CHAPTER 9

Virtual manufacturing and systems

Q. Wang
School of Engineering,
University of Durham, UK

Abstract

Since the 1970s, the world market has changed from the traditional, relatively stabilized state to dynamic diversification and from previously local competition to global competition. The mutual penetration and competition between the same trade and multi trades are progressively severe. In order to cope with the rapid market change and the increase in competition, the modern manufacturing organization must solve the Time, Quality, Cost, Services (TQCS) problems, i.e. satisfy different customer requirements with the fastest time to market, the best product quality, the lowest product cost, and the classical services.

In the meantime, with the rapid development of information technology (especially in computing technology, computer network technology, and information processing technology areas), various modern manufacturing technologies and systems are coming out. For example, in the early 1980s, computer integrated manufacturing systems began to be implemented in factories; in the late 1980s, concurrent engineering further enhanced manufacturing level; in the 1990s, advanced manufacturing technology further developed to a higher level, and new concepts such as Virtual Manufacturing, Lean Production, Agile Manufacturing, and Virtual Enterprise appeared (Figure 1). This chapter will discuss the concept of Virtual Manufacturing and Systems (VMS), its basic components and applications, etc.

1 Introduction

Virtual manufacturing is a new concept of the 1990s. It is driven by high market competition, manufacturing strategy (Figure 2) and advanced technologies. Along

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with the development of manufacturing technology, many new ideas, new concepts and new methods are used to improve the efficiency of manufacturing systems, such as Flexible Manufacturing Systems, Computer-integrated Manufacturing Systems, and Intelligent Systems, etc.

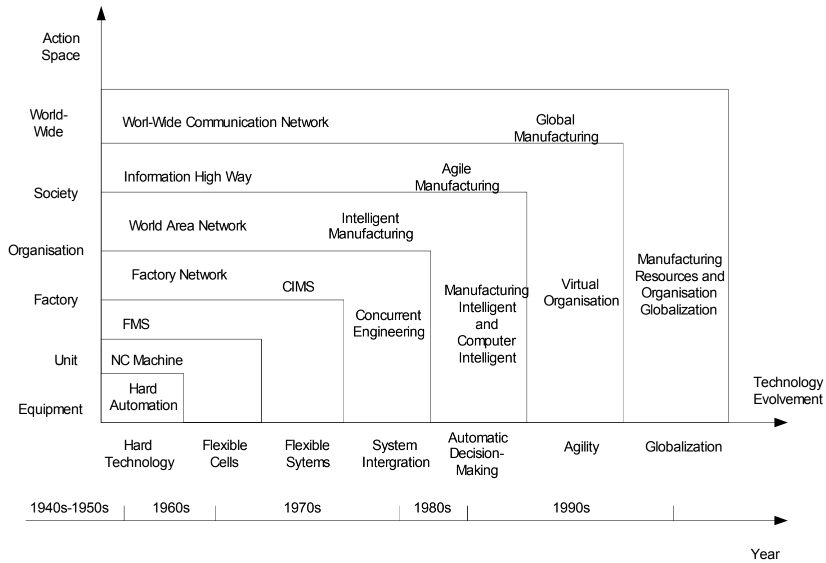

Figure 1: Manufacturing automation development mode and trends.

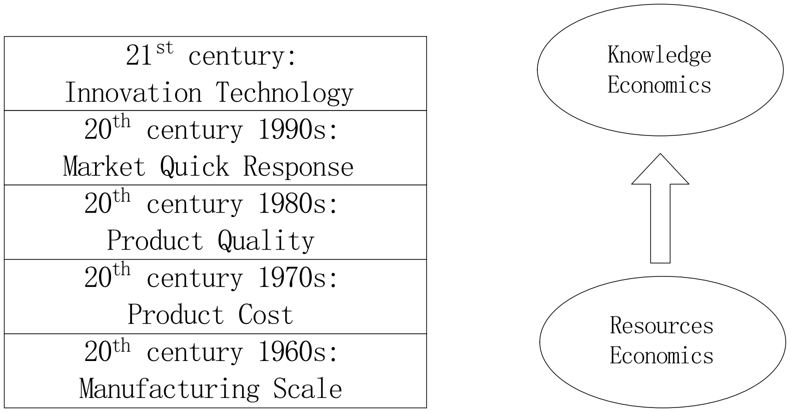

Figure 2: Manufacturing strategy changed for organizations.

These systems are highly flexible, highly integrated, and highly intelligent systems, and create a huge impact on increasing product quality and efficiency, cutting down production design and manufacturing time, reducing costs and increasing enterprise competition. However, these systems still have some problems; Table 1 lists the various scenarios.

Table 1: Factors that influence manufacturing systems.

1. Complex manufacturing environment; frequent product redesign; change of scheduling. 2. When a new product is designed, it is hard to evaluate the benefits and risks before it is put into production. 3. Difficult to gather the real manufacturing information in different production design stages. 4. Difficult to adjust the relationship between design and manufacturing to ensure the enterprise gets maximum benefit.

In order to solve these problems, virtual manufacturing and systems are emerging as time goes on.

2 Virtual manufacturing

2.1 The concept and classification of virtual manufacturing

Virtual manufacturing as illustrated in Figure 3 [1, 2], (also called manufacturing on pixels or screen manufacturing), is the essential implementation of the real manufacturing process in a computer environment. It uses computer simulation and virtual reality technology to model the whole manufacturing process. It allows the operator to be personally "present" on the scene, assimilating a synthetic environment to evaluate the production design; to carry out manufacturing and performance analysis, quality inspection, and sales and services, etc. It enhances the decision-making and control at all levels of the manufacturing process.

There are several different definitions of virtual manufacturing (VM). The typical definitions are:

(1) Virtual manufacturing is a concept of executing manufacturing processes in computers as well as in the real world, where virtual models allow for prediction of potential problems for product functionality and manufacturability before real manufacturing occurs – Gloria. J. Wiens, University of Florida [3].

(2) Virtual manufacturing is the integrated application of simulation, modelling and analysis technologies and tools to enhance manufacturing design and production decisions and control at all process levels - Wright-Patterson Air Force Base [4].

(3) Virtual manufacturing is an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control - Lawrence Associates' Virtual Manufacturing User Workshop Report [1].

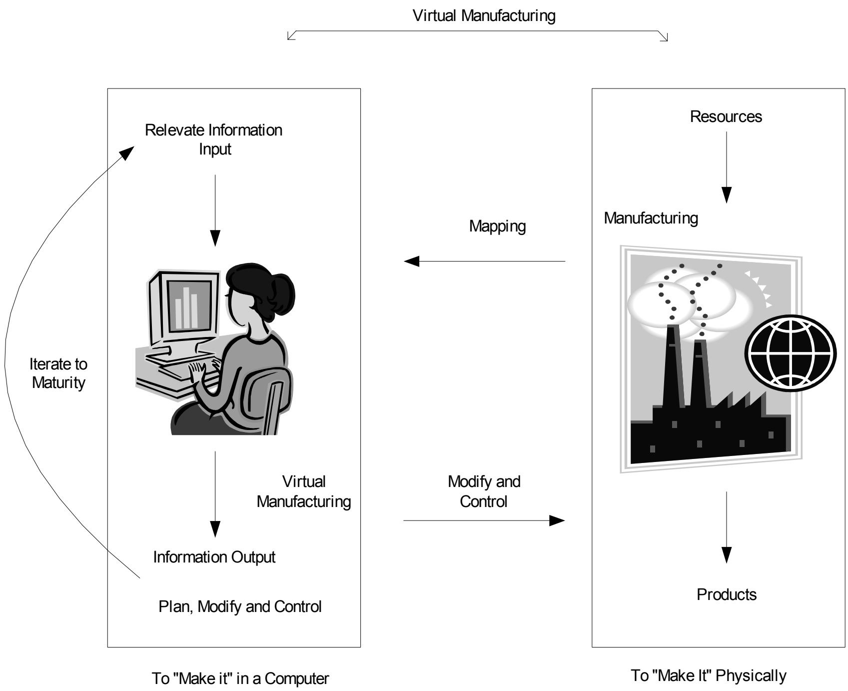

Figure 3: The concept of virtual manufacturing [1].

In definition (3):

Synthetic means a mixture of real and simulated objects, activities and processes.

Environment means to support the construction and use of distributed manufacturing simulations by synergistically providing a collection of analysis tools, simulation tools, implementation tools, control tools, models (product, process and resource), equipment, methodologies and organizational principles (culture).

Exercising means constructing and executing specific manufacturing simulations using the environment.

Enhance means increase the value, accuracy, and validity.

Levels means from product concept to disposal, from the shop-floor to the enterprise and beyond, from material transformation to knowledge transformation.

Decision means understand the impact of change (visualize, organize, and identify alternatives).

Control means predictions affect actuality.

According to the above concept, virtual manufacturing can be classified into three paradigms [1]:

Design-centred VM provides an environment for designers to design products and to evaluate the manufacturability and affordability of products. The results of design-centred VM include the product model, product performance evaluation, cost estimation, and so forth. Design-centred VM is the usage of manufacturing-based simulations to optimize product and processes design for a specific manufacturing goal such as design for assembly, quality, lean operations, and/or flexibility.

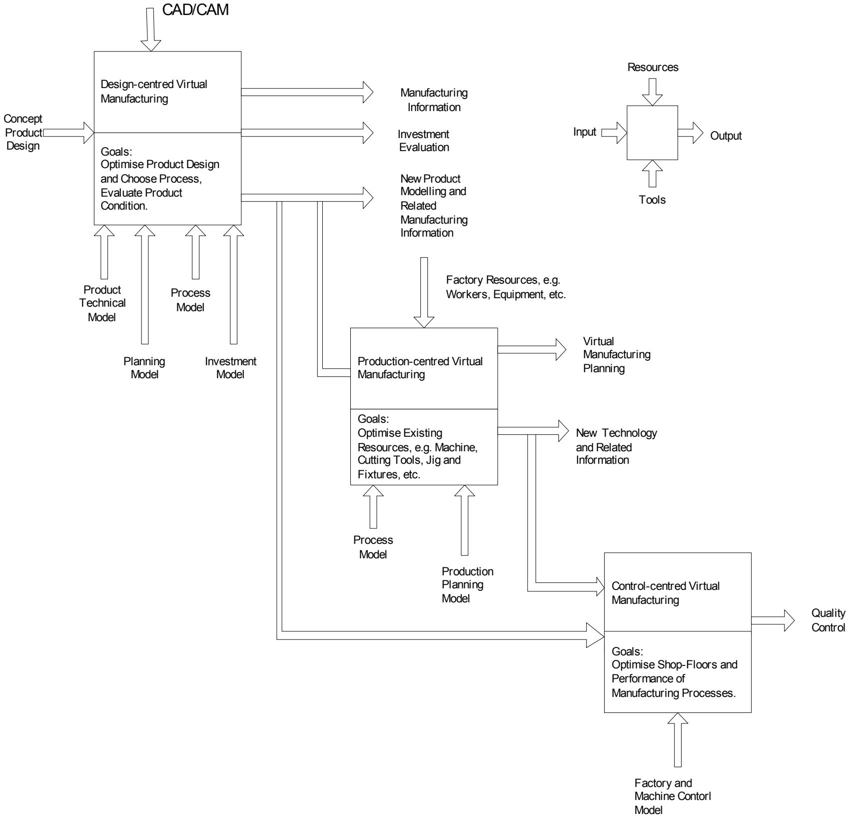

Figure 4: The relationships among three types of virtual manufacturing.

Production-centred VM provides an environment for generating process plans and production plans, for planning resource requirements, and for evaluating these plans. Production-centred VM adds simulation capability to manufacturing process models with the purpose of allowing inexpensive, fast evaluation of many processing alternatives. It can provide more accurate cost information and schedules for product delivery. An example would be evolutionary re-engineering/optimization of a fabrication facility. Production-centred VM adds analytical production simulation to other integration and analysis technologies to allow high confidence validation of new processes and paradigms.

Control-centred VM offers an environment for engineers to evaluate new or revised product designs for the shop floor related activities. Control-centred VM provides information for optimizing manufacturing processes and improving manufacturing systems. Control-centred VM uses machine control models to achieve process optimization during the actual production cycle.

In theory, design-centred virtual manufacturing provides manufacturing information for the designer in the design stage. Production-centred virtual manufacturing uses simulation technology to optimize the manufacturing process during the production planning period. Control-centred virtual manufacturing uses a machine control model in simulations, the goal of which is process optimization during actual production. Their relationships are shown in Figure 4.

2.2 Related technology for virtual manufacturing

The technical support for virtual manufacturing includes input/output and relative computer hardware, software technology and electronic technology integrated with hardware systems. Figure 5 describes the relationships among them. Computer simulation optimization technology, 3-D modelling and network technology are the core technologies of virtual manufacturing. It is necessary to undertake further research in these areas to fully understand and use virtual manufacturing.

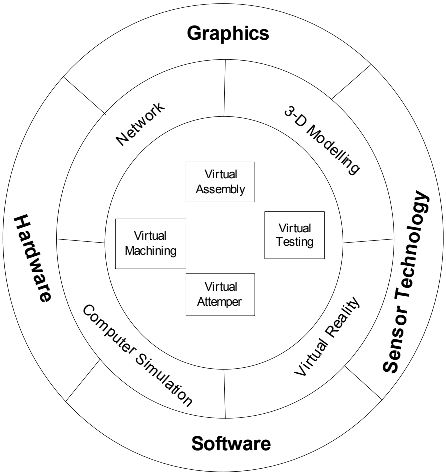

Figure 5: Technical support for virtual manufacturing.

In 1996, Lawrence Associates Inc [1] classified relative technologies of virtual manufacturing into four levels: core technology, enabling technology, show topper technology and common technology. Core technology is the foundation and key technology of virtual manufacturing; enabling technology is essential technology but not core technology to set up virtual manufacturing system; show topper technology refers to the technology that a virtual manufacturing system can not be established without it; common technology is the technology that is being extensively used.

2.2.1 Virtual reality

Virtual reality technology is one of the most successful technologies to be used since the 1990s [5]. It is a driver of the development of virtual manufacturing technology and makes significant support to virtual manufacturing technology.

Virtual reality refers to using a computer graphic system and various display and control interface equipment to create a three-dimensional interactive environment (which is called virtual environment) to provide immersion technology.

A virtual reality system [6] includes three fundamental elements: operator, machine and man-machine interface. Machine refers to a computer in which proper software has been installed so that the customer can interact with it in a virtual environment. Man-machine interface refers to transfer and control equipment to provide the connection between the operator and the virtual environment. The virtual reality system can make the real world dynamically. Computers in the virtual reality system can track the interactive input of the customer, modify the virtual environment and improve the performance of the virtual environment. Therefore interaction, immersion and imagination are the three basic characteristics of a man-machine relationship in a virtual reality system.

2.2.2 Software technologies

Ten technologies have been identified:

(1) Visualization: means to present the information in a way that is meaningful and easy to comprehend. In addition to graphical user interfaces (GUIs) and virtual reality technology, this technical area includes information distillation, aggregation and auto interpretation.

(2) Environment construction technology: a computer-based environment which facilitates the construction and execution of virtual manufacturing systems. The technology is used to extract information, to create simulation models, to properly configure the virtual environment, and to link real processes with virtual processes.

(3) Information representation: the technologies, methods, semantics, grammars and analytical constructs required to represent all of the types of information associated with product design and manufacture. In this way, information can be transparently shared between all software applications that support the representation technologies, methods, semantics, etc.

(4) Meta-modeling: this technology refers to, in essence, constructing, defining and developing models that accommodate inter-model interaction. The area involves standards and integration issues.
(5) Integrating infrastructure and architecture: the underlying infrastructure (e.g. network, communications) that supports the ability to share models and integrate product and process development across geographically distributed enterprises. The technology also includes creating a framework for the inter-operation of all virtual manufacturing technologies.
(6) Simulation: the ability to represent a physical system or environment in the computer. This technology includes a wide range of computer software applications and, in the long term, links to real world systems that enable simulation-based control. This technology includes model optimization and validation.
(7) Methodology: the methodology for developing, deploying and using virtual manufacturing systems, including “simulation-based reason.” The latter refers to “problems” that are defined in such a way that “simulation” will generate insights (i.e., alternatives, potential solutions, problem definition/refinement). Problem solutions will likely require more than just “simulation.” This methodology can not be identified during the different phases. However, it should be consistent across all phases.
(8) Manufacturing characterization: this technology involves the capture, measurement and analysis of the variables that influence material transformation during the manufacturing process. It also involves the techniques and methods for creating generic models of these processes based on actual shop floor data.
(9) Verification, validation and measurement: for virtual manufacturing, this technology refers to the methodologies and tools to support the verification and validation of a virtual manufacturing system. Making decisions on a virtual manufacturing “simulation” of manufacturing demands a confidence that the impacts of those decisions on physical manufacturing will be realized as predicted. The methodologies and tools are developed to provide the confidence. Measurement is included in this technical area because its central role in maintaining a mapping between the physical environment and the virtual environment is necessary for the verification and validation methodologies.
(10) Workflow: the work of an organization follows a path called the workflow. This technical area encompasses the capture, evaluation and continuous improvement of the processes that are associated with workflow.

2.2.3 Hardware equipment

The hardware equipment includes:

(1) The input/output equipment includes cathode-ray tube (CRT) head mounted display or liquid crystal display (LCD) head mounted display, computer monitor, projection system, stereoscope, data glove with flexible optics, data cloth, hearing and speech system, etc.

(2) Information access system and computer interface that is relevant with the input/output equipment.
(3) High speed data calculation system and high quality image processing system.
(4) Network structure (star type, field bus type, circle type), hardware, communication establishment and configuration with different nodes.

2.3 Virtual manufacturing and real manufacturing

It can be seen from the concept of virtual manufacturing [2], that it is very different from real manufacturing. It does not produce a real product and consumes no materials and energy. It is modelling the manufacture of an object from real resources and the actual manufacturing process. The virtual manufacturing can be used for the whole product life cycle simulation and organization behaviour simulation. Compared with real manufacturing, virtual manufacturing has the following four characteristics:

(1) Virtual: carrying out product design, manufacturing and testing in a virtual manufacturing environment. The designer and client can enter the virtual environment, change the product size, shape, structure, and observe and evaluate it. The observer can even be interactive with past, present, or future factory equipment. The observer can preview the activity involved in the factory or the whole product life cycle and practise the manufacturing process.
(2) Digital integrity: virtual manufacturing and its system are public platforms which include each individual manufacturing technology, such as Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), Computer-Aided Process Planning (CAPP), Computer-Aided Manufacturing (CAM), and the links among these technologies.
(3) Distribution: this allows different people in different places and different departments to work with the same product model, to communicate and share information, and so reduce the creation time and transfer time for large files, thereby reducing errors and facilitating the product development process.
(4) Reliable: the running of virtual manufacturing and the description of the manufacturing process are based on the person's understanding of the real physical process. Therefore the running of virtual manufacturing is a synthetic understanding of the manufacturing process: it can not create the new knowledge for the real physical process, and its simulation accuracy can not be better than that of the real process.

In general, virtual manufacturing is the abstract of real manufacturing; real manufacturing is the instance of virtual manufacturing.

2.4 Virtual manufacturing and other advanced manufacturing technology

2.4.1 Computer integrated manufacturing system (CIMS) and virtual manufacturing

Computer integrated manufacturing uses a local network and computer system to link the manufacturing, sales and management activities within the enterprise to achieve the integration of manufacturing resources. The integration of CIMS is physically and logically linking each activity within the enterprise and transfer of information in each node. Virtual manufacturing systems are integrated with digital models using each individual CAD, CAE, CAPP, CAM, etc., tools within the same virtual environment to map the manufacturing process. The research on CIMS provides support for information exchange and transfer in virtual manufacturing systems. Virtual manufacturing systems provide the simulation environment for implantation of CIMS, increasing the CIMS running efficiency, eliminating design error and providing technical support.

2.4.2 Agile manufacturing (AM) and virtual manufacturing

Agile manufacturing is about choosing a partner to form the virtual enterprise based on companies' rivalry and credit. It can share information and facilities, co-operate, increase competition as a whole enterprise, quickly respond to market change, and satisfy customer requirements [7, 8].

The meaning of agile manufacturing includes:

(1) Changing the traditional high quantity production mode.
(2) Improvement of the manufacturing process by using information technology and advanced manufacturing technology.
(3) Integration of the manufacturing process in different companies or different departments in one company as a whole system through construction of a common infrastructure to achieve the improvement of the manufacturing process.
(4) Offering a quick response to a rapid change or to an unpredictable customer requirement and to a market demand.

Agile manufacturing's core function is quick response [9]: in order to reach this aim, one of the key elements is where to choose partners and establish the virtual enterprise as quickly as possible. Virtual manufacturing provides technical support and the simulation environment for choosing partners, designing a co-operative process and evaluating the cooperation. The core function of a virtual enterprise is virtual manufacturing technology and research on how to choose a partner in a virtual manufacturing environment which is a major point in agile manufacturing research.

2.4.3 Concurrent engineering (CE) and virtual manufacturing

Concurrent engineering is a manufacturing method that can manufacture a high quality product with the fastest speed. It is a system-integrated mode that parallels and incorporates the model designed for the production of the product and corresponding process [10]. This working mode requires that the designer consider all the factors through the whole product life cycle, including design, manufacturing, quality, cost, process planning and customer requirements, etc. Simulation and evaluation are used to modify and consummate the design to make sure the manufacturing is right at the first time. In the concurrent engineering mode, each designer can work on his own workstation like the traditional CAD workstation to make his or her own design process. At the same time, this computer can communicate with other workstations. He or she can respond to other designers' requirements to modify his design. He or she can also ask other designers to respond to his or her own requirements. This multiple design work can be in parallel and in line with the design process.

Concurrent engineering is the start and aim of virtual manufacturing. Virtual manufacturing is the embodiment of concurrent engineering and one of the main technical tools. Virtual manufacturing enables the design process and manufacturing process to be run in parallel.

2.4.4 Lean production (LP) and virtual manufacturing

Lean production is an assembly-line manufacturing methodology developed originally for Toyota and some other automobile manufacturers [11]. It is also known as the Toyota Production System. The goal of lean production is described as "to get the right things to the right place at the right time, the first time, while minimizing waste and being open to change". There are four characteristics of lean production:

(1) Think deeply about customer requirements; use the fastest speed and suitable price to provide a high quality product and service.
(2) Pay attention to human resources, with emphases upon multi-functional team work. Carry out enterprise management.
(3) Eliminate any none-value added activity; reduce the management level; simplify the organization structure; create shorter production development processes and manufacturing processes; reduce non-manufacturing costs to emphasize insurance of quality.
(4) Continue improvement in product quality, cost reduction, and achieve zero stock and product variability.

Lean production requires simplifying the manufacturing process, eliminating waste, making the production and the manufacturing process simple and standardized. Consequently, it is suitable for simulation modelling in virtual manufacturing, i.e. the simpler the manufacturing process is, the easier the virtual manufacturing can make it. Virtual manufacturing provides a powerful tool for simplifying the manufacturing process. Through virtually running the process, designers can find the shortcomings of the process and evaluate the results.

2.4.5 Green manufacturing (GM) and virtual manufacturing

Green manufacturing is a modern manufacturing mode that refers to a multi-disciplinary approach aimed at the whole of the product life cycles such as design, manufacturing, packing, transformation, usage and broken stage to minimize the negative effect on the environment and improve effective usage of resources. Although the research of green manufacturing has only recently started, the influence on the environment in the manufacturing process was not considered when the virtual model was built. However, it will be one of the most important features of virtual manufacturing systems in the future.

2.4.6 Intelligent manufacturing technology (IMT) and virtual manufacturing

Intelligent manufacturing technology refers to each stage of manufacturing industry: designers can use highly flexible and highly integrated methods to simulate human experts' intelligent manufacturing activities, for example, analysis, estimations, reasoning, conceptions and decision-making for manufacturing problems. It aims at replacing or extending part of the human brainwork in a manufacturing environment, and collecting, storing, remedying, sharing, inheriting and developing human experts' intelligence in manufacturing technology. Virtual manufacturing provides simulation and evaluation of the intelligent manufacturing process and optimization of the intelligent manufacturing process.

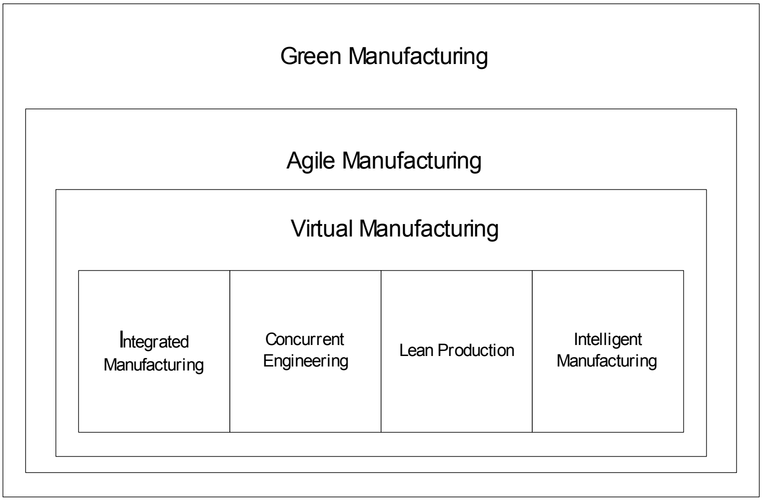

Figure 6: The relationships among virtual manufacturing and other advanced manufacturing technologies.

To sum up, virtual manufacturing is an approach to design and manufacture in a virtual world. It connects with the real world through networks, databases, etc., and provides guidance for real manufacturing. Concurrent engineering, integrated manufacturing, lean production, agile manufacturing, green manufacturing and intelligent manufacturing are the advanced manufacturing technologies used in the real world [12]. These manufacturing technologies not only provide technical support for virtual manufacturing, but also receive direction from virtual manufacturing. The relationships among these technologies are shown in Figure 6.

3 Virtual manufacturing technology

3.1 Introduction

Virtual manufacturing technology is the main support and key content of virtual manufacturing [13]. It is a system-integrated technology formed by multi-subject knowledge. It requires computer simulation technology as the precondition to unifying modelling in design and manufacturing processes [14, 15]. In the product design stage, the designer can simulate the whole manufacturing process of the future product and analyze the influence of the simulation for product design. Virtual manufacturing technology can predict product performance, product manufacturability, and product assembly possibility. Therefore, it can be used to arrange manufacturing in a more efficient, more economical and flexible way: making the factory and shop-floor layout more reasonable and efficient; to minimize cost, minimize product life cycle, improve product design quality and optimize the product design process.

3.2 Virtual design

Modern product design is a process facing the market and attractive to the customers and so is very marketable. It is a multi-level design and intelligent design. The design aims at quick response to market change, reducing consumption and protecting the environment. Therefore, the design methodology focuses on co-operation, synergism, and parallel design.

The product structure, function and cost depend on the performance of product design and manufacturing. Virtual product development can be treated as a virtual manufacturing technology that centres on design. It builds a digital model instead of a traditional model, and modifies the original product design to make sure the model is right first time, which reduces consumption of materials.

Virtual design makes the designer and co-operating engineers work in a multi-disciplinary way to complete tasks such as product design, and possible modification, manufacturing and testing [16]. Virtual design is not only used at the prototyping stage, it is also involved in the whole manufacturing and sales activities. Virtual design technology can be widely used in areas such as rapid design and rapid prototyping, design for assembly, design for manufacturing, design for disassembly, parallel processing for product design and staff training, product services, etc.

3.3 Virtual machining

Virtual machining refers to accomplishing changes in the geometrical characteristics and physical performance of the product in a virtual environment. The virtual machining process is shown in Figure 7.

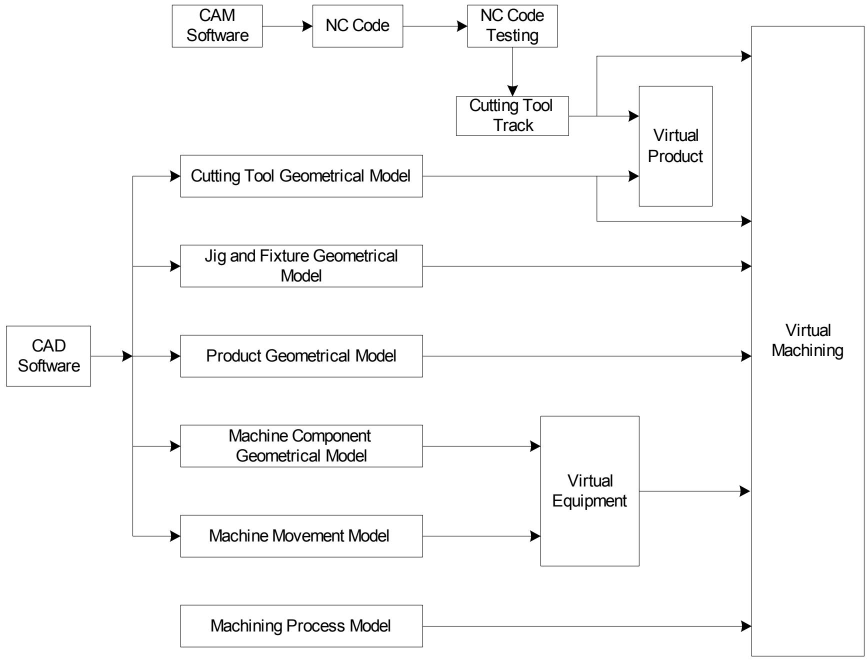

Figure 7: Virtual machining process.

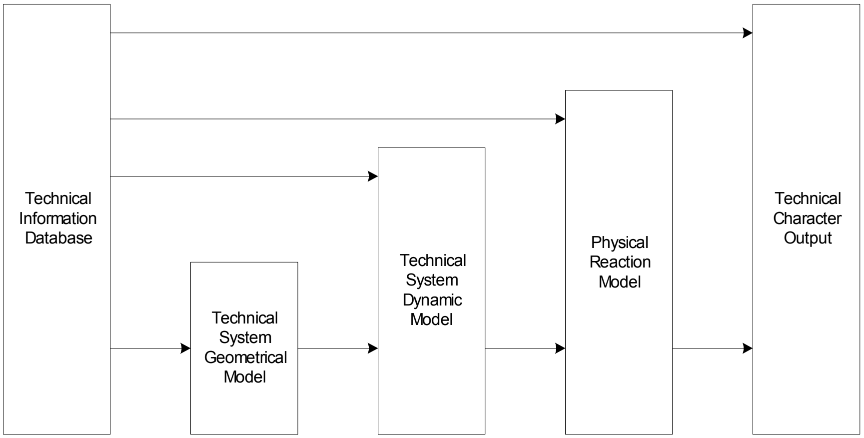

Figure 8: The structure of a virtual machining simulation system.

The machining process simulation includes cutting process simulation, welding process simulation, pressing process simulation and casting process simulation, etc.

The core of virtual machining is using information technology, modeling and simulating the whole manufacturing activities in three levels. At the technical process level, accurate and reliable data support and modelling are emphasized. At the real machining simulation process level, it provides a rapid, economical evaluation method in the design stage of the technical process. At the manufacturing system level, efficient evaluation of the manufacturing system performance, modelling the whole product life cycle, simulation of enterprise virtual running and using risk assessment to adjust and optimize the system are emphasized.

The structure of a virtual machining simulation system is shown in Figure 8.

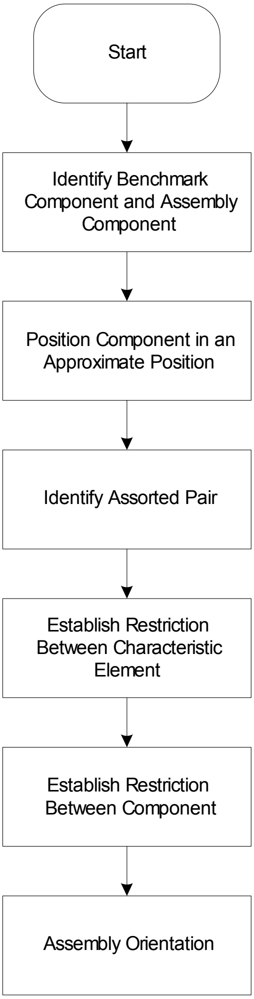

Figure 9: Virtual assembly modelling process.

3.4 Virtual assembly

Virtual assembly is built by an intuitionistic visible dynamic model in a computer and carried out by interferential inspection for each component assembly in virtual environment [17, 18]. The benefit is it can easily find out design error and quickly amend it to increase design efficiency and reduce cost. Virtual assembly applies the quotation method. It does not send all components to the assembly model: it only recalls the components' position in the model. When the components are required, they are then sent to the assembly model. Therefore, these processes save the hard disk space and memory space. The benefit of using the quotation method is that the assembly model only records the latest component assembly information. After modification, the assembly model can be updated automatically. Therefore, it can reduce the workload. Another benefit of using the quotation method is that it provides technical support for concurrent engineering. Each component that is quoted by the assembly model can be stored in a computer as a file. Consequently, it can be easily managed or transferred through networks, and it makes team-work possible.

Virtual assembly has two assembly modes: top to bottom assembly mode and bottom to top assembly mode. According to the different types of product characteristic, designers can select the different virtual assembly model.

A diagram that describes the virtual assembly model process is shown in Figure 9, which includes 5 basic steps.

3.5 Virtual test

Test, measurement or inspection is a powerful technical tool to guarantee product quality. In the manufacturing process stage, this involves making a test in the product design and manufacturing process, carrying out assembly performance analysis and quality inspection to make sure quality control and normal production are achieved.

A virtual test is based on simulation technology [14]. It uses various characteristics of the virtual product design model to complete the inspection, test, and monitor activities in the visible simulation environment. In a virtual manufacturing process, test items include virtual component geometry size tolerance, virtual dimension tolerance, virtual surface roughness, and virtual manufacturing process parameters. It also includes product performance test, virtual product test in displacement, distortion and stress distribution, inspection and diagnosis of the vibration impact, noise and failure, etc. Figure 10 illustrates a typical virtual test environment.

A virtual test system includes virtual design, virtual machining, virtual assembly, and product performance virtual test subsystems. The results of a virtual test can be used to optimize and improve the design and process parameters at each stage of virtual manufacturing technology. Virtual test is a widely-used technology in virtual manufacturing technology. It can accelerate the development of virtual manufacturing technology.

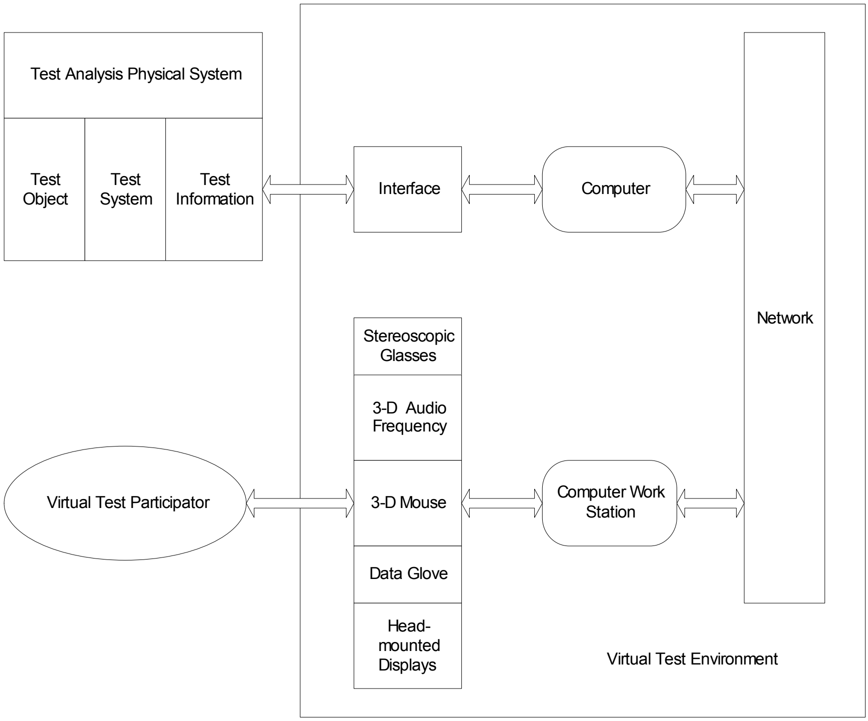

Figure 10: Virtual test environment.

Virtual design can carry out product tests in the design stage. Test engineers and design engineers can work together. Therefore, it can avoid and eliminate the test problems due to design changes. Virtual test can significantly reduce a new product development cycle.

4 Virtual manufacturing systems

4.1 The concept of a virtual manufacturing system

A virtual manufacturing system is built based on virtual manufacturing technology [19, 20]. It is the mapping of a real manufacturing system in a virtual environment. It consists of two subsystems: information systems and physics systems. Information systems include a real information system and virtual information system. Physics systems include a real physical system and virtual physical system.

Suppose a virtual information system and virtual physics system exist, then the virtual manufacturing system must be at least one of the following scenarios:

(1) Real physical system + real information system = real manufacturing system.
(2) Real physical system + virtual information system = manufacturing system with virtual process planning and management, e.g. making running test by computers for the factory already built.
(3) Virtual physical system + real information system = manufacturing system with virtual manufacturing activities, e.g. planning and evaluation for building a new factory.
(4) Virtual physical system + virtual information system = physical system and information system model virtually built in computers and the manufacturing system implemented by simulation.

4.2 The function of a virtual manufacturing system

A virtual manufacturing system is a system that integrates computing technology such as virtual reality, visualization, and multimedia to support modelling (Kimura [21]) and analysis of product development simulation (Iwata *et al*. [22]). A virtual manufacturing system provides the following functions:

(1) Achieve integration of product development process (Jayaram & Angster [23]) in manufacturing organization.
(2) Achieve close-loop product development mode for virtual product design and virtual manufacturing simulation.
(3) Improve decision-making and control ability in product development process.
(4) Improve enterprise ability in self-adjustment, self-consummation, self-change, and self-development.

4.3 The requirements for a virtual manufacturing system

A virtual manufacturing system is the mapping of a real manufacturing system in a virtual environment. It is an abstract expression of a real manufacturing system in the stage of modelling, computing and formalization. Virtual manufacturing systems and real manufacturing systems have similar functions. The main difference is that a virtual manufacturing system creates a digital product, not a real product.

The requirements for implementing a virtual manufacturing system (Jordan *et al*. [24]) include:

(1) Function consistency: the function of a virtual manufacturing system should coincide with its real manufacturing system. The control command and information created and transferred by a virtual information system (Iwata *et al*. [25]) should coincide with its real information system. The function of a virtual physical system responding to a control command should coincide with its real physical system. Inside a virtual information system, the communication and exchange between one virtual information system and another virtual information system /real information system, or between one virtual information system and one virtual physical system/real physical system should be taking place.
(2) Structure similarity: a virtual manufacturing system should have a similar structure to the corresponding real manufacturing system. Structure similarity provides designers with an intuitionistic platform to define, organize and modify the structure.
(3) Structure flexibility: a virtual manufacturing system is an advanced manufacturing system. It faces the market and customers; therefore the structure of a virtual manufacturing system has to be highly flexible to meet the requirements.
(4) System integration: a virtual manufacturing system relates to some advanced technologies such as systems engineering, knowledge engineering, concurrent engineering, man-machine engineering, etc. It is an integration of information, intelligent, serial/parallel working mechanism and a man-machine interface.
(5) Intelligence: each node of a virtual manufacturing system needs to have intelligence. It aims at finding a solution for disturbed parallel processing under a virtual environment and optimising the solution from a whole system point of view.

4.4 Core technology for the development of a virtual manufacturing system

Virtual manufacturing is an all-around research topic; it deals with a broad technical issue. Some core technologies in the development of virtual manufacturing systems are described as follows and their relationships are shown in Figure 11.

(1) Product modelling: a product model and an equipment model are used as core models in the stage of product design, process design, process planning, equipment layout and control, etc.
(2) Machining simulation: at present, research on computer-aided engineering such as cutting, machining, moulding, casting, assembly and the software development provide useful information for the development of a virtual manufacturing system. In particular, the development of simulation technology based on the finite element method and the boundary element method provides useful tools for various manufacturing processes.

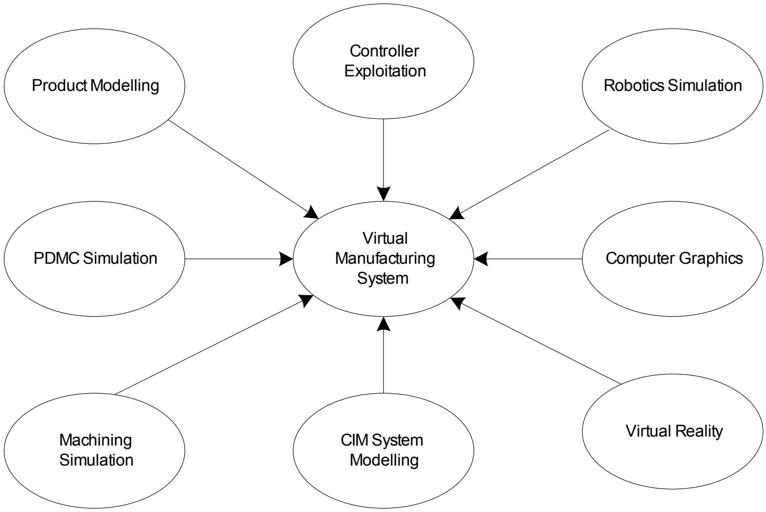

Figure 11: Core technology in the development of VMS.

(3) Physical distribution material circulation simulation: based on physical distribution material circulation simulation, the detailed relevant information such as equipment layout, distance between equipment, physical size of machine, etc., will be considered.
(4) Robotics simulation: current research has made progress on the detailed simulation of robotics movement. In a virtual manufacturing system, it extends to simulate manufacturing tasks performed by robotics. And thus operating in line with the other equipment is considered.
(5) Controller exploitation: research on a virtual manufacturing device which is based on a manufacturing message specification will become a useful method for modelling equipment in virtual manufacturing systems.
(6) Computer graphics: in this technical area, research on three-dimensional graphics and animation catches a lot of peoples' attention. For example, the status modelling for object dropping and object impact, material surface structures definition, etc., becomes core technology for implementing a virtual manufacturing system.
(7) Virtual reality: here, research on solid display equipment such as a head mounted display, etc., also becomes indispensable technology for the virtual manufacturing system.
(8) Computer integrated manufacturing system modelling: computer integrated system modelling technology CIM-OSA and an integrated system structure will form an important part of a virtual manufacturing system.

4.5 Exploitation strategy for the development of virtual manufacturing systems

The implementation of virtual manufacturing systems needs collaboration among research institutes and enterprises. Therefore, the exploitation strategies for developing virtual manufacturing systems focus on:

(1) Divide the system into several function modes, in order to develop each individual mode separately.
(2) Define the relationships among each function mode, and then integrate the modes to form a virtual manufacturing system.
    The whole system can be divided into 6 function modes (Iwata *et al.* [22]):
    - Device model preparation
    - Simulation service development
    - Virtual shop floor definition
    - System operation definition
    - Virtual shop floor simulation
    - Simulation interface
(3) Adapt a real/virtual mixture system for system exploration and application.

4.6 Virtual manufacturing system architecture

A virtual manufacturing system is build and constructed by a systematic approach. A reasonable virtual manufacturing system not only integrates design, manufacturing, assembly, process planning and quality control in a virtual product development process to achieve the integration of information, function and process, but also represents the motivation of human beings to achieve the requisite co-operation between people, organizations and management with technology, and to support manufacturing activity and manufacturing resources with a wide variety of characteristics.

In different application environments, virtual manufacturing systems have different structures. Typical structures are Iwata architecture, virtual exploitation platform architecture and a distributed virtual manufacturing system.

4.6.1 Iwata architecture

The structure described by Iwata is shown in Figure 12. It describes the macrostructure of a virtual manufacturing system. The whole system consists of the virtual information system, virtual physical system, timing control and data browser.

The whole system uses a time synchronizer for synchronization. A virtual information system and a virtual physical system communicate through a communication interface. The browser and virtual reality equipment will be used to provide an input/output interface for the system.

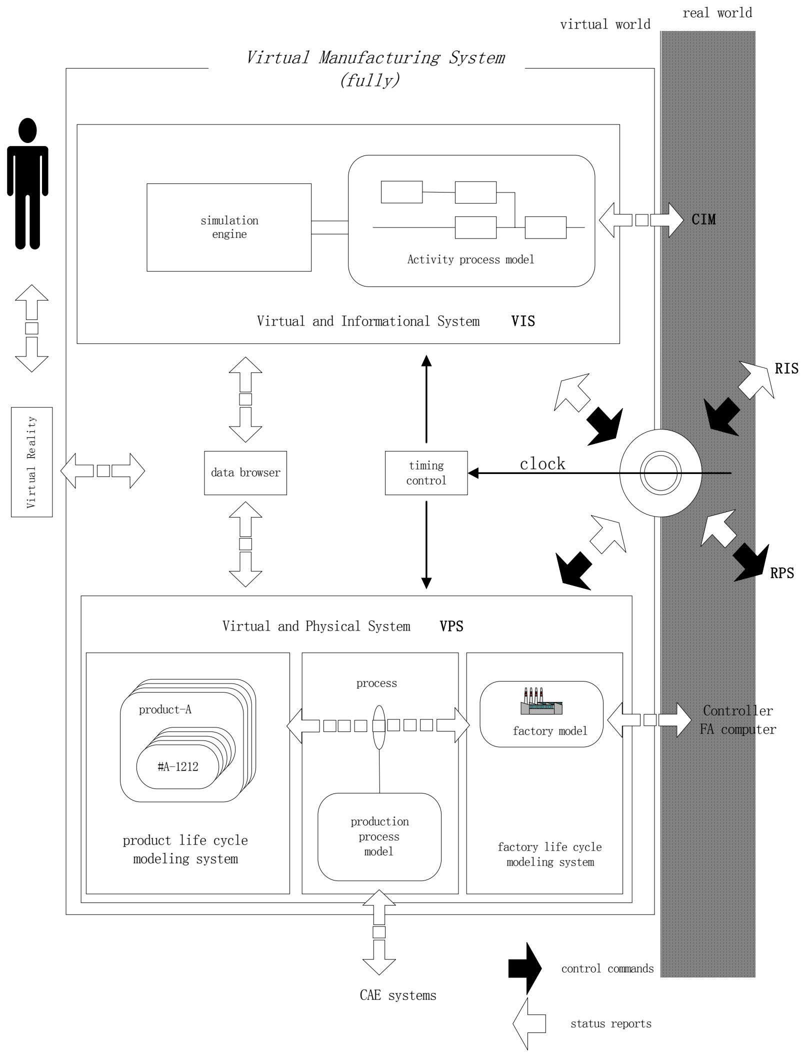

Figure 12: Iwata architecture (Onosato & Iwata [19]).

The virtual physics system consists of a product model, a factory model and a manufacturing process model. The product model is a whole life cycle model system for the product. It not only includes the final product model, but also includes a semi-manufactured product model in each manufacturing stage. The factory model is a whole life cycle model system for the factory. It not only records the original parameters of the factory equipment, but also records any activities in the product life cycle. The manufacturing process model is used to describe the effect between a factory model and a real product model.

The virtual information system includes a simulation engine and an activity process model. The activity process model describes the decision-making and information flow within a virtual information system. The simulation engine explains the process description and decision making process.

4.6.2 Virtual exploitation platform architecture

The virtual exploitation platform architecture includes a virtual machining platform, a virtual manufacturing platform, a virtual enterprise platform and a product data management system which supports these platforms. The structure is shown in Figure 13.

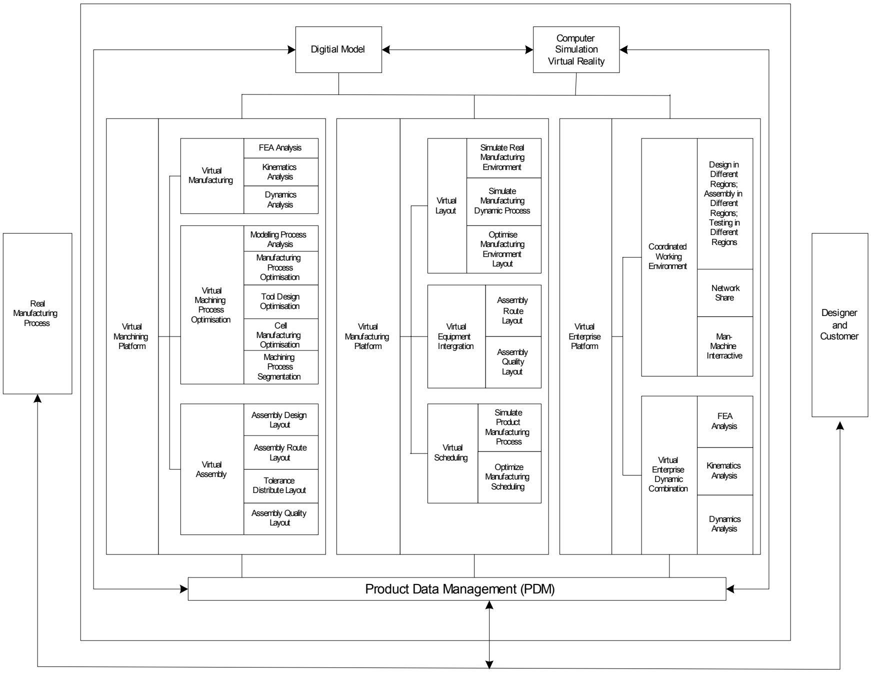

Figure 13: Virtual exploitation platform architecture.

The virtual machining platform supports product concurrent design, design layout and machining simulation, assembly simulation and maintenance simulation. It carries out manufacturability analyses such as performance analysis, cost analysis and process time analysis, etc.

The virtual manufacturing platform supports manufacturing layout and equipment integration. It also supports manufacturing planning and scheduling, product virtual test and producibility analysis.

The virtual enterprise platform provides designers with a virtual design environment to carry out producibility analysis. It offers a virtual enterprise co-ordinated working environment and a virtual enterprise running support environment. It also supports an environment for design, assembly, testing at different places, particularly for three-dimensional graphic transfer, process control and man-machine interaction.

4.6.3 Distributed virtual manufacturing system

A distributed virtual manufacturing system refers to connecting several customers at different places or connecting several virtual manufacturing environments through the network and sharing information to achieve the goal of manufacturing process simulation.

The characteristics of the distributed virtual manufacturing system are as follows:

(1) Wide personnel distribution: with the connection of Internet/Intranet, the technical engineers in the virtual manufacturing system can be located in different geographical areas.
(2) Distributed virtual resources: the designers share the data, knowledge and resources information to develop a virtual product.
(3) Various simulation tools: the designers use different engineering application tools and simulation tools at different network terminals.
(4) Long-distance virtual command: the designers can design, edit, modify and maintain a product process by long-distance virtual commands.
(5) Designers with different engineering backgrounds can work together for the same product design.

4.7 Virtual enterprise

4.7.1 Concept of virtual enterprise

Virtual enterprise (Afsarmanesh *et al.* [26]) is primarily an interoperable network of pre-existing enterprises with a common goal. The enterprises can work together to quickly respond and serialize the business opportunities supported by the multi-functional networks. These enterprises can be distributed in different areas, have different scales and technical combinations. Each enterprise can provide its core technologies to virtual enterprise and increase the ability to provide a high quality and low cost product on time. Virtual enterprise uses communication technology and the computer network to make enterprises in different areas come together to share skills and resources to achieve agile manufacturing. A framework of an agile manufacturing system is shown in Figure 14. Figure 15 shows the global manufacturing enterprise architecture.

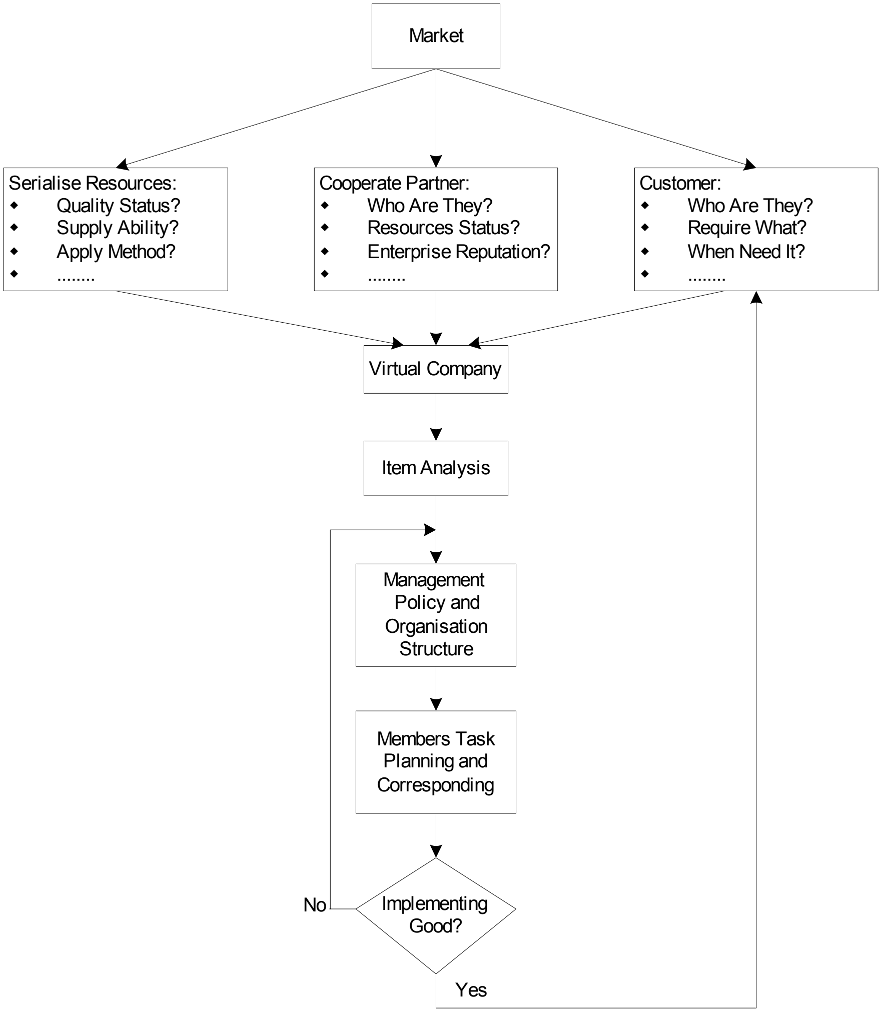

Figure 14: Agile manufacturing system framework.

4.7.2 Dispersed networked production system

Dispersed networked production system (DNPS) (also called distributed virtual manufacturing system) is one type of the virtual enterprise. It makes use of existing manufacturing resources in different areas, combining them together through communication facilities and uniform commands to make sure high quality and low cost products come out on the market.

A dispersed networked production system consists of an enterprise internal network, enterprise external network, system integration and database technology, system security and fire-wall technology, network and communication technology, and so on. A detailed structure is shown in Figure 16.

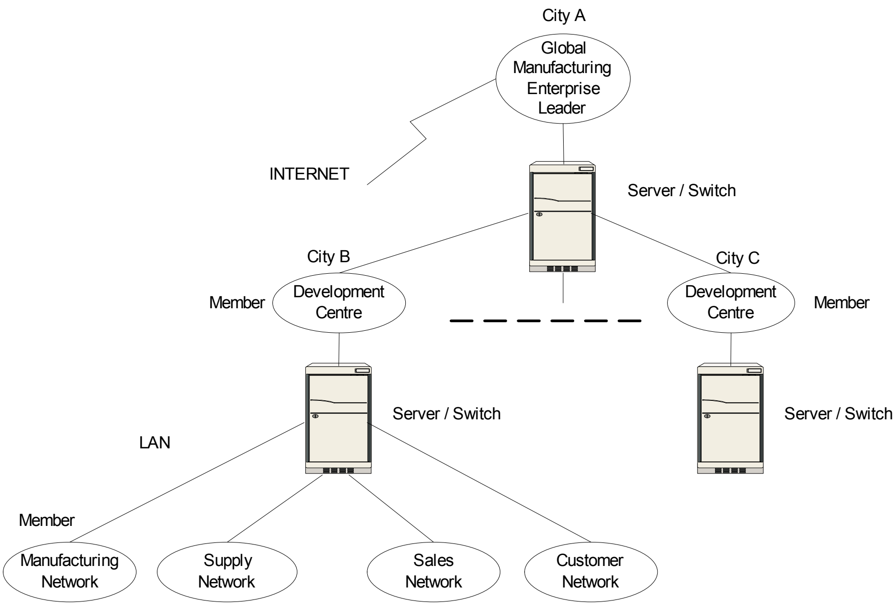

Figure 15: Global manufacturing enterprise architecture.

4.7.2.1 Core technology for building up a dispersed networked production system Six technologies have been used to build up a dispersed networked production system.

(1) Manufacturing enterprise information network – this network provides group members with manufacturing resources and proprietary technology to choose partners, establish dynamic alliances, effect quick product design and manufacturing. At the same time, this network can establish reliable supply chains and carry out highly efficient market activity.
(2) Quick product design and development network – this network integrates product design tools and experience in different units, such as finite element analysis, stress analysis, rapid prototyping, virtual reality, machining and testing simulation, etc. The network adopts a concurrent engineering method to design and develop the product.
(3) Product manufacturing network made by independent manufacturing islands – high-technology products sometimes require expensive or special equipment. Purchasing this equipment may bring high investment risk and low utilization rate. Through the network, resources can be used judiciously.
(4) Total quality management and customer service network – in a dispersed networked production system, each production has a recipient which is a customer. Total quality management should run through from pre-design

to the end of the product life cycle which includes repair, maintenance, abandonment and recycling, etc.

(5) E-commerce network – the activities of a dispersed networked production system involves different enterprises and persons. It is necessary to build an e-commerce network which can respond quickly to financing and exchange activities.

(6) Communication of manufacturing engineering information – the foundation of a dispersed networked production system includes information processing, exchange, transfer and communication.

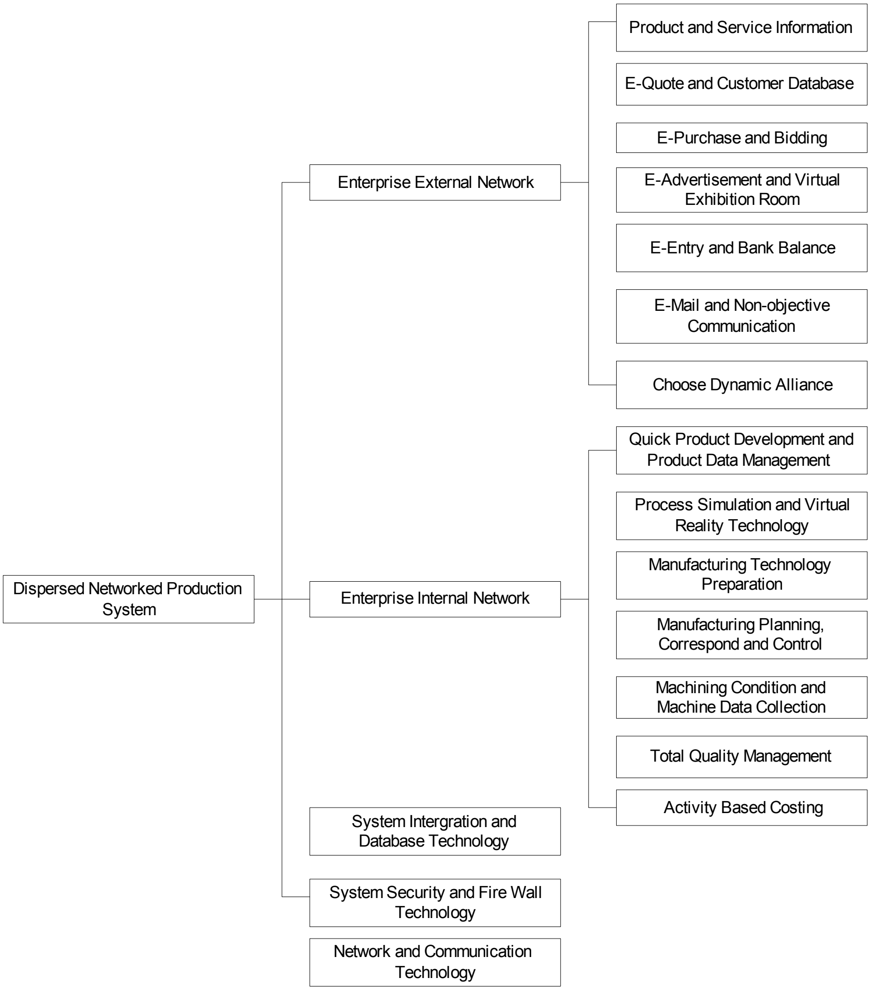

Figure 16: Formation of a dispersed networked production system.

4.7.2.2 Method for building a dispersed networked production system In order to cope with the quick changes of a market, enterprises should ensure their competitive position in the market. According to the market position, the enterprise will confirm the strategy goal, choose partners, recombine manufacturing processes and evaluate the processes based on their agility. According to item definition, enterprises make the framework design, arrange personnel training and organize team working. Finally, after the agreement for risk sharing and benefit distribution has been signed up, a dispersed networked production system is set up.

The detailed method is shown in Figure 17.

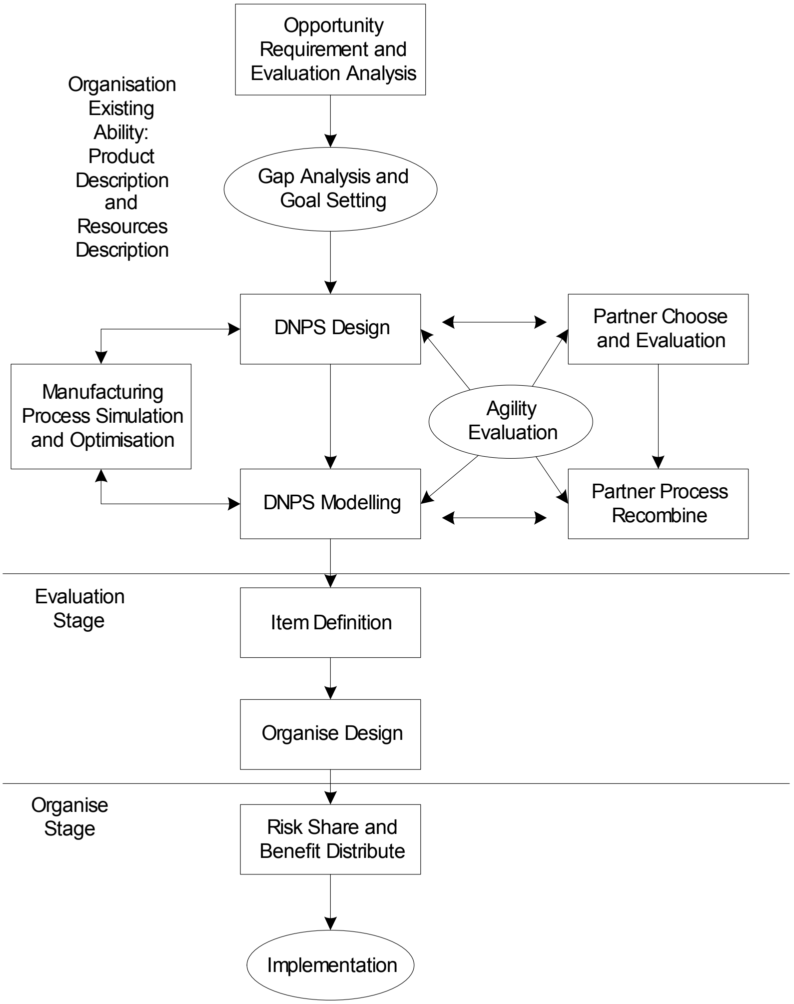

Figure 17: Method for building a dispersed networked production system.

5 Virtual manufacturing system applications

Although virtual manufacturing has multiple definitions, virtual manufacturing has been successfully used in different areas such as military, industrial, scientific and educational, etc. Virtual manufacturing has unlimited potential in production design and manufacturing process applications. It can significantly increase the products technological level, for example, Boeing used virtual manufacturing technology in the development and production of the Boeing 777 airplane. The first airplane was built without any drawings, mock-ups or development fixtures. It was 100% digitally designed. It significantly improved production flexibility, hence greatly reducing the cost.

The following examples represent the recent state of the arts virtual applications in one or several aspects of design and manufacturing.

Figure 18: Virtual steering wheels with control arms (Picture Courtesy: Virtual Reality Laboratory, University of Michigan).

5.1 Virtual car design

Virtual car design has developed rapidly in recent years. The modern car designer has the fantastic advantage of being able to design a car from concept to finished product in a few weeks using the Alias supercomputer program (Alias Image Studio [27]). A virtual prototype of a concept car (Figure 18) was created from a partial design in the Virtual Reality Laboratory of the University of Michigan. It enabled more cost effective and realistic design and evaluation of car ergonomics prior to the manufacture of physical models to be examined. In this concept car, the unusual idea of two arms extending on each side of the steering wheel to bring control switches closer to the driver was explored.

5.2 Product layout design

When evaluating alternative production layouts, traditionally, engineers have relied on 2-D drawings, cardboard cut-outs and flow charts to visualize and assess changes to the production plant and part flow. These can be very costly, time consuming and disruptive to rectify later on. These traditional methods are not really designed to help engineers create, evaluate and compare alternative scenarios in a measurable way. The state of the arts software tools such as VR-Fact! enable manufacturers to visualize, analyze, and maximize the efficiency of their proposed factory layouts.

VR-Fact! is an interactive virtual factory development software that was developed at the Virtual Reality Laboratory in the State University of New York at Buffalo. The software creates a digital mock-up of a factory shop-floor, shown in Figure 19. Designers can drag and place modular machines in the factory to study the shop-floor layout, cluster information, cell formation, and part flow. The user can interactively choose the machines which are required to produce a group of parts.

Figure 19: Digital mock-up of factory layouts (Picture Courtesy: Virtual Reality Laboratory, State University of New York at Buffalo).

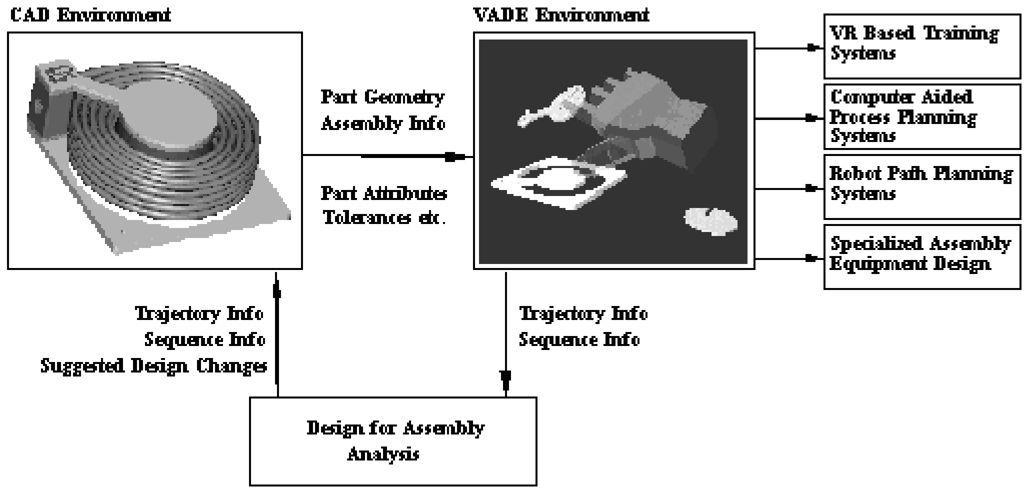

Figure 20: VADE usage scenario (Picture Courtesy: Hugh Connacher, Sankar Jayaram, School of Mechanical and Materials Engineering, Washington State University and Kevin Lyons, Manufacturing Systems Integration Division, National Institute of Standards and Technology [28]).

5.3 Product assembly simulation

Virtual assembly is a combination of several technologies such as advanced visualization, simulation, decision theory, assembly and manufacturing procedures, and assembly/manufacturing equipment development. It is necessary to keep all of these technologies in synchronization.

Figure 20 shows the information flow in the virtual assembly environment. The process starts with creating an assembly model in a CAD system. This model is then examined in a Virtual Assembly Design Environment (VADE) (Connacher *et al*. [28]) preprocessor for pertinent information. The visual attributes of the parts such as color, textures, etc., are extracted automatically. The geometry of each part is also extracted along with assembly information. Tolerances, locations and orientations of the parts, the number of instances of each part in the assembly, assembly constraints, etc., are all automatically extracted by VADE. In the virtual assembly environment, the user is presented with a method for "pre-planning" the assembly (Connacher *et al*. [28]). This involves locating the various parts in bins, racks, on a table, etc., redefining certain visual properties, defining the tolerances for the "snap-fit", etc. The users then enter an immersive environment and perform the assembly of the production. During the assembly process, users have the option of storing the trajectory information which was created or rejected by parts in the process of parts reassembling. Collision Detection Methods (Connacher *et al*. [28]) will warn the user of interference problems and tolerance problems.

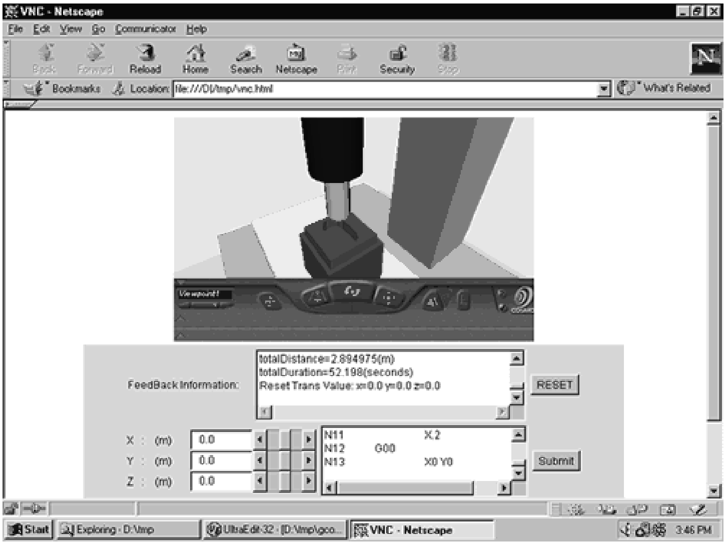

Figure 21: Web-based virtual milling machine (Picture Courtesy: National University of Singapore).

5.4 Product machining process simulation

A Web-based, platform-independent and scalable virtual CNC (Computer Numerical Control) milling system (as shown in Figure 21) has been developed with features of real-time work-piece removal, G-code interpreter, and collision detection. Using this system, users can easily set up a virtual milling machine, specify the cutter and work-piece, input the G-code program and virtually carry out a machining task on the internet without installing any extra software. Simulation parameters of machining, prediction of cutting force, torque, power consumption and tool life are implemented by using an empirical method. Hence, the user-defined machining task can be evaluated and optimized effectively on this system.

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