerned with the control and integration of applications. Integration at this level means providing a sufficient information technology infrastructure to permit the system wide access to all relevant information regardless of where the data reside.

Physical system integration is concerned with the interconnection of manufacturing automation and data-processing facilities to permit interchange of information between the so-called islands of automation (intersystem communications). The interconnection of physical systems was the first integration requirement to be recognized and fulfilled.

Even when business integration has been achieved at a given time, business opportunities, new technologies, and modified legislation will make integration a vision rather than an achievable goal. However, this vision will drive the management of the required changes in the enterprise operation.

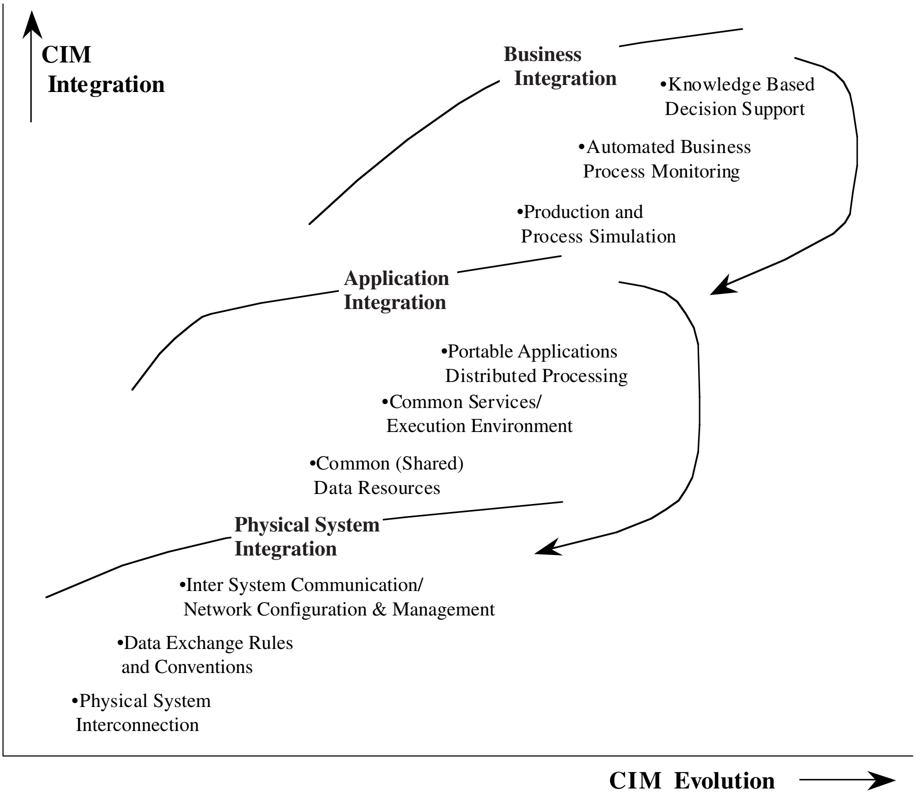


Figure 4 Three Levels of Integration. (From Esprit Consortium AMICE 1993. Reprinted by permission of Springer-Verlag.)

The classification of integration can also be given in another method, which is different from that given by CIMOSA. Regarding integration objectives and methods, integration can be classified as information integration, process integration, and enterprise-wide integration.

Information integration enables data to be shared between different applications. Transparent data access and data consistency maintenance under heterogeneous computing environments is the aim of information integration. Information integration needs the support of communication systems, data-representation standards, and data-transfer interfaces. Communication systems provide a data transfer mechanism and channel between applications located at different computer nodes. Data-representation standards serve as common structures for data used by different applications. Data-transfer interfaces are used to transfer data from one application to another. They fulfill two kinds of functions: data format transfer (from application-specified data structure to common structure and vice versa) and data transfer from application to interface module and vice versa. The traditional information-integration methods include database data integration, file integration, and compound data integration. The most efficient support tool for information integration is the integration platform (Fan and Wu 1997).

Process integration is concerned with the collaboration between different applications in order to fulfill business functions, such as product design and process control. The need to implement process integration arises from companies' pursuit of shorter product design time, higher product quality, shorter delivery time, and high business process efficiency. Business process reengineering (BPR) (Jacobson 1995) and concurrent engineering (CE) (Prasad 1996) have promoted the research and application of process integration. Business process modeling, business process simulation, and business process execution are three important research topics related to process integration.

A number of methods can be used in modeling business processes: CIMOSA business process modeling, IDEF3 (Mayer et al. 1992), Petri nets (Zhou 1995), event driven process chain (Keller 1995), and workflow (Georgakopoulos et al. 1995). The modeling objective is to define the activities within a business process and the relationships between these activities. The activity is a basic function unit within a business process. The control and data flow between these activities form the business process, which fulfils the business task of a company. Optimizing the flow path and shortening the flow time can help the company increase its working efficiency and reduce cost.

The third type of integration is called enterprise-wide integration. With the advent of agile manufacturing, virtual organization is ever more important than before. In agile manufacturing mode, a number of companies collaborate in a virtual company to gain new opportunities in the market. Enterprise-wide integration is required to enhance the exchange of information between the companies. The success of virtual organizations is predicated on the empowerment of people within the enterprise with the aid of computer technology including communication networks, database management systems, and groupware. These allow team members in the virtual organization to make more effective and faster group decisions. Such interaction lays the foundation for enterprise-wide integration, encompassing various plants and offices of an enterprise, possibly located in different cities, as well as customers and suppliers worldwide. Therefore, enterprise-wide integration is much broader than factory automation integration. It is the integration of people, technology, and the business processes throughout the enterprise.

Enterprise-wide integration is required to ensure that all the technical and administrative units can work in unison. This requires a great deal of information about a large number of activities, from product conception through manufacturing, customer delivery, and in-field support. All these life-cycle steps require a large volume of data. The transformation process from one stage to another yields volumes of new data. Furthermore, many of these design, manufacturing, distribution, and service activities responsible for generating and using volumes of data are scattered across a wide spectrum of physical locations. The information is generated by a diverse set of highly specialized software tools on heterogeneous computing hardware systems. Often, incompatible storage media with divergent data structures and formats are used for data storage. This is due to the peculiarities of the tools and systems that generate data without any regard to the needs of the tools or systems that will eventually use the data.

The main idea of enterprise-wide integration is the integration of all the processes necessary for meeting the enterprise goals. Three major tools for integration that are required for overcoming the local and structural peculiarities of an enterprise's data processing applications are network communications, database management systems, and groupware. A number of methods for enterprise-wide integration have been proposed; supply chain management, global manufacturing, and a virtual information system supporting dynamic collaboration of companies. The Web and CORBA (Otte et al. 1996) technologies are playing important roles in the realization of enterprise-wide integration.

3. CIMS STRUCTURE AND FUNCTIONS

3.1. CIMS Structure

The components of CIMS include both hardware and software. The hardware includes computer hardware, network, manufacturing devices, and peripherals. The software includes operating systems, communication software, database management systems, manufacturing planning and control software, management information software, design software, office automation software, and decision support software. These different hardware and software systems have different functions and work together to fulfill the company's business goals. To make it easier to understand, CIMS is normally decomposed into a number of subsystems interacting with each other. Unfortunately, no unique and standard decomposition method exists. Every company can define a method according to its specific situation and requirements. One decomposition method is shown in Figure 5.

From Figure 5, it can be seen that CIMS consists of four functional subsystems and two support subsystems. The four functional subsystems are management information, CAD/CAPP/CAM, manufacturing automation, and computer-aided quality management. These functional subsystems cover the business processes of a company. The two support subsystems are computer network and database management. They are the basis that allows the functional subsystems to fulfill their tasks. The arcs denote the interfaces between different subsystems. Through these interfaces, shared data are exchanged between different subsystems.

3.2. Components of CIMS

This section briefly describes the components of CIMS.

3.2.1. Management Information System

Management information system (MIS) plays an important role in the company's information system. It manages business processes and information based on market strategy, sales predictions, business decisions, order processing, material supply, finance management, inventory management, human resource management, company production plan, and so on. The aims of MIS are to shorten delivery time, reduce cost, and help the company to make rapid decision to react to market change.

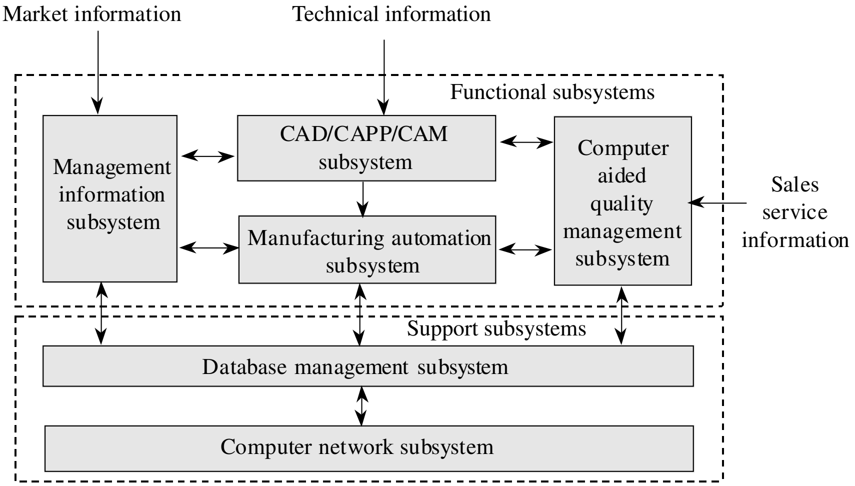


Figure 5 Decomposition of CIMS.

Currently, Enterprise Resource Planning (ERP) software is normally used as the key application software in MIS. Many commercial ERP software products are on the market, such as SAP R/3, developed by SAP, and BaanERP, developed by Baan.

3.2.1.1. Basic Concept of ERP In balancing manufacturing, distribution, financial, and other business functions to optimize company productivity, ERP systems are considered to be the backbone of corporate infrastructure. The ERP concept is derived from and extends the functions of MRPII (Manufacturing Resources Planning) system (Wright 1992). Besides the traditional functions of MRPII in manufacturing management, material supply management, production planning, finance, and sales management, ERP introduces new functions, such as transportation management, supply chain management, corporate strategy planning, workflow management, and electronic data exchange, into the system. The ERP system thus provides more flexibility and ability to the company in business process reengineering, integration with customers, and integration with material suppliers as well as product dispatchers.

3.2.1.2. Manufacturing Resource Planning The basis of MRPII is MRP (material requirements planning), which dates back to the 1940s. MRPII uses computer-enhanced materials ordering and inventory control methods. It enhances speed and accuracy in issuing raw materials to factory workstations. It is clear that linking materials with production demand schedules could optimize the flow of the product as it is being constructed in the factory. This could be done in such a manner that material queue times could be minimized (e.g., have the material show up only when needed), and the amount of material needed throughout the factory at any one time could be reduced ultimately. This is an optimization technique that allocates identified sets of materials (sometimes called kits) to specific jobs as they go through the manufacturing process.

Because it is possible for a computer to keep track of large numbers of kits, it is reserves or mortgages materials for specific jobs in time-order sequences. Linking these sequences with a production plan based on customer need dates allows management to release and track orders through the shop accurately. Prior to releasing orders by means of the kitting process based on the production schedule, it was necessary to obtain supplies. The supplies are based on a gross basis depending on the number of orders expected to be shipped to customers over the selected time period and by having the gross amount of inventory on hand at the start of the period to support production. Obviously, the kit will result in fewer extra materials on hand at any point in the production period. This results in large reductions in raw material and work in process and hence in lower operation costs.

Figure 6 gives a flow diagram of an MRPII system (Waldner 1992).

3.2.1.3. Just-in-Time Another method that has received much attention for production planning and control is just-in-time theory. In contrast to MRPII, which is "push" oriented, the JIT philosophy of management is "pull" oriented—that is, it calls for something to be manufactured only when there is a firm order for it. JIT is a productivity enhancer based on the simple proposition that all waste in the manufacturing process must be eliminated.

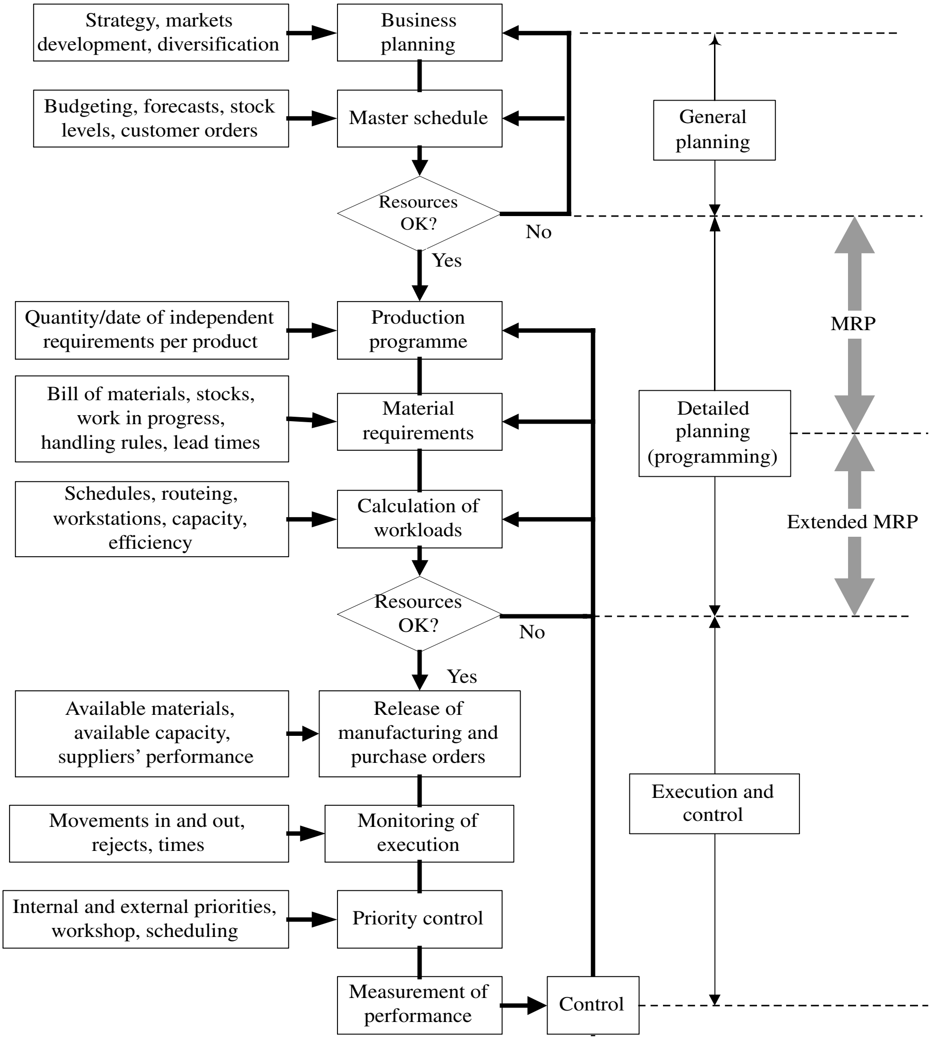


Figure 6 Flow Diagram of MRPII System. (From J. B. Waldner, *Principles of Computer-Integrated Manufacturing,* copyright 1992 John Wiley & Sons Limited. Reproduced by permission)

JIT theory states that wastes can only begin to be eliminated if the push production control system is replaced with a pull production control system. Inventory levels contain a very large volume of waste. Therefore, a way must be found to minimize inventory levels. If this is done without the analytical capability of the computer, it would be logical to conceive a system that would not let material move or be used until it is necessary. This is what Toyota did. They instituted a backward scheduling technique that started with the desired ship date. They had to know when the product needed to be at final assembly and before that when it needed to be at the subassembly levels and so forth, back through component part manufacturing. Ultimately, this means determining precisely when the raw materials should show up at the receiving dock. This in itself is not unusual or unique.

Although JIT proposes ways to reduce a great deal of waste, it cannot be implemented without the help of CIM and MRPII systems. For example, the means for producing products only at the rate at which the customer wants them can best be realized using the feedback control system production schedule of MRPII. By using the MRPII system, we can monitor the progress of all workstations carrying out the dictates of the strategic plan and thus speed up or slow down the preceding operation to optimize the usage of materials and labor. Koenig (1990) explains in detail the relationship of JIT with the MRPII and CIM systems.

Because JIT and MRPII have their advantages as well as limitations in applications, the combination of JIT and MRPII systems in the common framework of CIM may produce excellent results in production scheduling and control.

3.2.2. CAD/CAPP/CAM System

CAD/CAPP/CAM stands for computer-aided design/computer-aided process planning/computer-aided manufacturing. The system is sometimes called the design automation system, meaning that CAD/CAPP/CAM is used to promote the design automation standard and provide the means to design high-quality products faster.

3.2.2.1. Computer-Aided Design CAD is a process that uses computers to assist in the creation, modification, analysis, or optimization of a product design. It involves the integration of computers into design activities by providing a close coupling between the designer and the computer. Typical design activities involving a CAD system are preliminary design, drafting, modeling, and simulation. Such activities may be viewed as CAD application modules interfaced into a controlled network operation under the supervision of a computer.

A CAD system consists of three basic components: hardware, which includes computer and input–output devices, application software, and the operating system software (Figure 7). The operating system software acts as the interface between the hardware and the application software system.

The CAD system function can be grouped into three categories: geometric modeling, engineering analysis, and automated drafting.

Geometric modeling constructs the graphic images of a part using basic geometric elements such as points, lines, and circles under the support of CAD software. Wire frame is one of the first geometric modeling methods. It uses points, curves, and other basic elements to define objects. Then the surface modeling, solid modeling, and parametric modeling methods are presented in the area of geometric modeling area. Saxena and Irani (1994) present a detailed discussion of the development of geometric modeling methods.

Engineering design completes the analysis and evaluation of product design. A number of computer-based techniques are used to calculate the product's operational, functional, and manufacturing parameters, including finite-element analysis, heat-transfer analysis, static and dynamic analysis, motion analysis, and tolerance analysis. Finite-element analysis is the most important method. It divides an object into a number of small building blocks, called finite elements. Finite-element analysis will fulfill the task of carrying out the functional performance analysis of an object. Various methods and packages have been developed to analyze static and dynamic performance of the product design. The objectives and methods can be found in any comprehensive book discussion of CAD techniques. After the analysis, the product design will be optimized according to the analysis results.

The last function of the CAD system is automated drafting. The automated drafting function includes 2D and 3D product design drafting, converting a 3D entity model into a 2D representation.

3.2.2.2. Computer-Aided Process Planning CAPP is responsible for detailed plans for the production of a part or an assembly. It acts as a bridge between design and manufacturing by translating design specifications into manufacturing process details. This operation includes a sequence of steps to be executed according to the instructions in each step and is consistent with the controls indicated in the instructions. Closely related to the process-planning function are the functions that determine the cutting conditions and set the time standards. The foundation of CAPP is group technology (GT),

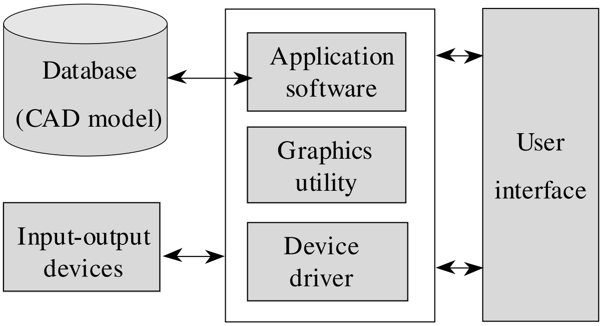


Figure 7 Basic Components of CAD.

which is the means of coding parts on the basis of similarities in their design and manufacturing attributes. A well-developed CAPP system can reduce clerical work in manufacturing engineering and provide assistance in production.

One of the first tasks of the CAPP system is to complete the selection of the raw workpiece. According to the functional requirements of the designed part, it determines the attributes of the raw workpiece, such as shape, size (dimension and weight), and materials. Other jobs for the CAPP system are determining manufacturing operations and their sequences, selecting machine tools, and selecting tools, fixtures, and inspection equipment. Determination of manufacturing conditions and manufacturing times are also part of the work of CAPP. These conditions will be used in optimizing manufacturing cost.

The CAPP system consists of computer programs that allow planning personnel interactively to create, store, edit, and print fabrication and assembly planning instructions. Such a system offers the potential for reducing the routine clerical work of manufacturing engineers. Figure 8 presents the classification of various CAPP systems.

3.2.2.3. Computer-Aided Manufacturing In this section, *computer-aided manufacturing* (CAM) refers to a very restricted area that does not include general production control functions. The production control functions will be introduced in the manufacturing automation subsystem (MAS) section. Here, CAM includes preparing data for MAS, including producing NC code for NC machines, generating tool position, planning tool motion route, and simulating tool movement. Automatic NC code generation is very important for increasing work efficiency. Before the NC code for NC machine centers can be generated, a number of parameters regarding machine tool specification, performance, computer numerical control system behavior, and coding format should be determined first. The manufacturing method and operations will be selected according to these parameters, geometric dimensions, solid forms, and designed part specifications. The CAM system will calculate the tool position data. Then the data regarding the part dimension, the tool motion track, cutting parameters, and numerical control instructions are generated in a program file. This file, called the NC program, is used by the machine tool to process part automatically.

3.2.2.4. CAD/CAPP/CAM Integration Besides the utilization of CAD, CAPP, and CAM technology alone, the integration of CAD, CAPP, and CAM is an important way to enhance the company's product design standards. Three methods can be used in the integration of CAD/CAPP/CAM: exchange product data through specific defined data format; exchange product data through standard data format, such as STEP, IGES, and DXF; and define a unified product data model to exchange product information.

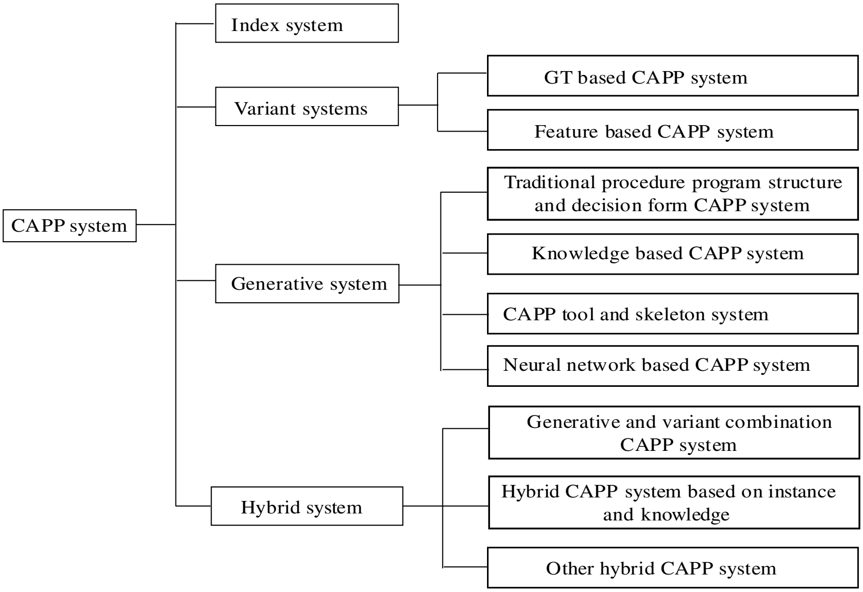


Figure 8 Classification of CAPP System.

Figure 9 is a STEP-based CAD/CAPP/CAM integration system developed at the State CIMS Engineering Research Center of China (located at Tsinghua University, Beijing). It was developed as a part of the CIMS application integration platform (Fan and Wu 1997) for manufacturing enterprises. This system focuses on part-level CAD/CAPP/CAM integration. XPRESS language and the STEP development tool ST-developer are used to define and develop the integration interfaces. Different kinds of CAD, CAPP, and CAM systems can be integrated using the interfaces provided.

3.2.3. Manufacturing Automation System

Manufacturing automation system is a value-added system. The material flow and information flow come together in MAS. For a discrete manufacturing company, MAS consists of a number of manufacturing machines, transportation systems, high-bay stores, control devices, and computers, as well as MAS software. The whole system is controlled and monitored by the MAS software system. For the process industry, MAS consists of a number of devices controlled by DCS, the monitor system, and the control software system. The objectives of MAS are to increase productivity, reduce cost, reduce work-in-progress, improve product quality, and reduce production time.

MAS can be described from three different aspects: structural description, function description, and process description. *Structural description* defines the hardware and the software system associated with the production processes. *Function description* defines the MAS using a number of functions that combine to finish the task of transforming raw material into products. The input–output mapping presented by every function is associated with a production activity of the MAS. *Process description* defines the MAS using a series of processes covering every activity in the manufacturing process.

In the research field of MAS, a very important topic is the study of control methods for manufacturing devices, from NC machines to automatic guided vehicles. But the focus of this chapter is on studying MAS from the CIM system point of view. We will describe the shop-floor control and management system functions and components below.

The shop-floor control and management system is a computer software system that is used to manage and control the operations of MAS. It is generally composed of several modules as shown in Figure 10. It receives a production plan from the MRPII (ERP) system weekly. It optimizes the sequence of jobs using production planning and scheduling algorithms, assigns jobs to specific devices and manufacturing groups, controls the operation of the material-handling system, and monitors the operations of the manufacturing process.

Task planning decomposes the order plan from MRPII system into daily tasks. It assigns job to specific work groups and a set of machines according to needed operations. Group technology and optimization technology are used to smooth the production process, better utilize the resources, reduce production setup time, and balance the load for manufacturing devices. Hence, good task planning is the basis for improving productivity and reducing cost of production.

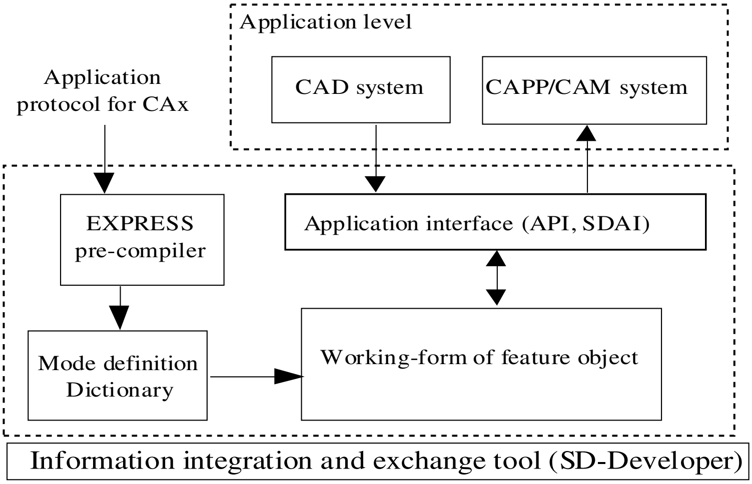


Figure 9 CAD/CAPP/CAM Integration System Structure.

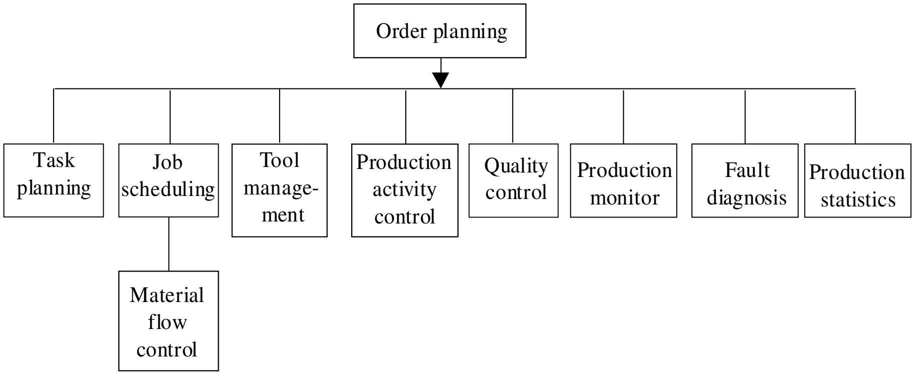


Figure 10 Function Modules of Shop-Floor Control and Management System.

Job scheduling is used to determine the entry time and sequence for different production jobs. It consists of three main functions: static scheduling, dynamic scheduling, and real-time resource scheduling. Material-flow control is one of the tasks for real-time resource scheduling. Static scheduling is a off-line scheduling method. It determines operation sequences before the production starts. The aim of static scheduling is to reduce the makespan (the time duration between when the first task enters the system and when the last task leaves the system). Operations research is an important method for generating static scheduling. Because errors and uncertainties may be caused by machine breakdown, task priorities change and dynamic scheduling is needed for rescheduling the operation sequences and production routes. It is the best method for increasing the flexibility of production system. Heuristic rules are normally used in generating dynamic scheduling. Job scheduling aims to optimize the operation of production system and increase the system flexibility.

Production activity control is used to control the operations of tasks, material flow, and manufacturing resources. Real-time data collecting, processing, and decision making are important tasks of production activity control, which aims to regulate and smooth the production processes even when errors and disturbances occur.

Tool management is also a very important task for the shop-floor control and management system. In a manufacturing system, a large number of tools are needed and the supply of necessary tools on time is vital for improving productivity. Tool quality is important to product quality. The parameters of every tool should be maintained in a correct and real-time fashion because these parameters will be used by machine centers in controlling manufacturing processes.

Quality control, production monitoring, fault diagnosis, and production statistics are important supplementary functions for the shop-floor control and management system to be operated efficiently and effectively.

3.2.4. Computer-Aided Quality-Management System

Since the 1970s, quality has become an extremely important factor for a company to win market competition. Customers always want higher product quality for their investment. The computer-aided quality-management system of CIMS is a system used to guarantee the product quality. It covers a wide range, from product design to material supply to production quality control. The International Standards Organization (ISO) has established a series of quality assurance standards, such as ISOs 9000, 9001, 9002, 9003, and 9004. The computer-aided quality-management system has also been called the integrated quality system.

The computer-aided quality system consists of four components: quality planning, inspection and quality data collection, quality assessment and control, and integrated quality management.

The quality-planning system consists of two kinds of functions: computer-aided product-quality planning and inspection-plan generating. According to the historical quality situation and production-technology status, computer-aided product-quality planning first determines the quality aims and assigns responsibility and resources to every step. Then it determines the associated procedure, method, instruction file, and quality-inspection method and generates a quality handbook. Computer-aided inspection planning determines inspection procedures and standards according to the quality aims, product model, and inspection devices. It also generates automatic inspection programs for automatic inspection devices, such as a 3D measuring machine.

Guided by the quality plan, the computer-aided quality inspection and quality data collection receive quality data during different phases. The phases include purchased-material and part-quality inspection, part-production-quality data collection, and final-assembly quality inspection. The methods and techniques used in quality inspection and data collection are discussed in special books on quality control (Taguchi et al. 1990).

Quality assessment and control fulfills the tasks of manufacturing process quality assessment and control and supply part and supplier quality assessment and control. Integrated quality management includes the functions of quality cost analysis and control, inspection device management, quality index statistics and analysis, quality decision making, tool and fixture management, quality personnel management, and feedback information storage on quality problems, and quality problems backtrack into manufacturing steps.

Quality cost plays an important role in a company's operation. The quality cost analysis needs to determine the cost bearer and the most important cost constituent part to generate a quality cost plan and calculate real cost. It also optimizes the cost in the effort to solve quality problems. Figure 11 presents a quality cost analysis flowchart.

3.2.5. *Computer Network and Database Management Systems*

Computer network and database management systems are supporting systems for CIMS. The computer network consists of a number of computers (called nodes in the network) and network devices, as well as network software. It is used to connect different computers together to enable the communication of data between different computers. The computer network can be classified as a local area network (LAN) or a wide area network (WAN). *LAN* normally means a restricted area network, such as in a building, factory, or campus. *WAN* means a much wider area network, across a city or internationally. Network technology is developing rapidly. The Internet concept has changed manu-

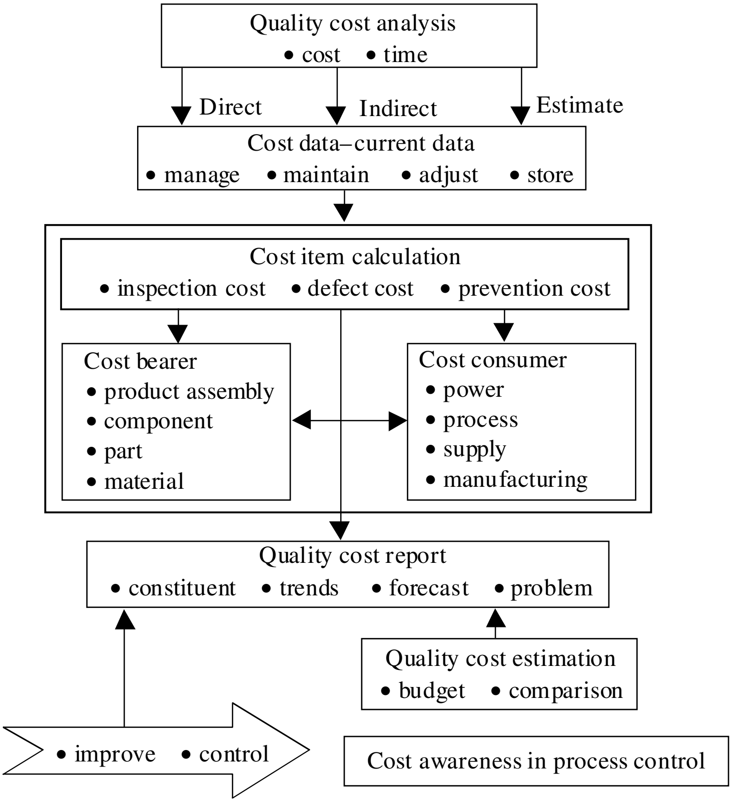


Figure 11 Quality Cost Analysis Flowchart.

facturing companies' operation method greatly. Global manufacturing, agile manufacturing, and network-based manufacturing paradigms have seen rapid development. A computer network is the infrastructure for these new manufacturing paradigms to be realized in a cost-effective way.

The database management system provides basic support for the data storage and information sharing of manufacturing companies. Currently, relational database management systems are the principal databases used. Information integration of a company is concerned with integration data sources in different locations and with different kinds of database management systems. The heterogeneous properties of computer operating systems and database management systems are the major difficulties in information integration. Advanced software techniques have been developed to cope with the heterogeneity problem. Techniques include CORBA, as well as OLE/DCOM, developed by Microsoft, and the Java language, developed by Sun.

Hundreds of books discussing computer network and database techniques can be found in almost any bookstore.

4. FLEXIBLE MANUFACTURING SYSTEMS

Flexible Manufacturing Systems (FMS) is a manufacturing system with a high degree of flexibility. It was developed due to the need to increase productivity, improve product quality, and reduce cost for product production under the constraints of various uncertainties or disturbances both internal and external to the manufacturing system.

4.1. Flexibility and Components of FMS

4.1.1. Flexibility of Manufacturing System

A number of papers have studied different aspects of FMS. Gupta and Goyal (1989) provide a comprehensive review of the literature on flexibility. Flexibility can be defined as a collection of properties of a manufacturing system that supports changes in production activities or capabilities (Carter 1986).

In a manufacturing system, various types of flexibility are needed to fulfill different requirements. The types most discussed are machine flexibility, routing flexibility, process flexibility, product flexibility, production flexibility, and expansion flexibility. Machine flexibility is the capability of a machine to perform a variety of operations on a variety of part types and sizes. Machine flexibility can reduce the changeover frequency, setup time, and tool-changing time, hence reducing the lead time and making small-lot-size production more economic. Machine flexibility is the basis for routing and process flexibility.

Routing flexibility provides the chance for a part to be manufactured or assembled along alternative routes. Routing flexibility is required to manage shop-floor uncertainties caused by such problems as machine breakdown, tool error, and controller failure. It can also be used to tackle the problems caused by external events such as change of product mix or product due date and emergency product introduction. These changes alter machine workloads and cause bottlenecks. The use of alternative routing helps to solve these problems and finally increase productivity.

Process flexibility, also called mix flexibility, is the ability to absorb changes in the product mix by performing similar operations or producing similar produces or parts on multipurpose, adaptable CNC machining centers.

Product flexibility, also known as mix-change flexibility, is the ability to change over to a new set of products economically and quickly in response to markets or engineering changes or even to operate on a market-to-order basis. In the current global market, high product flexibility is a very important factor for a company to compete.

Expansion flexibility is the ability to change a manufacturing system with a view to accommodating a changed product envelope. It has become more important in the current agile manufacturing era. Improving expansion flexibility can significantly reduce system expansion or change cost, shorten system reconfiguration time, and hence shorten the delivery time for new products.

4.1.2. FMS Definition and Components

An FMS is an automated, mid-volume, mid-variety, central computer-controlled manufacturing system. It can be used to produce a variety of products with virtually no time lost for changeover from one product to the next. Sometimes FMS can be defined as ''a set of machines in which parts are automatically transported under computer control from one machine to another for processing'' (Jha 1991).

A more formal definition of FMS is that it consists of a group of programmable production machines integrated with automated material-handling equipment and under the direction of a central controller to produce a variety of parts at nonuniform production rates, batch sizes, and quantities (Jha 1991).

From this definition, it can be seen that an FMS is composed of automated machines, material-handling systems, and control systems. In general, the components of an FMS can be classified as follows:

1. *Automated manufacturing devices* include machining centers with automatic tool interchange ability, measuring machines, and machines for washing parts. They can perform multiple functions according to the NC instructions and thus fulfill the parts-fabrication task with great flexibility. In an FMS, the number of automated machining centers is normally greater than or at least equal to two.
2. *Automated material-handling systems* include load/unload stations, high-bay storage, buffers, robots, and material-transfer devices. The material-transfer devices can be automatic guided vehicles, transfer lines, robots, or a combination of these devices. Automated material-handling systems are used to prepare, store, and transfer materials (raw materials, unfinished parts, and finished parts) between different machining centers, load/unload stations, buffers, and high-bay storage.
3. *Automated tool systems* are composed of tool setup devices, central tool storage, tool-management systems, and tool-transfer systems. All are used to prepare tools for the machining centers as well as transfer tools between machining centers and the central tool storage.
4. *Computer control systems* are composed of computers and control software. The control software fulfills the functions of task planning, job scheduling, job monitoring, and machine controlling of the FMS.

Figure 12 shows the FMS layout at the State CIMS Engineering Research Center (CIMS-ERC) of China. (HMC stands for horizontal machining center and VMC stands for vertical machining center.)

Another example of FMS is shown in Figure 13, from Kingdream. This system produces oil well drill bits, mining bits, hammer drills, high-pressure drills, and so on.

4.2. General FMS Considerations

Although FMS was originally developed for metal-cutting applications, its principles are more widely applicable. It now covers a wide spectrum of manufacturing activities, such as machining, sheet metal working, welding, fabricating, and assembly.

The research areas involved in the design, implementation, and operation of an FMS are very broad. Much research has been conducted and extensive results obtained. In this section, we present the research topics, problems to be solved, and methods that can be used in solving the problems.

4.2.1. FMS Design

FMS is a capital investment-intensive and complex system. For the best economic benefits, an FMS should be carefully designed. The design decisions to be made regarding FMS implementation cover

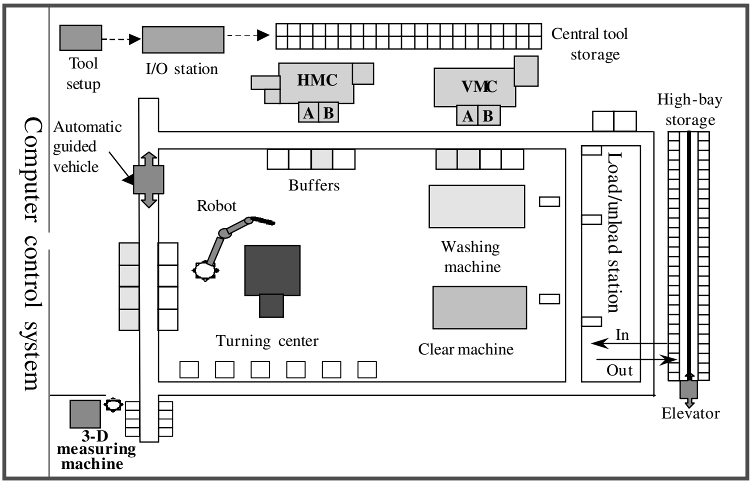


Figure 12 FMS Layout at State CIMS-ERC of China.

Figure 13 FMS for Oil Well Drill Production.

system configuration and layout, manufacturing devices, material-handling systems, central tool storage, buffers, and high-bay storage.

Before these decisions can be made, the part types to be made, the processes needed to make them, and the possible numbers of processing parts (workload) should first be determined. Based on these basic requirements, the number of machines and their abilities, tools, buffers, and storage system can be roughly determined. A rough system layout and material-handling system can be designed. The designed FMS can be simulated using an FMS simulation tool to test its ability to fulfill the requirements.

The design of an FMS is a system approach. Besides the above-mentioned basic requirements for part manufacturing, many other factors should be considered in designing an FMS. An economic assessment should always be done for every FMS plan obtained. System reliability, productivity, and performance evaluation should also be done for every FMS plan. The design of FMS is an iterative process that requires many experts from different disciplines to work together. Many alternative plans are compared and modified before an optimized plan is decided upon.

Talavage and Hannam (1988) summarize the work of other researchers in FMS design methodology and present a five-step approach to FMS design:

1. Development of goals
2. Establishment of criteria on which goal achievement can be judged
3. Development of alternative candidate solutions
4. Ranking of alternatives by applying the criteria to the alternate solutions
5. Iteration of the above four steps to obtain a deeper analysis of alternate solutions and to converge on an acceptable solution

Other considerations regarding FMS design can be found in Tetzlaff (1990).

4.2.2. FMS Planning, Scheduling, and Control

Planning, scheduling, and control are important and difficult problems in FMS operations. A good planning and scheduling system will improve FMS operation efficiency and yield economic benefits. Extensive research and development of FMS planning and scheduling has been done. The general optimization indexes are:

1. Maximizing the productivity at certain period of time
2. Minimizing the makespan for a group of parts
3. Minimizing the cost for parts manufacturing
4. Maximizing the utility of key manufacturing devices
5. Minimizing the work in progress
6. Minimizing the production time for certain parts
7. Satisfying the due dates of parts

Figure 14 presents a function model for FMS planning, scheduling, and resource management.

The resource management and real-time control functions of FMS are closely related to the dynamic scheduling system. The resource-management system should be activated by a dynamic scheduling system to allocate resources to production process to achieve real-time control for FMS. The resources to be controlled involve tools, automatic guided vehicles, pallets and fixtures, NC files, and human resources.

4.2.2.1. Planning Planning seeks to find the best production plan for the parts entered into the FMS. Its aim is to make an optimized shift production plan according to the shop-order and part-due dates. The FMS planning system receives the shop-order plan in the weekly time scale from the MRPII system. According to the product due dates, it analyzes the shop order and generates a daily or shift production plan. Group technology is used for grouping parts into families of parts. The capacity requirement is calculated for every shift plan generated. Capacity balance and adjustment work should be carried out if the required capacity is higher than that provided by machines.

After feasibility analysis, capacity balancing, and optimization, a shift plan is generated. The shift plan gives detailed information for the following questions:

1. What kind of parts will be machined?
2. In what sequence will the parts enter the FMS?
3. What operations are needed to process the parts? What is the operation sequence?
4. What are the start time and complete time for processed parts?
5. What materials are needed? In what time?
6. What kinds of tool are needed?

4.2.2.2. Static Scheduling Static scheduling is the refinement of the shift production plan. It seeks to optimize machine utility and reduce system setup time. Three functions are performed by a static scheduling system: part grouping, workload allocating and balancing, and part static sequencing. Because all these functions are performed before production starts, static scheduling is also called off-line sequencing.

A number of factors affecting production sequence should be taken into account for static scheduling, such as the part process property, FMS structure, and optimization index. The part process property determines what kind of production method should be used. Flow-shop, flexible-flow-line, and job-shop are three major strategies for producing parts. Different methods can be used to generate static scheduling for the different production strategies.

The second factor affecting static scheduling is FMS structure. The main structural properties are whether a central tool system, a fixture system, or bottleneck devices are present. The third factor is the optimization index chosen. The general optimization index is a combination of several optimization indexes, that is, the FMS static scheduling is a multiobjective optimization process.

The following parameters have an important effect on implementing optimal static scheduling.

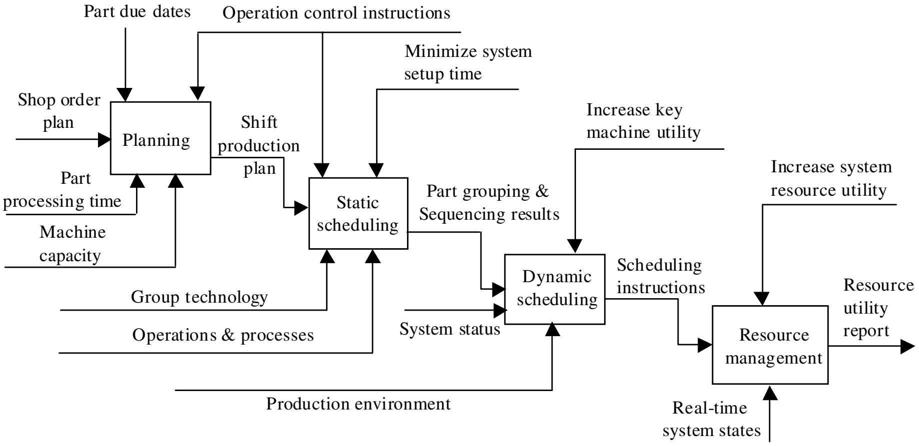


Figure 14 Function Model of FMS Planning and Scheduling.

1. *Time distribution,* such as time distributions for part arrival, tool setup, part fixture, part transfer, machine failure, and delivery time
2. *Shop conditions,* such as device type, transfer system, storage method, shop layout, and device condition
3. *Shop control conventions,* such as priority rule, operation method, hybrid processing route, task decomposition, performance-evaluation method, and workload
4. *Alternate processing route,* such as alternate processing device, alternate processing routing, and alternate processing sequence

A great deal of literature about static scheduling algorithms and systems can be found in the academic journals on FMS, operations research, and manufacturing technology and IEEE magazines on systems, robotics, and automatic control.

4.2.2.3. Dynamic Scheduling Dynamic scheduling is used to control the operations of FMS according to the real-time status of the AFMS. It is a real-time (online) system that focuses on solving uncertainty problems such as device failures, bottlenecks on certain machines, workload unbalance, and resource-allocation conflict. These problems are not anticipated by off-line static scheduling. They can only be solved using real-time dynamic scheduling or rescheduling.

Three strategies can be used to complete the rescheduling functions. The first is periodical scheduling. A certain time interval must be set as a production cycle. A periodical scheduling system calculates a period operation sequence before the next period starts. The sequence is the job list execution instructions followed by the FMS. The second strategy is continuous scheduling, which monitors the FMS and executes scheduling whenever an event (such as the arrival of a new part or a machine completing the production of a part) occurs and the system states has been changed. Since the calculation of work content is effective for rescheduling FMS operations for every event (so as to get optimal scheduling at every point), the third strategy, hybrid scheduling, is frequently used. The hybrid strategy combines periodical and continuous scheduling so that only when an unexpected event occurs is the continuous scheduling algorithm used. Otherwise, periodical scheduling is executed at certain intervals.

For a dynamic manufacturing environment with possible disturbances both internal and external to the FMS, dynamic scheduling seeks to optimize the sequencing for the queue before the device is manufactured. Because the dynamic scheduling of an FMS is an NP-hard problem, it is impossible to find the optimal solution in a short time, especially for continuous scheduling with a very high speed requirement. Normally a suboptimal solution is used in real-time FMS operations. A number of heuristic rules are frequently used for finding the suboptimal solutions in dynamic scheduling. The heuristic rules that are frequently used are:

1. *RANDOM:* assigns a random priority to every part entering the queue and selects a part with smallest priority to be processed
2. *FIFO* (*LIFO*)*:* first-in-first-out (last-in-first-out)
3. *SPT* (*LPT*)*:* selects the part that has the smallest (largest) current operation processing time to be processed
4. *FOPNR* (*MOPNR*)*:* selects the part that has the fewest (most) remaining operations to be processed
5. *LWKR* (*MWKR*)*:* selects the part that has the smallest (largest) remaining processing time to be processed
6. *DDATE:* selects the part that has the earliest due date to be processed
7. *SLACK:* selects the part that has the smallest slack time (due date minus remaining processing time) to be processed

In most cases, several rules will be used in a dynamic scheduling system to reach the satisfied sequencing solution. Besides rule-based scheduling, simulation-based and knowledge-based scheduling systems are also widely used.

4.2.3. FMS Modeling and Simulation

Modeling and simulation are important topics for both design and operation of FMS. FMS modeling is the basis for simulation, analysis, planning, and scheduling. Because FMS is a typical discrete event dynamic system (DEDS), a number of methods for DEDS modeling and analysis can be used to model an FMS, such as Petri nets, network of queues (Agrawal 1985), and activity cycle diagram (Carrie 1988). This section briefly introduces Petri nets, their application in FMS modeling, and the FMS simulation method.

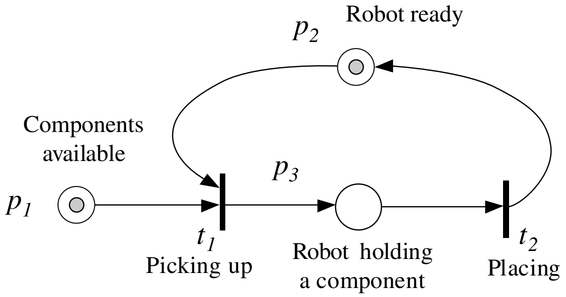


Figure 15 A Simple Petri Net Example. (From M. C. Zhou, Ed., *Petri Nets in Flexible and Agile Automation,* Figure 1, copyright 1995, with kind permission from Kluwer Academic Publishers)

4.2.3.1. Petri Nets and Their Application in FMS Modeling A Petri net (PN) may be identified as a particular kind of bipartite directed graphs populated by three types of objects. These objects are places, transitions, and directed arcs connecting places to transitions and transitions to places. Pictorially, places are depicted by circles, transitions by bars or boxes. A place is an input place to a transition if a directed arc exists connecting this place to the transition. A place is an output place of a transition if a directed arc exists connecting the transition to the place. Figure 15 represents a simple PN. Where places p_1 and p_2 are input places to transition t_1, place p_3 is the output place of t_1.

Formally, a PN can be defined as a five-tuple PN = (P, T, I, O, m_0), where

1. $P = \{p_1, p_2, \ldots, p_n\}$ is a finite set of places
2. $T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions, $P \cup T \neq \phi$, $P \cap T = \phi$.
3. $I{:}(P \times T) \mapsto N$ is an input function that defines directed arcs from places to transitions, where N is a set of nonnegative integers.
4. $O{:}(P \times T) \mapsto N$ is an output function that defines directed arcs from transitions to places.
5. $m_0{:}P \mapsto N$ is the initial marking.

The state of the modeled system is represented by the tokens (small dots within the places) in every place. For example, in Figure 15, a small dot in place p_1 means components available. The change of the states represents the system evolution. State changing is brought by firing a transition. The result of firing a transition is that for every place connected with the transition, after the firing of the transition, a token will be removed from its input place and a token will be added to its output place. In the example of Figure 15, the firing of transition t_1 will cause the tokens in places p_1, p_2 to disappear and a token to be added to place p_3.

Due to the advantages of its formal theory background, natural link with DEDS, and mature simulation tool, PN is well suited to FMS modeling. Figure 16 shows a two-machine production line to demonstrate the modeling of FMS using PN.

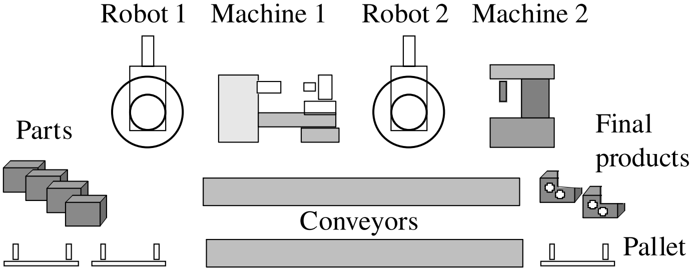


Figure 16 A Two-Machine Production Line.

The production line consists of two machines (M1 and M2), two robots (R1 and R2), and two conveyors. Each machine is serviced by a dedicated robot that performs the load/unload task. One conveyor is used to transport workpieces, a maximum two at one time. The other conveyor is used to transport empty pallets. Three pallets are available in the system. Each workpiece is machined on M1 and then on M2. The machining time is 10 time units on M1 and 16 time units on M2. The load and unload tasks takes 1 time unit.

As with modeling general FMS or other systems, the modeling of this system using PN takes several steps:

1. Major activities are identified. In this example, they are R1 loading, M1 processing, R1 unloading, R2 loading, M2 processing, and R2 unloading. The resources are raw materials with pallets, conveyors, M1, M2, R1, R2.
2. The relationships between the four major activities form a sequential order.
3. A partial PN model is defined to describe the four major activities and their relations as shown in Figure 17(*a*), where four transitions are used to represent four short operations, i.e., R1 loading, R1 unloading, R2 loading, and R2 unloading. Two places are used to represent two long operations, i.e., M1 and M2 processing.
4. Through a stepwise process, gradually adding resources, constraints, and links to the partial PN model will finally form the refined model as shown in Figure 17(*b*).
5. The model is checked to see whether it satisfies the specification. The PN simulation tool can also be used in this phase to check the model. If some problems are found, the model will be modified.

4.2.3.2. FMS Simulation Simulation is a useful computer technology in FMS modeling, design, and operation. Simulation modeling allows real-world objects to be described in FMS, such as moving of workpieces from one place to another. There are three approaches to simulation modeling for FMS. The first is network or graphical models, where some objects (such as machines) may be represented by graphical symbols placed in the same physical relationship to each other as the corresponding machines are in the real world. The graphical aspects of this kind of models are relatively easy to specify, and once completed they also provide a communication vehicle for the system design that can be readily understood by a variety of people. SLAM (Pritsker 1984) and SIMAN (Pegden 1982) are two widely used network modeling tools for FMS.

The second approach to FMS modeling is data-driven simulation. The model consists of only (or mainly) numerical data, usually representing, for example, a simple count of machines in a system or a table of operation times for each process on the route of a given part type. The nature of these data is such that, if they were collected in the factory information system, it would only be necessary to access them and place them in proper format in order to run a simulation of the corresponding

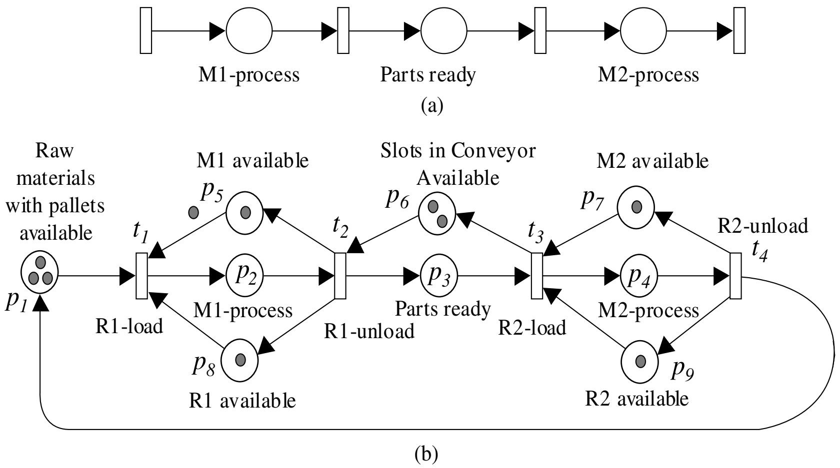


Figure 17 Petri Net Model for the Two-Machine Production Line. (From M. C. Zhou, Ed., *Petri Nets in Flexible and Agile Automation,* Figure 8, with kind permission of Kluwer Academic Publishers)

real-world system. This concept is quite close to automated simulation. It has the ultimate ease of use. The first such program for FMS was developed at Purdue, the general computerized manufacturing system (GCMS) simulator (Talavage and Lenz 1977).

The third approach for FMS modeling uses a base programming language, such as SIMULA and SIMSCRIPT, which provides more model-specific constructs that can be used to build a simulation model. This approach thus has a much stronger modeling capability. Unfortunately, it is not widely used. One reason may be that few people know it well enough to use it.

Another method for DEDS simulation, called activity cycle diagram (ACD), can also be used in FMS simulation. This is a diagram used in defining the logic of a simulation model. It is equivalent to a flowchart in a general-purpose computer program. The ACD shows the cycle for every entity in the model. Conventions for drawing ACDs are as follows:

1. Each type of entity has an activity cycle.
2. The cycle consists of activities and queues.
3. Activities and queues alternate in the cycle.
4. The cycle is closed.
5. Activities are depicted by rectangles and queues by circles or ellipses

Figure 18 presents an ACD for a machine shop. Jobs are arriving from the outside environment. Jobs are waiting in a queue for the machine. As soon as the machine is available, a job goes to the machine for processing. Once processing is over, the job again joins a queue waiting to be dispatched.

Because ACDs give a better understanding of the FMS to be simulated, they are widely used for FMS simulation.

4.3. Benefits and Limitations of FMS

FMS offers manufacturers more than just a flexible manufacturing system. It offers a concept for improving productivity in mid-variety, mid-volume production situations, an entire strategy for changing company operations ranging from internal purchasing and ordering procedures to distribution and marketing. The benefits of FMS can be summarized as follows:

1. Improved manufacturing system flexibility
2. Improved product quality, increased equipment utility
3. Reduced equipment cost, work-in-progress, labor cost, and floor space
4. Shortened lead times and improved market response speed
5. Financial benefits from the above

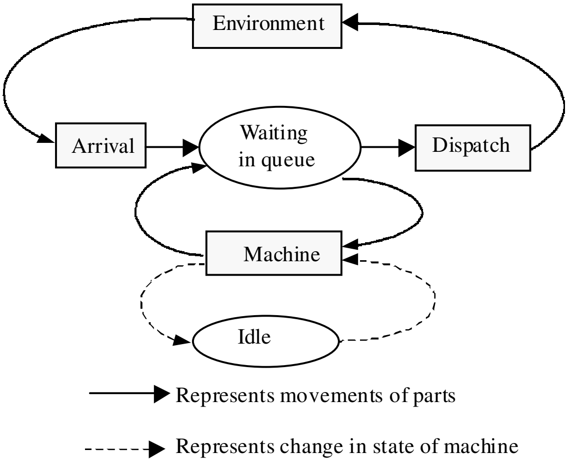


Figure 18 Activity Cycle Diagram. (From A. Carrie, *Simulation of Manufacturing Systems,* copyright 1988 John Wiley & Sons Ltd. Reproduced with permission)

Talavage and Hannam (1988) contains a chapter discussing the economic justification for FMS.

The difficulties with FMS should also be given attention. First, FMS is expensive, normally requiring large capital resources. Even if a company is able to afford the investment, FMS may not be financially beneficial if the company does not have much product variety and volume. Second, the design, implementation, and operation of FMS is a quite complex process. Money may be lost if any of the work in the process is not well done. Third, the rapidly changing market may compel the company to change its product. This change may have a negative impact on the production system, causing the large investment in FMS not to be returned before it is abandoned.

5. CIM ARCHITECTURE AND ENTERPRISE MODELING

An enterprise is a complicated social, economic, and physical system. The implementation of CIMS in an enterprise is an even more complicated feat of system engineering. To implement CIMS successfully, engineers with an excellent analytical and technological background and abundant experience are needed, as well as the guidance of advanced CIM system architecture and implementation methodology and powerful support tools. CIM system architecture studies the components and their relationship to CIM to provide the basis and guidelines for the design and implementation of CIMS in a company. A good system architecture can not only act as a basis for describing the system components but also provide a good way to communicate among users, designers, and other parties. A number of CIM system architectures are available, such as the SME wheel structure (Figure 3), CIM open system architecture (CIMOSA), the Purdue enterprise reference architecture (PERA) (Williams 1992), the architecture for information system (ARIS) (Scheer 1992), and GRAI (graphs with results and activities interrelated) integrated methodology (GIM) (Doumeingts et al. 1992).

With the development of CIM reference architecture, a number of enterprise modeling methods have been put forward to describe the enterprise. Because the enterprise is a very complex system, it is difficult to describe it using a simple and unified model. A typical method used by almost all enterprise modeling methods is to describe the enterprise using several view models. Each view defines one aspect from a specific point of view, and then the integration method between the different view models is defined. The general view models now used in describing enterprise are function view, information view, organization view, resource view, and process view. Other views are also presented by researchers are control view, defined in ARIS, decision view, defined in GRAI/GIM, and economic view, proposed by Chen et al. (1994).

5.1. Views of the Enterprise Model

As discussed above, the enterprise model consists of several interrelated view models. Each view describes a specific aspect of the enterprise and has its own modeling method. This section gives a brief description of the aims of each view and the method currently used in building the view model.

5.1.1. Process View

The process view model takes a major role in defining, establishing, analyzing, and extracting the business processes of a company. It fulfills the requirements of transforming the business process, the manufacturing process, and the product-development process into a process view model. The process model is the basis for business process simulation, optimization, and reengineering.

5.1.1.1. Modeling Method for Process View Process view modeling focuses mainly on how to organize internal activities into a proper business process according to the enterprise goals and system restrictions. Traditional function-decomposing-oriented modeling methods such as SADT and IDEF0, which set up the process based on activities (functions), can be used in business process modeling.

The business description languages WFMC (Workflow Management Coalition 1994), IDEF3, and CIMOSA are process-oriented modeling methods. Another modeling method uses object-oriented technology, in which a business process can be comprehended as a set of coordinated request/service operations between a group of objects. Jacobson (1995) presents a method for using object-oriented technology, the use case method, to reengineer the business process. Object-oriented methods offer intrinsic benefits: they can improve systemic extendibility and adaptability greatly, their services based on object-operated mode can assign systemic responsibility easily, existing business processes can be reused easily, and distribution and autonomy properties can be described easily.

The main objective of the process view modeling method is to provide a set of modeling languages that can depict the business process completely and effectively. To depict a business process, it should be able to depict the consequent structure of processes, such as sequence, embranchment, join, condition, and circle, to establish a formal description of the business process. Generally accepted modeling languages today are IDEF3, CIMOSA business process description language, and WFMC workflow description language.

Some business process description methods originating in the concepts and models of traditional project-management tools, such as the PERT chart and other kinds of network chart, are generally adopted in practical application systems because they can be easily extended from existing project management tool software. If the business process is relatively complex, such as existing concurrent or collision activities, some superformal descriptions, such as Petri net, should be used.

Figure 19 is a workflow model of a machine tool-handle manufacturing process. The process model is designed using the CIMFlow tool (Luo and Fan 1999). In Figure 19(*a*), the main sequential process is described and the icon ▦ stands for a subprocess activity. Figure 19(*b*) is the decomposition of the subprocess activity Rough Machining in Figure 19(*a*). After Turning activity is executed, two conditional arcs are defined that split the activity route into two branches. The activity Checking is a decision-making task that is in charge of the product quality or the progress of the whole process.

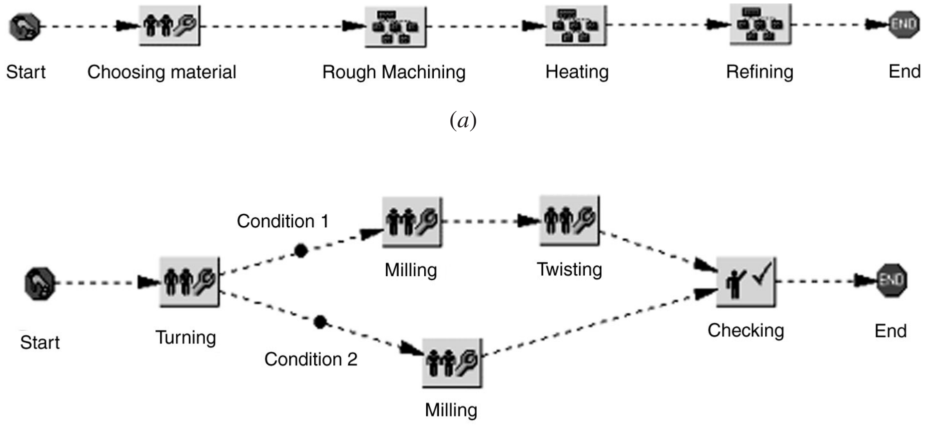
5.1.2. *Function View*

The function view is used to describe the functions and their relationships in a company. These functions fulfill the objectives of the company, such as sales, order planning, product design, part manufacturing, and human resource management. The efficient and effective operation of these functions contributes to the company's success in competing in the market.

5.1.2.1. Modeling Method for Function View Function view modeling normally uses the top-down structural decomposition method. The function tree is the simplest modeling method, but it lacks the links between different functions, especially the data flow and control flow between different functions, so it is generally used to depict simple function relationships. In order to reflect data and control flow relationships between different functions, SADT and IDEF0 (Colquhoun and Baines 1991) methods are used to model function view. The IDEF0 formalism is based on SADT, developed by Ross (Ross 1985).

The IDEF0 model has two basic elements: activity and arrow. Figure 20 gives the basic graphic symbol used in the IDEF0 method. IDEF0 supports hierarchical modeling so that every activity can be further decomposed into a network of activities. In order to organize the whole model clearly, it is advised that the number of the child activities decomposed from the parent activity be less than 7 and greater than 2. Figure 21 gives a demonstration IDEF0 model (A0 model) of the control shop floor operation function.

In the CIMOSA model, the overall enterprise functions are represented as an event-driven network of domain processes (DPs). An individual domain process is represented as a network of activities. The domain process is composed of a set of business processes (BPs) and enterprise activities (EAs). The BP is composed of a set of EAs or other BPs. An EA is composed of a set of functional operations (FOs). The BP has a behavior property that defines the evolution of the enterprise states over time in reaction to enterprise event generation or conditions external or internal to the enterprise. It is defined by means of a set of rules called procedure rules. The structure property of BP describes the functional decomposition of the enterprise functions of enterprise. This can be achieved by means of a pair of pointers attached to each enterprise function. EA has an activity behavior that defines



(*a*)

(*b*)

Figure 19 Process Model for Tool-Handle Manufacturing.

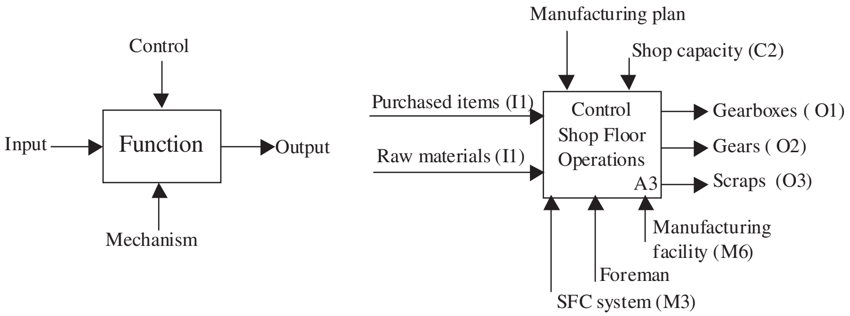


Figure 20 General Symbol and a Practical Model of IDEF0. (From Vernadat 1996. Reprinted with kind permission of Kluwer Academic Publishers.)

the internal behavior (or flow of control) of enterprise activities. It specifies how to perform the functionality of an EA in terms of an algorithm making use of FO.

It can be seen that the process view and the function view are closely related to the CIMOSA modeling method. Hence, any tool that supports the CIMOSA modeling methodology should be process oriented and include function decomposition.

5.1.3. Information View

The information view organizes the information necessary to support the enterprise function and process using an information model. Data for a company are an important resource, so it is necessary to provide a method to describe or model the data, such as data structures, repository types, and locations, especially the relationships among different data. It is very important for the company to maintain the data resource consistently, eliminate possible data redundancy, and finally enable data integration.

The information view modeling method provides different models for different phases of a company's information system, from requirement analysis to design specification to implementation. The most commonly used model to express data today is the relational data model, which is the basis

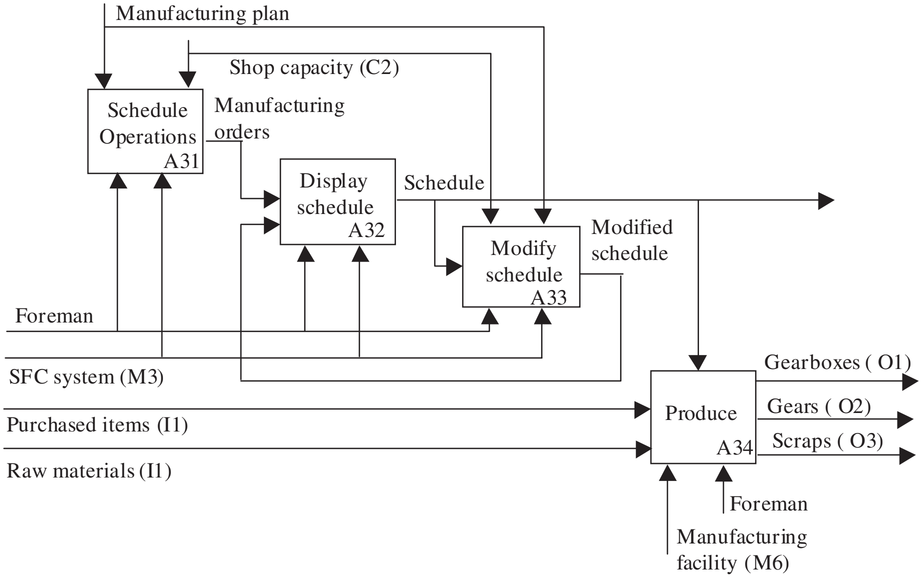


Figure 21 IDEF0 Model of the Control Shop-Floor Operation Function. (From Vernadat 1996. Reprinted with kind permission of Kluwer Academic Publishers.)

for the relational database management system. The currently used IDEF1X method is an extension of the entity-relationship model proposed by Chen (1976). Three phases of the modeling process, a conceptual model, a logical model, and a physical model, are used in designing and implementing an information system. Vernadat (1996) gives a good introduction to information modeling in the context of enterprise modeling.

5.1.4. Organization View

The organization view is used to define and represent the organization model of a company. The defined model includes the organization tree, team, faculty, role, and authority. It also creates an organization matrix. In the organization view, the relationships between different organization entities are defined. It provides support for execution of the company's functions and processes.

The hierarchical relationship between the organization units forms the organization tree, which describes the static organization structure. The team describes the dynamic structure of the company. It is formed according to the requirements of business processes. Personnel and organization units are the constituents of the team.

Figure 22 shows the organization view structure. The basic elements of the organization view are organization unit, team, and personnel.

The attributes of the organization unit include organization unit name, position, description, role list, leader, and the organization's associated activities and resources. The leader and subordinate relationships between different units are also defined in the organization unit. In defining a team, the attributes needed are team name, description, project or process ID, associated personnel, and resources.

5.1.5. Resource View

The resource view is similar to the organization view. It describes resources used by the processes to fulfill the company's business functions. Three main objects are defined in the resource view model: resource type object, resource pool object, and resource entity object. Resource type object describes the company's resource according to the resource classification. The resource type object inherits the attributes from its parent object. A resource classification tree is created to describe the company's resource. The resource pool object describes resources in a certain area. All the resources located at this area form a resource pool. Resource entity object defines the atomic resources. An atomic resource is some kind of resource that cannot be decomposed further—that is, the smallest resource entity.

Figure 23 gives the resource classification tree structure. In this tree, the parent node resource consists of all its child node resources. It depicts the static structure of the company's resources.

The resource–activity matrix (Table 1) defines the relationships between resources and process activities. Every cross (×) means that the resource is used by this activity. The resource–activity matrix presents the dynamic structure of the resources.

5.2. Enterprise Modeling Methods

As pointed out in the previous section, there are many enterprise modeling methods. Here we only give a brief introduction to the CIMOSA, ARIS, and GIM methods.

5.2.1. CIMOSA

CIMOSA supports all phases of a CIM system life cycle, from requirements specification, through system design, implementation, operation and maintenance, even to a system migration towards a

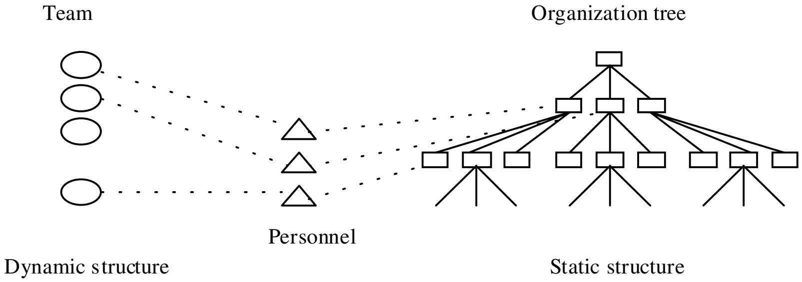


Figure 22 Organization View Structure.

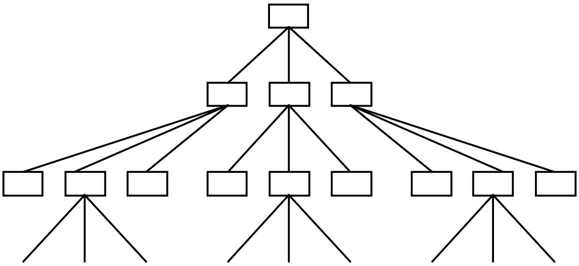


Figure 23 Resource Classification Tree Structure.

CIMOSA solution. CIMOSA provides modeling, analysis, and design concepts in a set of languages and methodologies adapted to enterprise users at different levels and according to different users' viewpoints.

The CIMOSA reference architecture, developed by the AMICE consortium within the European ESPRIT project, is a set of semiformal structures and semantics that is intended to be used as a modeling language environment for any business enterprise. The basic constructs and fundamental control structures of the architecture are collected in volumes called Formal Reference Base II (FRB) and Formal Reference Base III. FRB consists of two parts: the modeling framework and the integrating infrastructure (IIS).

The CIMOSA modeling framework, known as the CIMOSA cube, is shown in Figure 24. The modeling framework provides a reference architecture and a particular architecture. It contains three modeling levels (requirements definition, design specification, implementation description) and four views (function, information, resource, organization). The CIMOSA reference architecture (two left slices of the CIMOSA cube) provides a set of generic building blocks, partial models, and user guidelines for each of the three modeling levels. The particular architecture (right slice of the CIMOSA cube) is the part of the framework that is provided for the modeling of a particular enterprise, that is, it exhibits a given CIM solution.

Generic building blocks or basic constructs are modeling elements with which the requirements and solutions for a particular enterprise can be described. Partial models, which are partially instantiated CIMOSA solutions applicable to one or more industrial sectors, are also provided in the reference architecture. The user can customize partial models to a part of the model of his or her particular enterprise. The CIMOSA modeling framework ensures that partial models from different sources can be used to build a model of one particular enterprise.

The CIMOSA integrating infrastructure (IIS) provides services to integrate all specific application processes of the enterprise into one cooperating system. IIS consists of the following services:

- *Information services:* administering all information required by the various application processes
- *Business process services:* scheduling the provision of resources and dispatching the execution of enterprise activities
- *Presentation services:* representing the various types of manufacturing resources to the business process services in a homogeneous fashion
- *Communication service:* being responsible for system-wide homogeneous and reliable data communication

CIMOSA model creation processes, namely instantiation, derivation and generation, define how generic building blocks and partial models are used to create particular enterprise models.

TABLE 1 Resource-activity Matrix

	Activity 1	Activity 2	–	Activity *n*
Resource 1	×			
Resource 2	×	×		
–			×	
Resource m		×		×

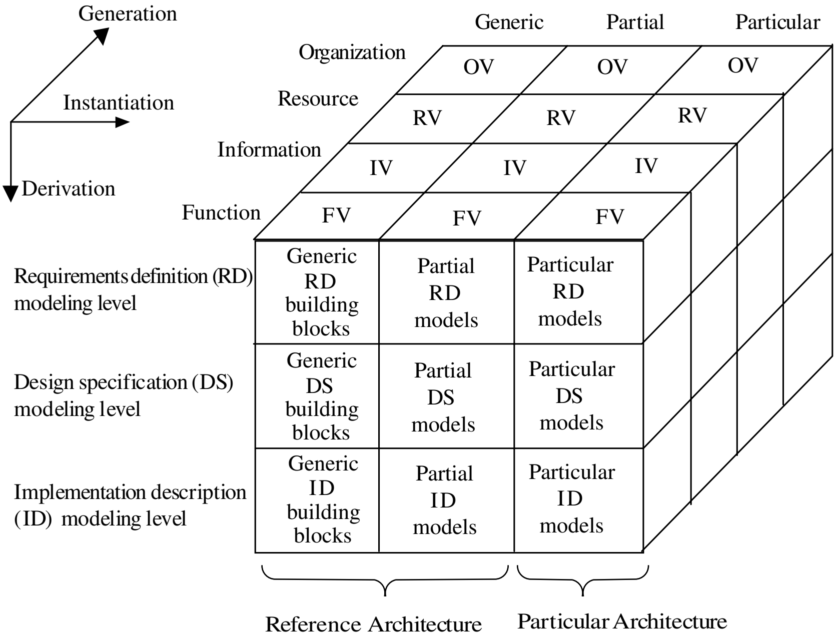


Figure 24 CIMOSA Modeling Framework. (From Esprit Consortium AMICE 1993. Reprinted by permission of Springer-Verlag.)

The instantiation process is a design principle that suggests: (1) going from a generic type to particular type (types are refined into subtypes down to particular instances); and (2) reusing previous solutions (i.e., using particular models or previously defined models) as much as possible. This process applies to all four views. It advocates going from left to right of the CIMOSA cube.

The derivation process is a design principle that forces analysis to adopt a structured approach to system design and implementation, from requirements specification through design specification and finally to full implementation description. This process also applies to all four views. It advocates going from the top to the bottom of the CIMOSA cube.

The generation process is a design principle that encourages users to think about the entire enterprise in terms of function, information, resource, and organization views, in that order. However, the complete definition of the four views at all modeling levels usually requires going back and forth on this axis of the CIMOSA cube.

5.2.2. ARIS

The ARIS (architecture of integrated information systems) approach, proposed by Scheer in 1990, describes an information system for supporting the business process. The ARIS architecture consists of the data view, function view, organization view, and control view. The data view, function view, and organization view are constructed by extracting the information from the process chain model in a relatively independent way. The relationships between the components are recorded in the control view, which is the essential and distinguishable component of ARIS. Information technology components such as computer and database are described in the resource view. But the life-cycle model replaces the resource view as the independent descriptive object. The life-cycle model of ARIS is divided into three levels. The requirement definition level describes the business application using the formalized language. The design specification level transfers the conceptual environment of requirement definition to the data process. Finally, the implement description level establishes the physical link to the information technology. The ARIS architecture is shown in Figure 25.

The ARIS approach is supported by a set of standard software, such as the application systems ARIS Easy Design, ARIS toolset, and ARIS for R/3, which greatly help the implementation of ARIS.

5.2.3. GIM

GIM (GRAI integrated methodology) is rooted in the GRAI conceptual model shown in Figure 26. In this method, an enterprise is modeled by four systems: a physical system, an operating system, an information system, and a decision system.

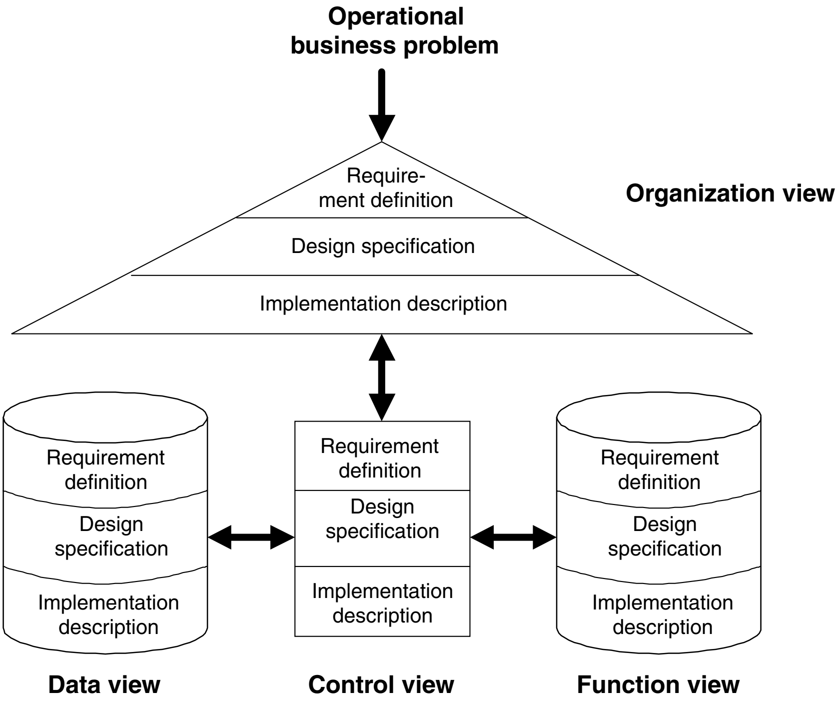


Figure 25 ARIS Architecture. (From Scheer 1992 by permission of Springer-Verlag New York, Inc.)

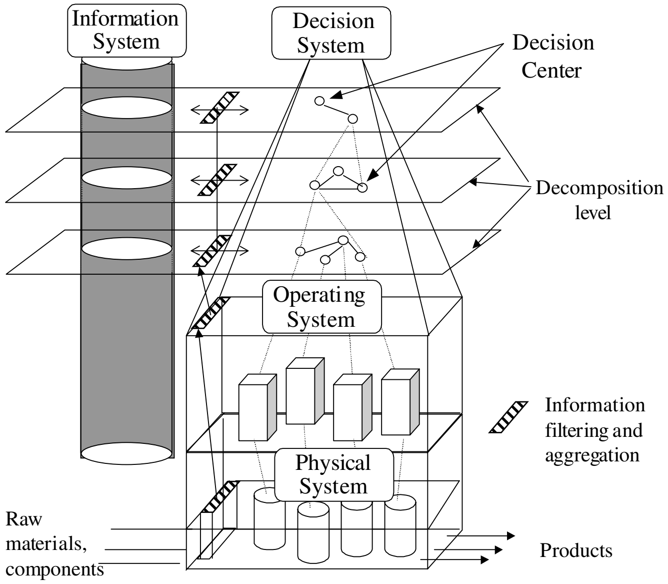


Figure 26 The GRAI Conceptual Model. (From Vernadat 1996)

The GRAI method makes use of two basic modeling tools: the GRAI grid and the GRAI net. The GRAI grid is used to perform a top-down analysis of the domain of the enterprise to be analyzed. It is made of a 2D matrix in which columns represent functions and lines represent decision levels. The decision level is defined by a horizon H and a period P. Long-term planning horizons are at the top and short-term levels are at the bottom of the grid. Each cell in the matrix defines a decision center. The grid is then used to analyze relationships among decision centers in terms of flows of information and flows of decisions.

GRAI nets are used to further analyze decision centers in terms of their activities, resources, and input–output objects. With this method, a bottom-up analysis of the manufacturing systems studied can be made to validate the top-down analysis. In practice, several paths in both ways are necessary to converge to a final model accepted by all concerned business.

GRAI and GIM are supported by a structured methodology. The goal is to provide specifications for building a new manufacturing system in terms of organization, information technology, and manufacturing technology viewpoints. The methodology includes four phases: initialization, analysis, design, and implementation.

6. CIM IMPLEMENTATION

CIM implementation is a very important but also very complex process. It requires the participation of many people with different disciplines. Benefits can be gained from successful implementation, but loss of investment can be caused by inadequate implementation. Therefore, much attention should be paid to CIM implementation.

6.1. General Steps for CIM Implementation

The general life-cycle model discussed in CIM architecture and modeling methodology is the overall theoretical background for CIM implementation. In a practical application, due to the complexity of CIM implementation, several phases are generally followed in order to derive the best effect and economic benefits from CIM implementation. The phases are feasibility study, overall system design, detailed system design, implementation, operation, and maintenance. Each phase has its own goals and can be divided into several steps.

6.1.1. Feasibility Study

The major tasks of the feasibility study are to understand the strategic objectives, figure out the internal and external environment, define the overall goals and major functions of a CIM system, and analyze the feasibility of CIM implementation from technical, economical, and social factors. The aim of this phase is to produce a feasibility study report that will include, besides the above, an investment plan, a development plan, and a cost–benefit analysis. An organization adjustment proposal should also be suggested. A supervisory committee will evaluate the feasibility study report. When it is approved, it will lay the foundation for following up the phases of CIM implementation. Figure 27 presents the working steps for the feasibility study.

6.1.2. Overall System Design

Based on the results of the feasibility study, the overall system design phase further details the objectives and plans regarding proposed CIM system implementation. The tasks of overall system design are to define the CIM system requirements, set up the system function and information model, put forward an overall system design plan, design the system architecture, draft the implementation plan, present the investment plan, carry out the cost–benefit analysis, and finally form the overall system design report. The key technologies and their problem-solving methods should also been given in the overall system design report. Data coding is important work to be done in the overall system design phase.

In order to keep the whole CIM system integrated, in the functional and logical model design, the overall system design follows the top-down decomposition principle. The top level and general functions should be first considered, then decomposed to low-level and detailed operations.

The general procedures and contents of overall system design are as follows:

1. *System requirement analysis:* determines the system requirements of function, performance, information, resource, and organization. This phase's work focuses on the managerial and tactical point of view.
2. *System architecture design:* determines the overall system architecture of the CIM system.
3. *System function and technical performance design:* determines the functions needed to meet the system requirements and system performance.
4. *Information model design:* determines the logical data model of the information system.

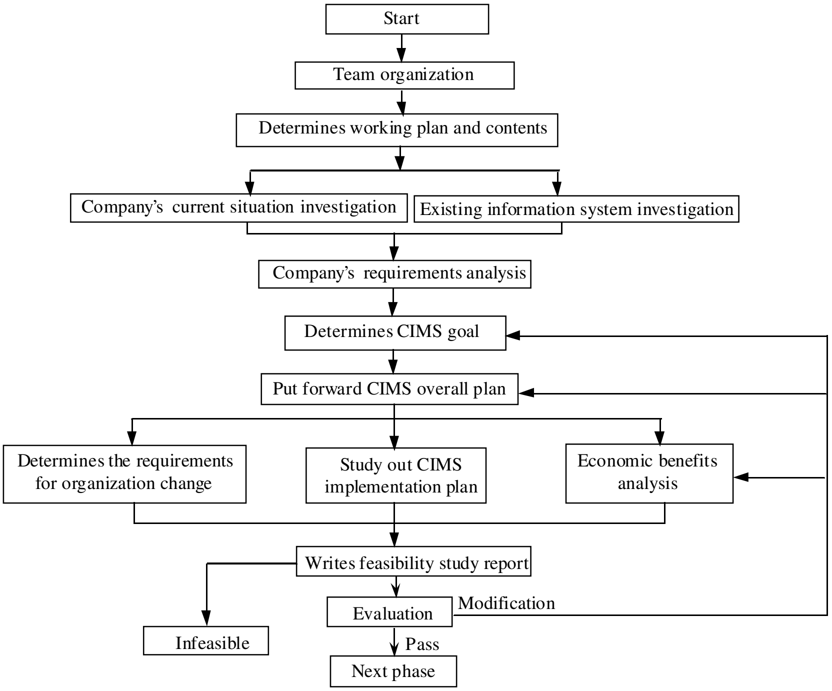


Figure 27 Steps of Feasibility Study.

5. *Internal and external interface design:* determines these interfaces for the purpose of system integration, including the functional interfaces between different subsystems and data interfaces between different applications.
6. *Key technology:* lists all key technologies that have important influence on CIM system implementation, gives their solution methods;
7. *System configuration specification:* determines the hardware and software configurations.
8. *Implementation schedule definition:* defines the implementation schedule for the CIM system in the network plan or other forms.
9. *CIM system organization definition:* defines the suitable organization structure for the CIM environment.
10. *Budget making and cost–benefit analysis.*
11. *Overall system design report generation.*

6.1.3. Detailed System Design

The detailed system design phase solves the problem of system specification definition, the associated hardware and software configuration assignment, the functional and data interface definition, the implementation plan and making of steps, the forming of the associated implementation team, and the assignment of responsibility and setting of benchmarks.

In this phase, an important goal is to define the interfaces between different subsystems. The shared data physical model for the CIM system needs to be specified. The number, type, and configuration of hardware systems should be defined. The detailed software products that should meet the requirements defined in overall system design should also be specified. The network scheduling for the implementation plan should be generated and evaluated. A leadership group is formed that will manage the entire CIM implementation. A number of implementation teams with personnel from different disciplines and different business sectors are formed. Each implementation team will be engaged in the implementation of a specific part of the CIM system.

After the detailed system design phase is finished, the CIM system is ready to go into practical implementation.

6.1.4. Implementation and Operation

The implementation phase follows a bottom-up approach. Subsystems are implemented in order according to the implementation scheduling. When the subsystem implementation is finished, integration interfaces between the subsystems are developed and several higher-level subsystems are formed through integration of some low-level subsystems. Finally, the whole CIM system is implemented through an integration.

After the system is built and tested, it becomes an experimental operation, which will last for three to six months. During that period, errors that occur in the operation are recorded and system modifications are carried out. The CIM system is turned to practical use. In the implementation and operation phase, the following steps are generally followed:

1. *Building computer supporting environment:* including computer network, computer room, network and database server, UPS, air conditioner, and fire-proof system
2. *Building manufacturing environment:* including whole system layout setup, installation of new manufacturing devices, and old manufacturing configuration
3. *Application system development:* including new commercial software installment, new application system development, old software system modification
4. *Subsystem integration:* including interface development, subsystem integration, and system operation test
5. *CIM system integration:* including integration and testing of whole CIM system
6. *Software documentation:* including user manual writing, operation rule definition, setting up of system security and data backup strategies
7. *Organization adjustment:* including business process operation mode, organization structure, and operation responsibility adjustment
8. *Training:* including personal training at different levels, from top managers to machine operators
9. *System operations and maintenance:* including daily operations of CIM system, recording of errors occurring in the operation, application system modification, and recording of new requirements for future development

6.2. Integration Platform Technology

6.2.1. Requirements for Integration Platform

The complexity of manufacturing systems and the lack of effective integration mechanisms are the main difficulties for CIMS implementation. Problems include lack of openness and flexibility, inconvenient and inefficient interaction between applications, difficulty in integrating a legacy information system, the long time required for CIMS implementation, and the inconsistency of user interfaces.

To meet the requirements enumerated above, the integration platform (IP) concept has been proposed. IP is a complete set of support tools for rapid application system development and application integration in order to reduce the complexity of CIMS implementation and improve integration efficiency. By providing common services for application interaction and data access, IP fills the gaps between the different kinds of hardware platforms, operating systems, and data storage mechanisms. It also provides a unified integration interface that enables quick and efficient integration of different applications in various computing environments.

6.2.2. The Evolution of Integration Platform Technology

IP has evolved through a number of stages. It was initially considered an application programming support platform that provided a common set of services for application integration through API. A typical structure of the early IPs is the system enabler/application enabler architecture proposed by IBM, shown in Figure 28. Under such a structure, the IP provides a common, low-level set of services for the communication and data transfer (the system enabler) and also provides application domain specific enabling services (the application enabler) for the development of application systems. Thus, the application developer need not start from coding with the operating system primitive services. One disadvantage of the early IP products was that they only provided support for one or a limited number of hardware and operating system and the problem of heterogeneous and distributed computation was not addressed. Also, the released products often covered a specific domain in the enterprises, such as the shop-floor control. These early IPs focused mainly on support for the development of application software, and their support for application integration was rather weak.

Since the 1990s, IP has developed for use in a heterogeneous and distributed environment. An example is shown in Figure 29, where the architecture is divided into several layers, the communication layer, the information management service layer, and the function service layer, providing

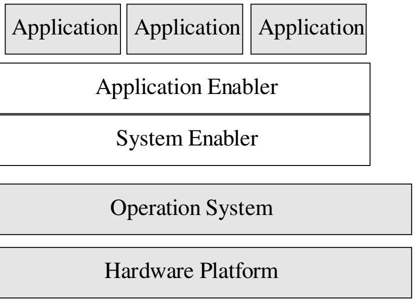


Figure 28 IBM System Enabler/Application Enabler.

commonly used system-level services. These services form the middleware layer of IP. The higher layers of IP are classified as general-purpose API, domain-specific API, and application development integration tools. The integration supporting area is extended from a specific domain to the whole enterprise, including management, planning, and manufacturing execution.

6.2.3. MACIP System Architecture

MACIP (CIMS Application Integration Platform for Manufacturing Enterprises) is a Chinese national high-technology R&D key technology research project. The MACIP project is designed to develop a research prototype of an application platform oriented to the new IP technology described above.

The MACIP system architecture is presented in Figure 30. It is a client–server structured, object-oriented platform with a high degree of flexibility. MACIP consists of two layers, the system enabling level and the application enabling level. The system enabling level is composed of two functions, the communication system and the global information system (GIS). The primary function of these components is to allow for the integration of applications in a heterogeneous and distributed computing environment. The communication system provides a set of services that allow transparent communication between applications. The global information system allows applications to have a common means for accessing data sources in a variety of databases and file systems. These functions are implemented in the form of application independent API (AI API). Application independence means that these functions are not designed for specific applications but are general services for communication, data access, and file management. Hence, the system enabling level provides the basic integration mechanisms for information and application integration.

The application enabling level, which utilizes the functions contained within the system enabling level, is composed of three domain sub-integration platforms (SIPs): MIS SIP, CAD/CAM/CAPP SIP, and shop-floor control SIP. Each SIP is designed according to the requirements of a domain application and provides functions for applications in the form of Application Dependent API (AD API). The AD API functions are designed specifically to enable the quick and easy development of

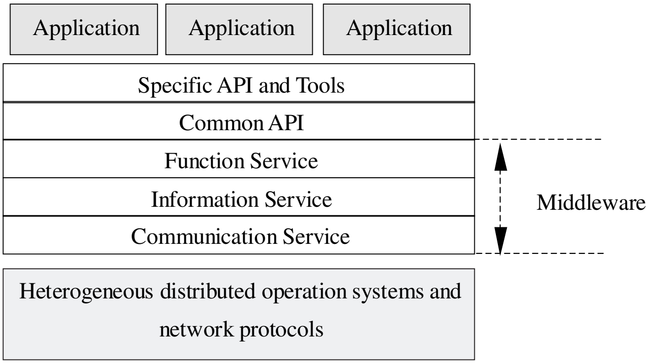


Figure 29 A Multilayer IP Structure.

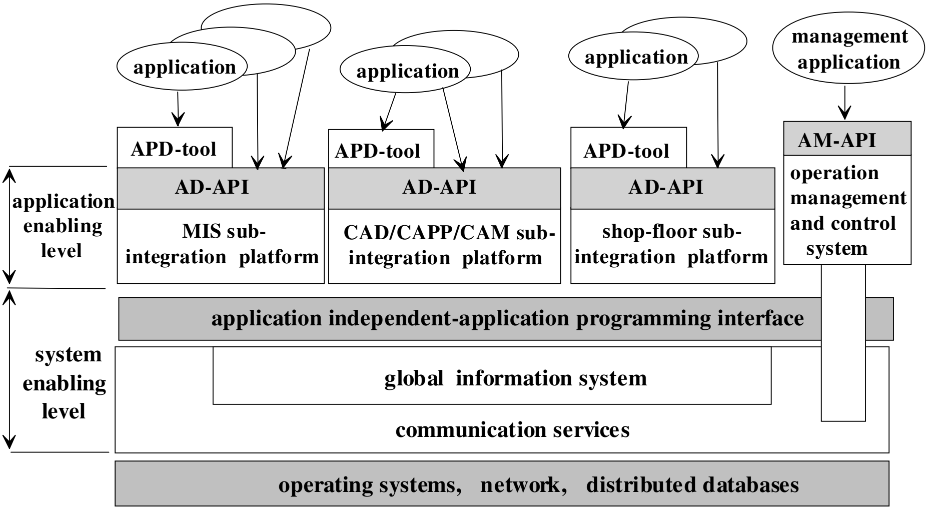


Figure 30 System Architecture of MACIP.

domain specific applications. These functions enable the complete integration of the application. Application development tools (APD tools) are developed using the AD-API. Users can also develop applications using the functions provided by AD-API. Existing applications are integrated by modifying the data exchange interface using AD-API functions. An Internet interface is also included in the application enabling level interfaces and provides access to MACIP through appropriate Internet technologies.

An operation management system was also designed that uses AI API functions to provide an application management API (AM API) for the users. Users use AM API to develop management applications that manage the IP resources and coordinate the operation of different applications.

The development of MACIP was finished in early 1999. It has since been used in several companies to support the rapid implementation of CIMS.

7. CIMS IN PROCESS INDUSTRY

7.1. Introduction

Process industry, by which we refer to continuous or semicontinuous production industry processes, principally includes the petroleum industry, the electric power industry, the metallurgical industry, the chemical industry, the paper industry, the ceramic industry, the glass industry, and the pharmaceutical industry. Process industry is a kind of highly complicated industrial system that not only includes biochemical, physical, and chemical reactions but also transmission or transition of matter and energy. Most process industries are subject to the interlocked relations of enterprise decision making, business marketing, schedule planning, material supplying, repertory transportation, and product R&D, in addition to the characteristics of continuity in wide scope, uncertainty, high nonlinearity, and strong coupling. All these factors are responsible for the unusual difficulty of comprehensive management, scheduling, optimization, and control in process industry enterprises. Therefore, these problems cannot be solved relying on either control and optimization theory, which are based on accurate mathematical models and exact analytical mathematical methods, or automation techniques alone (Ashayberi and Selen 1996). The CIMS technique is one possible solution to complex, comprehensive automation of process industry.

7.1.1. Definitions

- *Process industry:* Those industries in which the values of raw materials are increased by means of mixing and separating, molding, or chemical reaction. Production can be continuous or batch process. The characteristics of process industry must be considered when CIMS is applied to those industries.

- *Architecture structure:* The models that reflect these characteristics of production and business in process industry. The models represent all aspects of CIMS in the multiview and multilayer approach.
- *Models:* The structural representations of object concepts. Models include rules, data, and formal logical methods that are used to depict states, behaviors, and the interactive and inferential relations of objects or events.
- *Reference model:* The model definition for the architecture structure.
- *Modeling method:* According to the architecture descriptions, designers obtain the descriptions of all the states in an enterprise by abstracting the business function, business data, and business period.
- *Information integration:* Information integration activities in the production process or enterprise or even group can be described as a process of obtaining, handling, and processing information so that accurate information can be sent punctually and in the right form to the right people to enable them to make correct decisions.

7.1.2. Key Technologies

Because CIMS in process industry is in the developmental stage, some key technologies still need to be developed further:

1. *Total technology:*
    - Architecture structure and reference model of CIMS in process industry
    - Business reengineering model and managerial modes of enterprise
    - Control modes of Material and cost streams
    - Modeling methods for CIMS in process industry
    - Structural design methods for CIMS in process industry
    - Design specifications for CIMS in process industry
2. *Integration technologies:*
    - Information integration in enterprise and between enterprises
    - Integration of relation database and real-time database systems
    - Core data model, data booting, data compression, and data mining
    - Integration and Utilization of development tools and applications
    - Information integration-based Internet, data navigation, and browser technology
3. *Network technologies:*
    - Architecture structure of computer network system
    - Openess, reliability, safety, expandability, monitoring and management of networks
    - Speed, collisions resolution, concurrency control of networks
4. *Supervisor control technologies:*
    - Distributed intelligent decision-making support system-based intelligent agent
    - Optimization model establishment of large-scale systems
    - Description and analysis of hybrid system
    - Multimode grouping modeling and production operation optimization
    - Advanced process-control strategy and intelligent coordination control
    - Production safety monitoring, fault diagnosis and isolation, failure forecast
    - “Soft” measurement, intelligent data synthesis and coordination

7.2. Reference Architecture of CIMS in Process Industry

CIMS in process industry involves complex systematic engineering. Since its inception, advanced management theories, such as BPR (business process reengineering), CE (concurrent engineering), and TQM (total quality management), have been introduced. Using these theories, managers could reorganize departments that overlapped in function so as to facilitate the development of the enterprise. The realization of CIMS in these enterprises must build a clear reference architecture that can depict all functions in various phases and levels. Under the guidance of the reference architecture, the designers can simulate all potential solutions in an appropriate workbench and determine the total integration solution. The reference architecture of CIMS in process industry can refer to the frame of CIMS-OSA and PERA. The CIMS-OSA frame has many definitions and modeling approaches, in which the concepts are very clear. The PERA frame is very suitable for the definition of every phase in the CIMS life cycle, which considers every human factor that will affect the enterprise integration.

7.2.1. *Architecture Structure Model*

The architecture structure model of CIMS in process industry has four phases (Aguiar and Weston 1995): the strategic planning, requirement analysis, and definition phase; the conceptual designs phase; the detailed design and implementation phase; and the operation and maintenance phase, as shown in Figure 31. They reflected all the aspects of building process of CIMS. The strategic planning and requirement definition phase relates to senior management. The models in this phase manipulate information with reference to enterprise models and external factors to assess the enterprise's behavior, objective, and strategy in multiview and multidomain so as to support decision making. The conceptual design phase is the domain of system analysis. According to the scope defined in the previous phase, the models in this phase give a detailed description of a system in formalized system modeling technology. A solution will be found that satisfies the demands for performance and includes what and how to integrate. In general, the solution is expressed in the form of functions. Detailed design and implementation will be carried out in the system design phase. In this phase, the physical solutions should be specified, which include all subsystems and components. The models given in this phase are the most detailed. The models in the operation and maintenance phase embody the characteristics of the system in operation. These models, which define all active entities and their interaction, encapsulate many activities in enterprise operation.

The reference models depicted in Figure 31 consist of run-time models, resource models, integration models, system models, and business models, which correspond to the descriptions of the AS-IS system and the TO-BE system in the process of designing CIMS in process industry. Their relationships are abstracted step by step from down to up, opposite to the process of building CIMS.

- *Run-time models* encapsulate the information related to system operation, such as dynamic math models of production, input–output models, and order management models.
- *Resource models* contain the information related to relationships between the resource and the satisfaction of demands. In these models, the resource information that designers will add for some special functions is still included.

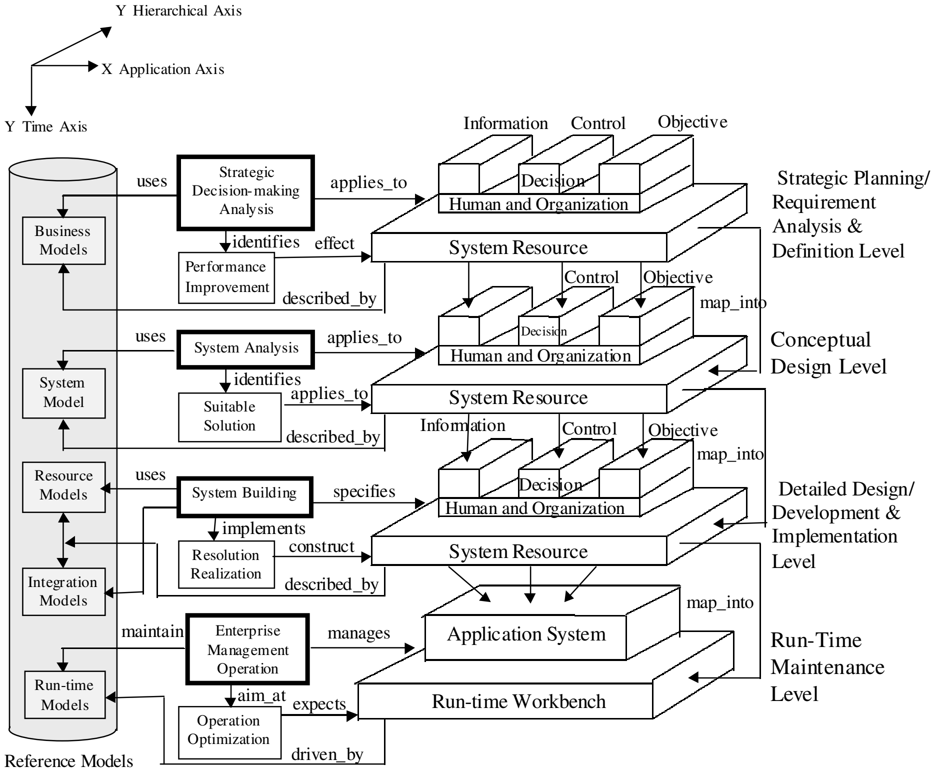


Figure 31 Architecture Structure Model. (From Aguiar and Weston 1995)

- *Integration models* present the way in which various component elements of the AS-IS system and the TO-BE system could be integrated to complete an integrated system.
- *System models* capture the structure and knowledge of the department in related domains that are currently organized or should be organized to improve the performance of the system. They encapsulate the experiences of system analysts and the descriptions of the prototype.
- *Business models* collectively contain the business knowledge required to accomplish strategic analysis and requirement definition, including business rules and the accumulated experience from analyzing enterprise performance.

With these reference models, CIMS in process industry could be built from up to down. Each phase is dynamic in nature and can be related to each other phase. That is, the implementation in every phase can be modified to adapt to changes in environment and demands.

7.2.2. Hierarchical Structure Model

The hierarchical structure model is a structured description of CIMS engineering. It is an aggregation of models and their relationships in the whole CIMS of an enterprise. It is the foundation of the design and realization of CIMS. A hierarchical structure model used in CIMS in process industry is shown in Figure 32. It has five levels and two supporting systems. The five levels are the direct control system, the supervisory control system, the production scheduling system, the management information system, and the enterprise decision making system. The two supporting systems are the database system and the computer network system.

The main function of the hierarchical structure model is:

- *Direct control system level:* This is the lowest level of automated system in the production process, including the distributed control system used in production devices and the fundamental automated equipment used offsite. The parameters of the production process are measured and controlled by the automated system. They also receive instruction from the supervisory control system level and accomplish the process operation and control.
- *Supervisory control system level:* The system in this level fulfills supervisory control of main production links in the whole production process. According to the instructions from the sched-

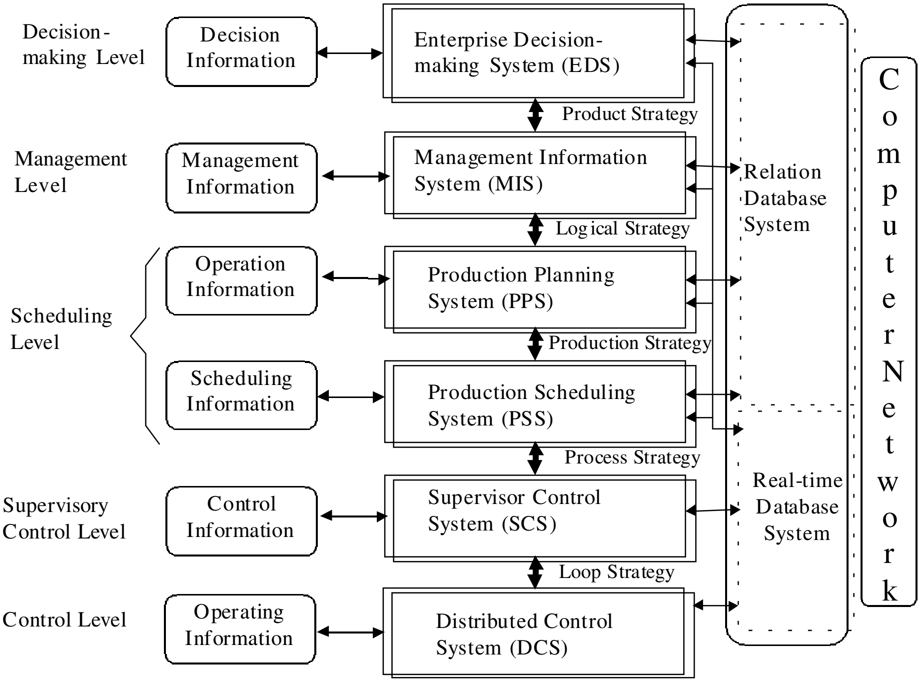


Figure 32 Hierarchical Structure Model.

uling system level, it formulates process tactics and conducts the actions at the direct control system level, including operation optimization, advanced control, fault diagnosis, and process simulation.

- *Production scheduling system level:* At this level, the production load is determined and the production planning is decomposed into five days rolling work planning for every month, according to the information from the decision-making system and the material-stream and energy-stream data. By optimizing scheduling, allocating energy, and coordinating operations in every workshop, the production becomes balanced, stable and highly efficient.
- *Management information system level:* The system at this level accomplishes the MIS function for the whole enterprise and carries out integrated management of production and business information. According to the instructions from the decision-making system, it makes logical decisions. It is in charge of day-to-day management, including business management and production management.
- *Enterprise decision-making system level:* The system at this level comes up with decisions supporting enterprise business, product strategy, long-term objectives, and developing planning and determines the strategy of production and business. Within the company group, it aims at integration optimization in the whole enterprise so as to yield the maximum benefit.

7.3. Approach to Information Integration for CIMS in Process Industry

The core of CIMS in process industry is the integration and utilization of information. Information integration can be described as follows: The production process of an enterprise is a process of obtaining, processing, and handling information. CIMS should ensure that accurate information is sent punctually on in the right form to the right people to enable them to make correct decisions.

7.3.1. Production Process Information Integration

Production is the main factor to be considered in CIMS design for a process industry. Driven by the hierarchical structure model discussed in Section 7.2.2, these information models of every subsystem at all levels are built. In these models, the modeling of production process information integration is the crux of the matter. This model embodies the design guidance, centering on production in three aspects:

1. Decision → comprehensive planning → planning decomposition → scheduling → process optimization → advanced control
2. Purchase → material management → maintenance
3. Decision → comprehensive planning → planning decomposition → scheduling → product storage and shipment control

The computation of material equilibrium and heat equilibrium and the analysis/evaluation of equipment, material and energy can be done using this model so as to realize the optimized manipulations in the overall technological process.

7.3.2. Model-Driven Approach to Information Integration

Figure 33 depicts the mapping relationship of the models in the building process of CIMS in process industry. It demonstrates that the designed function related to every phase of building CIMS can be depicted from the design view using the structural and model-driven approach (Aguiar and Weston 1995).

The realization of model mapping relies on the building of software tools supporting every phase in a hierarchical way. *Model mapping* refers to the evolutionary relationships of models between the phases of building CIMS. As the enterprise hierarchy is developed downwards, the description in the models becomes more detailed. In contrast, with the increasing widening of modeling scope, the granularity of descriptions in models will be reduced so as to form more abstract models. For example, at the detailed design and implementation level, various dynamic math models should be used, and detailed IDEF0 and static math models should be used in the conceptual design phase. We can conclude that the models of various phases in the building CIMS can be evolved step by step in the model-driven approach from up to down.

In the previous analysis, the realization of the model-driven information integration method requires a workbench. This consists of a series of tools, such as modeling tools from entity to model, simulating tools supporting the simulations in various levels from higher-level strategic planning to lower-level detailed design, and assessing tools appraising the performance of solution simulation at various levels.

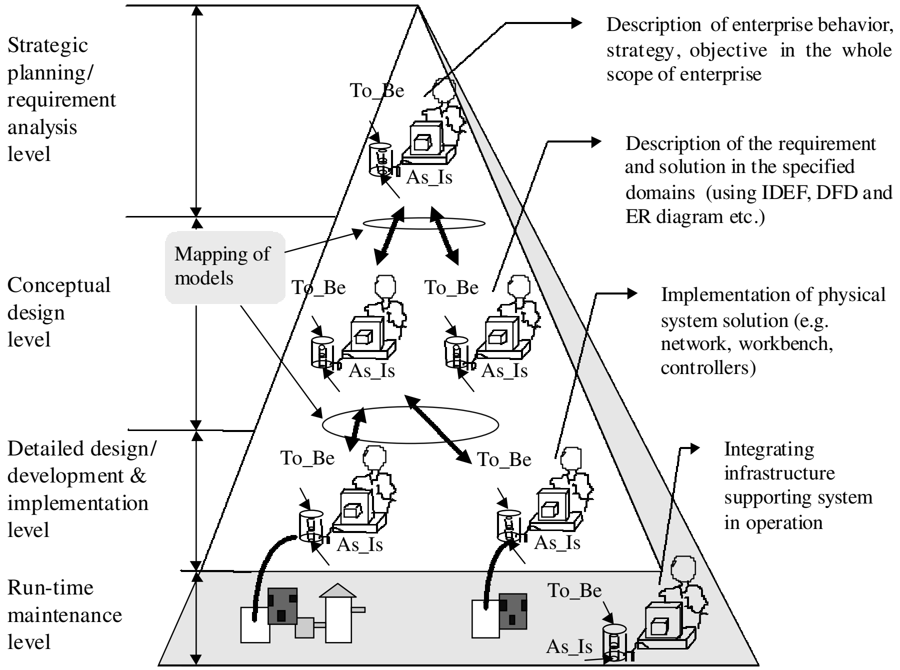


Figure 33 Integrating Map of Models Based on Model-Driven Approach. (From Aguiar and Weston 1995)

7.4. An Application Example

We will discuss an application example of CIMS in a giant refinery enterprise. The technological process of the refinery is continuous, the material stream cannot be interrupted, and strict real-time demands for production manipulation are made. The enterprise aims at the following objectives: material equilibrium, energy equilibrium, safety and high efficiency, low cost and good quality, and optimized operation of the technological process. The realization of CIMS in this type of enterprise requires the consideration not only of problems such as production management, production scheduling, operation optimization, and process control, but also of business, marketing, material supply, oil product transport and storage, development of new products, capital investment, and so on (Fujii et al. 1992). The computer integrated production system of the enterprise is constructed according to changes in crude oil supply, market requirements for products, flexibility of the production process, and different management modes. The integration of business decision making, production scheduling, workshop management, and process optimization is realized in the giant refinery.

7.4.1. Refinery Planning Process

The refinery enterprise consists of many production activities (Kemper 1997). If the blend operation day is called the original day, then the production activities on the day 90 days before that day include crude oil evaluation, making of production strategy, and crude oil purchasing. In the same way, the production activities on the day 10–30 days after the original day include stock transportation and performance adjustment of oil products. Every activity in the production process is relevant to each other activity. For example, in crude oil evaluation, the factors in the activities following the making of production strategy must be analyzed. In another example, people in the activity of crude oil evaluation need to analyze those production activities following the refinery balance in detail. Deep analysis of those activities in the refinery enterprise is the basis of design of CIMS in that enterprise. Figure 34 depicts the refinery planning process.

7.4.2. Integrated Information Architecture

By analyzing of the refinery planning process, we can construct the integration frame depicted in Figure 35.

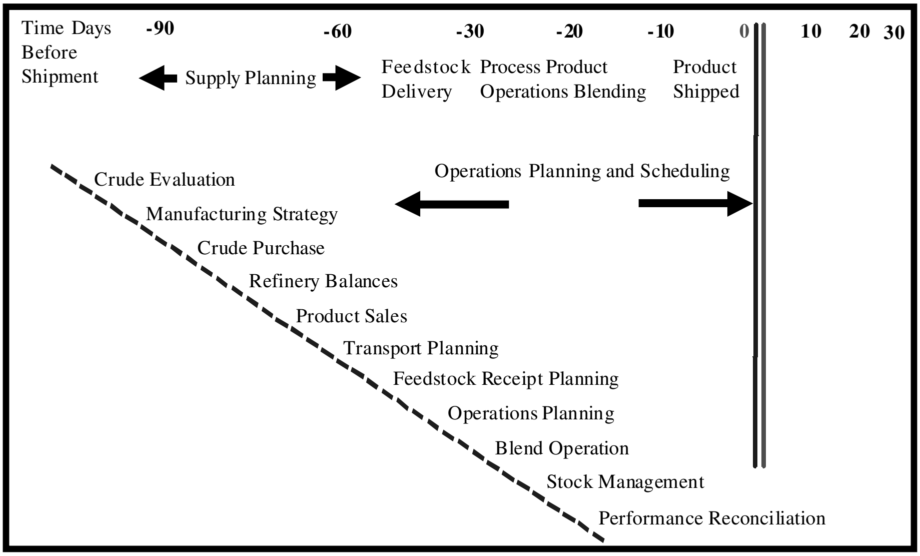


Figure 34 Refinery Planning Process.

Using the model-driven approach to the modeling of all subsystems, the information integration model in this refinery enterprise could be built as shown in Figure 36 (Mo and Xiao 1999). The model includes the business decision-making level, the planning and scheduling level and the process supervisory control level. Their integration is supported by two database systems.

The relevant information, such as market, costing, financial affairs, and production situation, is synthesized to facilitate business decisions of the enterprise, and crude oil supply and oil product sale planning are both determined at the business decision-making level.

The planning and scheduling level synthesizes management information, decomposes production planning to short-term planning and executes the daily scheduling, and gives instructions directly to process supervisory control level. In the meantime, it accomplishes the management and control of oil product storage and transport, including the management and optimized scheduling control of the harbor area and oil tank area.

The process supervisory control accomplishes process optimization, advanced control, fault diagnosis, and oil product optimized blending.

7.4.3. Advanced Computing Environment

The information integration model of the giant refinery depicted in Figure 36 is built using the model-driven method. The model is the design guidance of the realization of CIMS in the enterprise. Figure

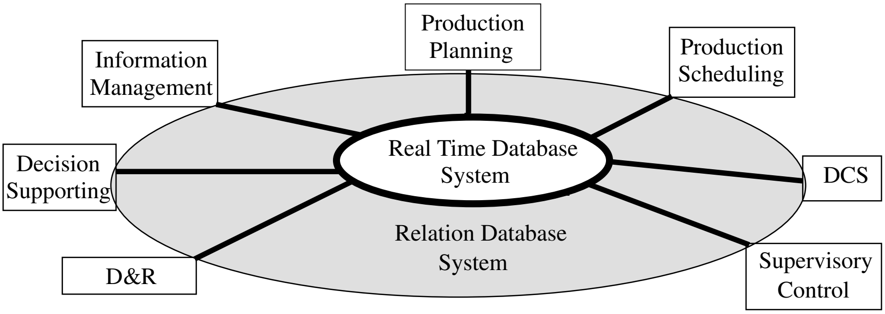


Figure 35 Integration Frame.

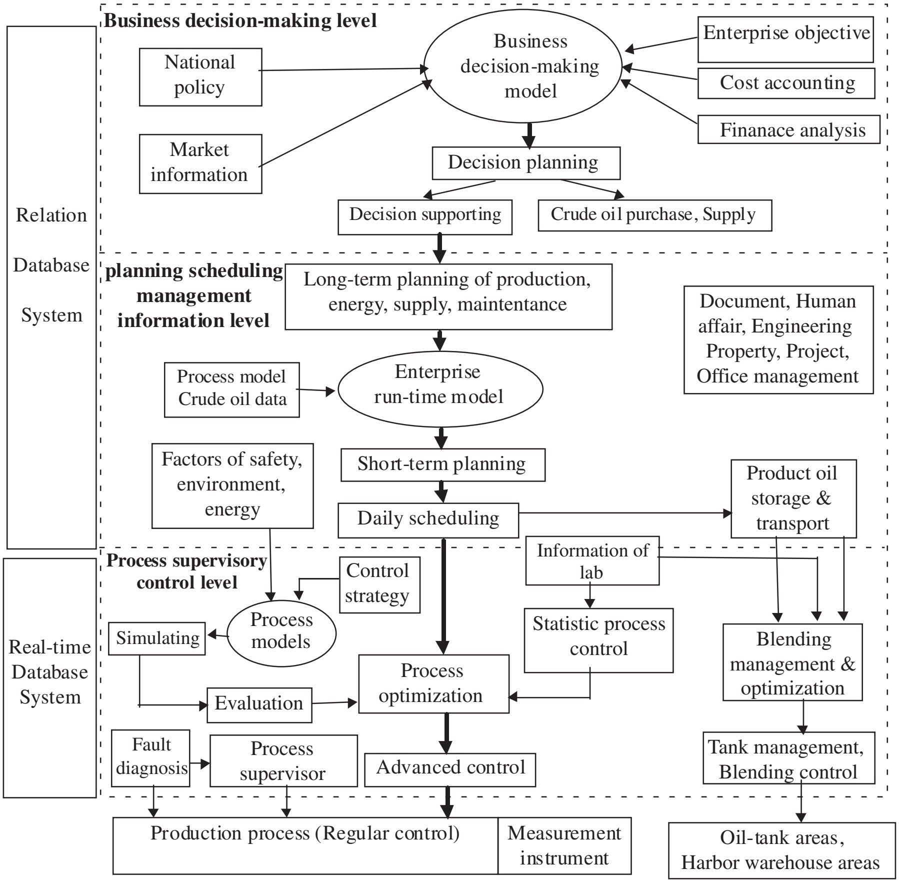


Figure 36 Information Integration Model.

37 depicts the computing environment for the realization of the information integration model, using the client–server computing mode (Kemper 1997).

7.5. Conclusions

The reference architecture of CIMS in process industry can instruct designers to optimize solutions by repeatedly optimizing and simulating so as to obtain the final physical system realization in an enterprise. Practical experience indicates that CIMS in process industry is not like selling a car. With the progressive development of technology and the changes in the external environment, CIMS in process industry needs to continue adjusting to yield the maximum economic and social benefit.

8. BENEFITS OF CIMS

Many benefits can be obtained from the successful implementation and operation of a CIM system in a manufacturing company. The benefits can be classified into three kinds: technical, management, and human resources quality.

8.1. Technical Benefits

Technical benefits obtained from implementation CIM system are:

1. *Reducing inventory and work-in-progress:* This can be accomplished through the utilization of an MRPII or ERP system. Careful and reliable material purchasing planning and production planning can to a great extent eliminate high inventory and work-in-progress level, hence reducing capital overstock and even waste through long-term material storage.

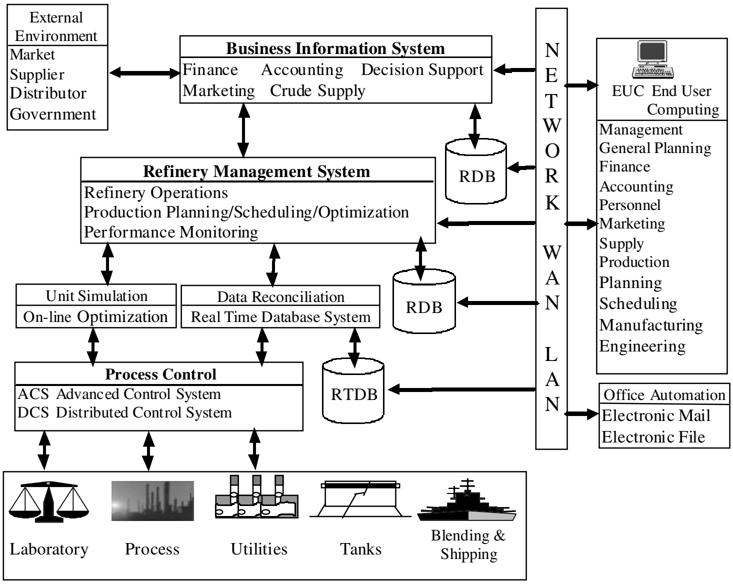


Figure 37 Advanced Computing Environment.

2. *Improving production efficiency:* Through the integration of a production system, planning system, and material supply system, the production processes can be operated in a well-organized way and hence production can be carried out with the shortest possible waiting times and machine utilization greatly increased. Through the integration of CAD, CAPP, and CAM systems, the setup time for NC machines can be reduced significantly. The improvement of production efficiency will bring economic returns from investment in the CIM system.
3. *Improving product quality:* The integration of the company's business processes, design processes, and production processes will help in improving product quality. TQM can be put into effect in the CIM integrated environment.
4. *Reducing cost:* This is the direct effect obtained from the above three benefits.
5. *Improving product design ability:* Through the integration of CAD, CAPP, and CAM systems, by using the current engineering method, the product design ability of the company can be significantly improved. New and improved products can be designed and developed in a shorter time, and the company can win the market competition with these products.

8.2. Management Benefits

The following management benefits can be obtained from the CIM sysem implementation:

1. *Standardizing processes:* The business processes, design processes, and production processes can be standardized. This can help to streamline the company's processes and reduce errors caused by uncontrolled and random operations.
2. *Optimizing processes:* The business processes, design processes, and production processes can be optimized. This can help to locate bottlenecks in the processes and cost-intensive activities and thus to provide methods to reduce the cost.
3. *Improving market response ability:* The traditional pyramid organization structure will be changed to flat structure that can greatly improve the speed of response to market change and user requirements.

8.3. Human Resource Quality

Almost all employees will be involved in the implementation of the CIM system. Through different courses of training, from CIM philosophy to computer operation, the total quality of the employees can be improved at all levels, from management staff to production operators. More importantly, employees will get to know better the company's objectives, situation, technical standards, and manufacturing paradigm, inspiring them to devote their energy to improving the company's operation efficiency.

9. FUTURE TRENDS OF CIM

As a manufacturing paradigm, CIM concepts and practice have developed for more than 20 years. CIM is still in active development and has received much attention from researchers and companies. Some of the development trends for CIM are as follows.

9.1. Agile Manufacturing

In today's continuously, rapidly, and unforeseeably changing market environment, an effective way to keep the company competitive is to use the agile manufacturing strategy. Agile manufacturing has been called the 21st-century manufacturing enterprise strategy (Goldman and Preiss 1991; Goldman et al. 1995). By agile, we mean that the company can quickly respond to market change by quickly reengineering its business processes, reconfiguring its manufacturing systems, and innovating its products.

A number of papers discuss the characteristics of an agile manufacturing company, such as:

- Greater product customization
- Rapid introduction of new or modified products
- Increased emphasis on knowledgeable, highly trained, empowered workers
- Interactive customer relationships
- Dynamic reconfiguration of production processes
- Greater use of flexible production technologies
- Rapid prototyping
- An agile and open system information environment
- Innovative and flexible management structures
- Rapid collaboration with other companies to form a virtual company.

9.2. Green Manufacturing

The increasingly rapid deterioration of environment has caused many problems for society. During the production of products, manufacturing companies also produce pollution to the environment. Pollution produced during the manufacturing processes includes noise, waste gas, wastewater, and waste materials. Another kind of pollution is caused by waste parts at the end of the product's life, such as batteries, printed circuit boards, and plastic covers. Green manufacturing aims at developing a manufacturing paradigm and methods for reducing pollution by a manufacturing company of the environment. The green manufacturing paradigm covers the whole life cycle of a product, from requirements specification, design, manufacturing, and maintenance to final discarding. Research topics in green manufacturing include:

- *Green design* (also called *design for environment*) considers the product's impact on the environment during the design process, designing a product that causes minimal pollution. Multi-life-cycle design, which considers multiple use of most parts and recycling one-time-use parts, has received much attention.
- *Green materials* involves development of materials that can be easily recycled.
- *Green production* involves developing methods to reduce pollution during the production process.
- *Green disposal:* developing new methods to recycle the discarded products.

9.3. Virtual Manufacturing and Other Trends

By using virtual reality and high-performance simulation, virtual manufacturing focuses on building a digital model of the product and studies the dynamic and kinetic performance of the product to reduce product development cost and time.

Many development trends are affecting CIM and its related technologies. Technologies that may have a great influence on CIM include network (Web) technology, distributed object technology, intelligent agent technology, knowledge integration technology, and CSCW technology. CIM systems, using these advanced paradigms and technologies, will have a brilliant future. In the future, a manufacturing company supported by an advanced CIM system may be operated in an Internet environment (Web user interface), running on a virtual dynamic organization structure, using CSCW tools, to design and produce products in a cooperated and integrated way. The company will fully satisfy user requirements and produce products quickly and cheaply. Materials and products will be delivered on time.

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