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An Integrated Framework for Assembly-Oriented Product Design and Optimization

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Abstract

This paper presents an integrated framework for assembly-oriented product design and optimization (AOPDO). In AOPDO, the three main activities of an assembly planning system (design for assembly (DFA), assembly process planning, and production simulation) are integrated in a single framework. Moreover, in AOPDO the three main activities of an assembly planning system support each other, in accordance with the practice of concurrent engineering. Function models for AOPDO are also presented. The IDEF0 (Integration Definition for Function Modeling) analysis method is used to describe the activities and provide communication between models. Through AOPDO, all assembly activities and their applications are integrated into a powerful computer aided product design and optimization system.

Introduction

Industrial Technologists often work as technical or managerial professionals in design and manufacturing sectors. It is necessary to equip industrial technologists with up-to-date technological practices to keep their organizations competitive in the global market. Concurrent engineering and design for manufacturing are two important product design methods used in modern industry to reduce lead-time and increase productivity. In academia, in order to meet market needs and to produce well-prepared future industrial technologists, CAD/CAM programs are increasingly integrating concurrent engineering and design for manufacturing into their curricula.

For concurrent engineering, good communication methods between different technical and managerial professionals are needed. For some technical manufacturing problems, design changes might be needed. To reduce design changes, it is important for design personnel to communicate with manufacturing personnel concerning manufacturability matters, early in the design stage. Technical managers also need to understand the importance of design for manufacturing in order to lead a successful production system.

The scope of design for manufacturing not only includes manufacturability issues but also testability, serviceability, maintainability, and so forth (Kalpakjian & Schmid, 2001; Groover, 1999). Tackling design for manufacturing often involves assembly activities, as well. According to Delchambre (1996), assembly activities make up, on average, 40% of product costs and 50% of production investments. In order to reduce cost, reduce technical problems, improve quality, and increase productivity, it is important to concurrently consider product assemblability, assembly sequence, and possible production layout early in the design stage.

Background

<u>Design for Assembly /Disassembly</u>

Design for assembly is a design technique that takes assemblability and ease of assembly into design consideration (Delchambre, 1996; Boothroyd, Dewhurst, & Knight, 2002; Redford. & Chal, 1994). A significant amount of research has been conducted in design for assembly (DFA)/disassembly (DFD). DFA and DFD methods are similar to some extent. DFA concentrates more on simplifying product assembly structure, to save production time and cost. DFD concentrates on simplifying disassembly effort, to reduce maintenance and recycling costs.

Zha, Du, and Qiu (2001) used a knowledge-based approach and framework for intelligent assembly-oriented design. They incorporated concurrent engineering knowledge into their assembly design process. Boothroyd, Dewhurst, and Knight (2002) reduced production cost by reducing the number of fasteners and the number of separate parts. By applying DFA methods, a given product structure can be optimized to dramatically improve product quality and reduce both production cost and time to market.

Assembly Process Planning

Assembly process planning is an activity that determines part assembly order and resource usage to minimize assembly cost and time (Homem de Mello & Lee,1993; Jones, Wilson & Calton, 1998). The cost and quality of a product are not only determined by component design but also by assembly processes. Assembly process planning contains three aspects: assembly sequence planning, assembly tool and fixture planning, and assembly instruction generation.

Recently, many researchers have conducted research in computer-aided assembly sequence planning (Ellis & Bhoja, 2002; Shimizu & Nishiyachi, 1996; Smith & Smith, 2003; Smith, Smith, & Liao, 2001; Zhao & Masood, 1999). Based on the results of assembly sequence planning, facilities, tools, and fixtures for each assembly operation can be determined and planned. For different types of companies, assembly facilities, tools, and fixtures might be different. After assembly sequences and resources have been determined, assembly instructions can be generated. Figure 1 presents a systematic flowchart to show the relationship between each action.

Assembly Production Planning

Production simulation is an activity that analyzes and optimizes possible production plans (Little & Hemmings, 1994; Fuh, Wong, Yee, Zhuang, & Neo, 1996). Product production must be conducted under two types of constraints: hard constraints (such as available facilities, tools, fixtures, assembly robots, assembly workstations, assembly vehicles, assembly lines, and manpower) and soft constraints (such as process plans and production schedules). Therefore, in production optimization, not only the hard constraints need to be considered, but also the soft constraints. Based on this perspective, a production optimization architecture is proposed in figure 2.

Within the architecture, the physical view represents assembly system hardware. In the physical view, the three circles represent the three different types of production methods (manual, mechanical, and automatic). The operational view of the system represents the assembly soft constraints. The model view of the system represents some selected types of modeling methods (for example, Petri nets, neural networks, genetic algorithms) for creating a simulation model of the physical system. The model view can be used to calculate assembly properties, such as assembly time, assembly cost, facility and utility usage rates, etc. Moreover, using a simulation model, the differences between different systems and production schedules can be compared.

After reviewing the three aspects of an assembly system described above, it was found that the existing assembly related research mainly focuses on a certain single area of assembly problems. The three areas of study are usually conducted separately and have not been integrated and investigated systematically, from design to production, as a whole.

Purpose

From a concurrent engineering point of view, the three assembly planning activities cannot be considered separately. It is necessary to have a design tool which incorporates design for assembly, assembly process planning, and assembly production simulation in an integrated system. This paper proposes an integrated framework for

Figure 1. Assembly process planning

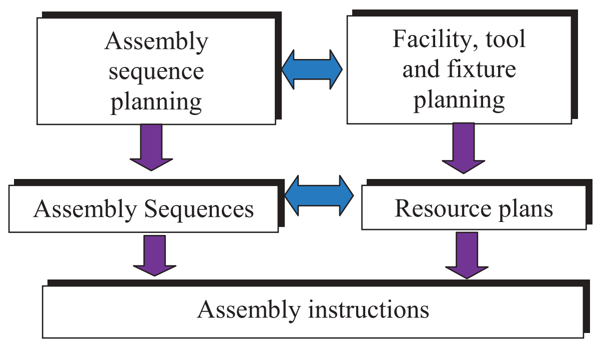
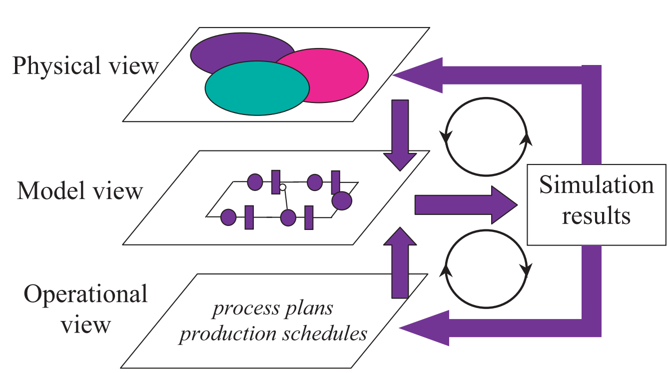


Figure 2. The architecture for assembly production optimization



assembly-oriented product design and optimization (AOPDO). The purpose of the AOPDO system is to take all assembly related issues into consideration, in accordance with the practice of concurrent engineering, as shown in figure 3. In this framework, the following integration functions are realized:

- Product design is integrated with a DFA analysis system.
- The DFA analysis system is integrated with assembly sequence planning (ASP).
- Assembly production simulation is integrated with assembly process planning.

In this system, downstream and upstream assembly activities and their applications are integrated into a powerful computer aided product design and optimization system. This system can act as an advisor that designers can use to consider assembly issues throughout the product design stages. The IDEF0 (Integration Definition for Function Modeling) technique is used to establish and define communication between each function (Knowledge Based Systems Inc., 1993).

Function Models

IDEF Modeling Method

During the 1970s, the U.S. Air Force Program for Integrated Computer Aided Manufacturing (ICAM) sought to increase manufacturing productivity through systematic application of computer technology. As a result, the ICAM program developed a series of techniques known as the IDEF (Integration DEFinition) technique (U. S. Air Force, 1981; Knowledge Based Systems Inc., 1993). The objective of the IDEF methodology is to decompose a process being analyzed into activities and sub-activities, in a logical and progressive manner. The IDEF technique includes sixteen methods: IDEF0 - IDEF14 and IDEF1X. IDEF0 – IDEF4 are the methods most commonly used.

The IDEF0 method is used to produce "function models". A function model is a structured representation of the functions, activities, or processes within the modeled system or subject

Figure 3. Concurrent engineering oriented integrated model for assembly planning

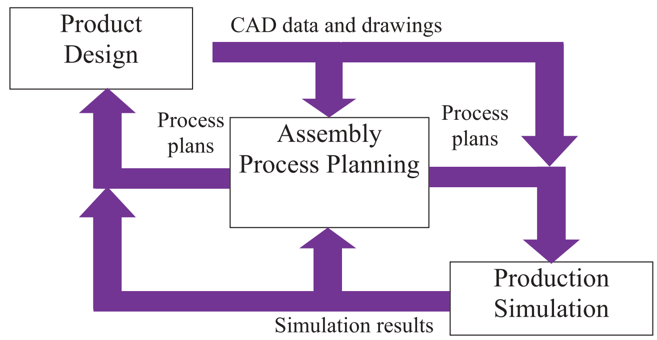


Figure 4. IDEF0 Function Box and Interface Arrows (Knowledge Based Systems Inc., 1993)

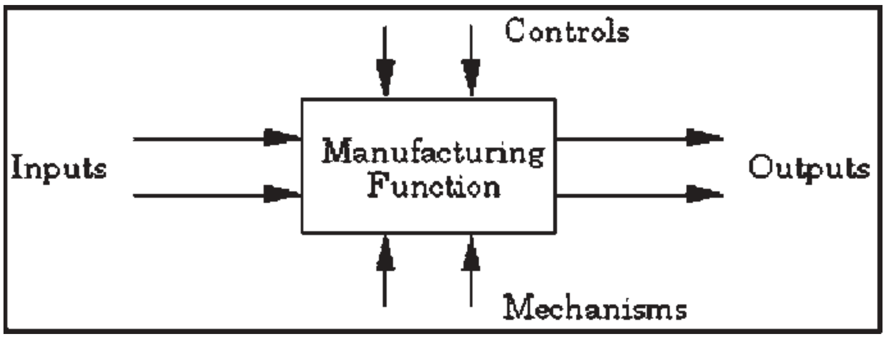
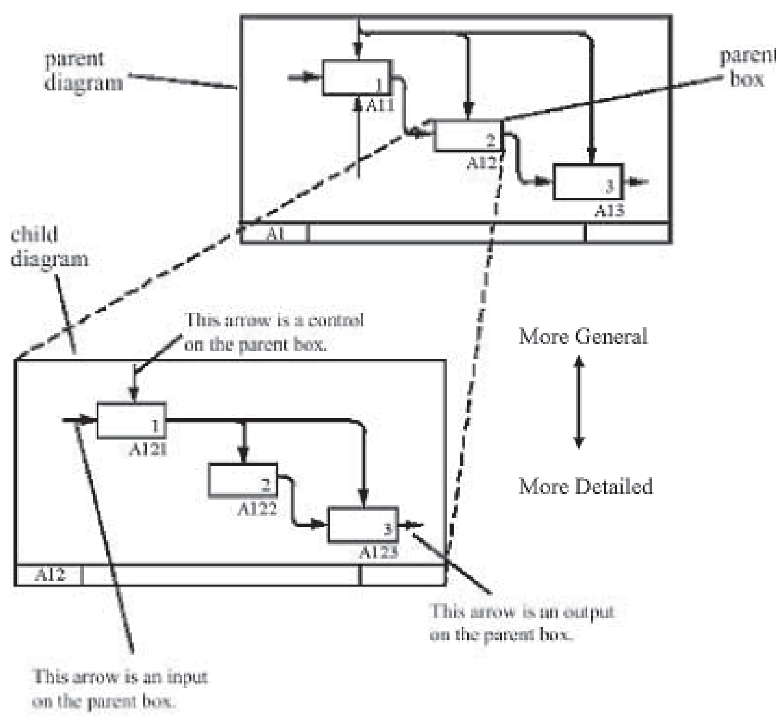


Figure 5. Decomposition Structure (Knowledge Based Systems Inc., 1993)



area (Knowledge Based Systems Inc., 1993). In 1993, the National Institute of Standards and Technology (NIST) released IDEF0 as a software standard for function modeling. The IDEF0 modeling language consists of simple boxes, arrows, and English text labels to describe the meanings of diagram elements. Activities can be described by their inputs, outputs, controls, and mechanisms. Figure 4 gives an example for a manufacturing function.

In addition, the description of the activities of a system can be recursively refined into greater and greater detail until the model is as descriptive as necessary for decision-making or implementation. For example, in figure 5, function A1 can be refined into functions A11, A12, and A13, and function A12 can be refined into functions A121, A122, and A123.

An effective IDEF0 model helps to organize the analysis of a system and to promote communication between the different functions. Thus, IDEF0 models are often created as one of the first tasks in a system development effort.

The Function Models for AOPDO

To specify the activities, functions, and communication between the subsystems in AOPDO, the IDEF0 modeling method is used. The top-level system is modeled as IDEF0_A1, as shown in figure 6. IDEF0_A1 contains three function modules:

Module 1, structure design, includes drafting, product modeling, and part modeling. Module 1 can be further divided into three sub-modules, as shown in figure 7 (IDEF0_A11).

Module 2, assembly process planning, includes assembly sequence planning, resource planning, and detailed operation instruction generation. Module 2 contains three sub-modules as shown in figure 8 (IDEF0_A12).

Module 3, production simulation, includes simulation and optimization of the assembly system and production schedule. Module 3 contains three sub-modules as shown in figure 9 (IDEF0_A13).

From figures 6 to 9, assembly-oriented product design is concurrently conducted from three views: structure,

Figure 6. The whole system (IDEF0_A!)

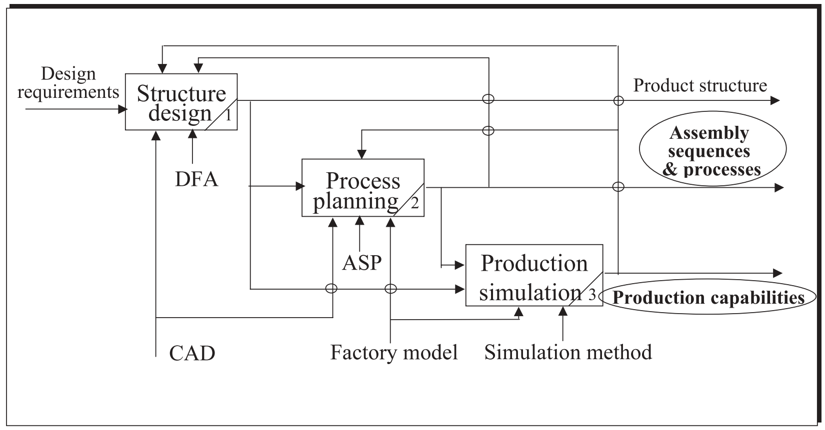


Figure 7. Structure design (IDEF0_A11)

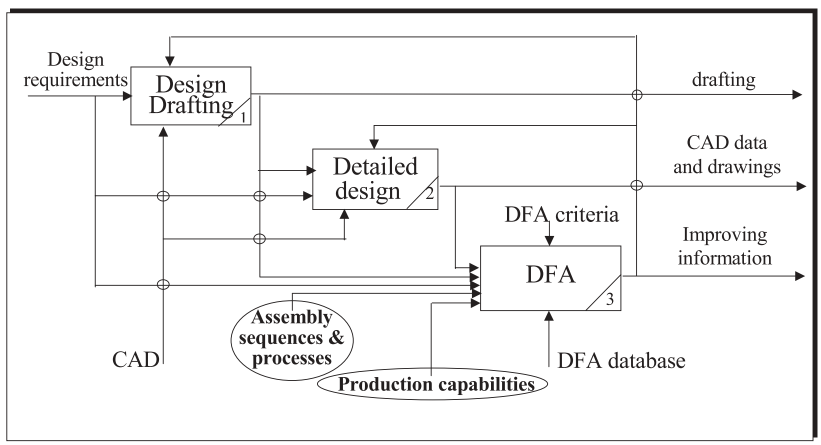
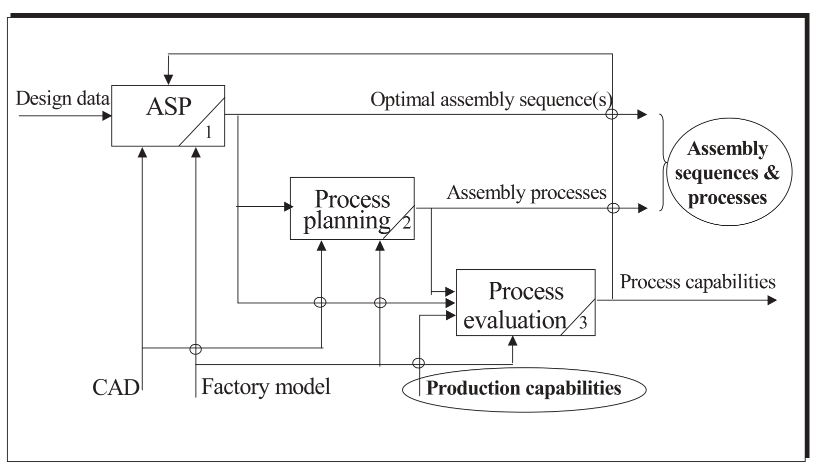
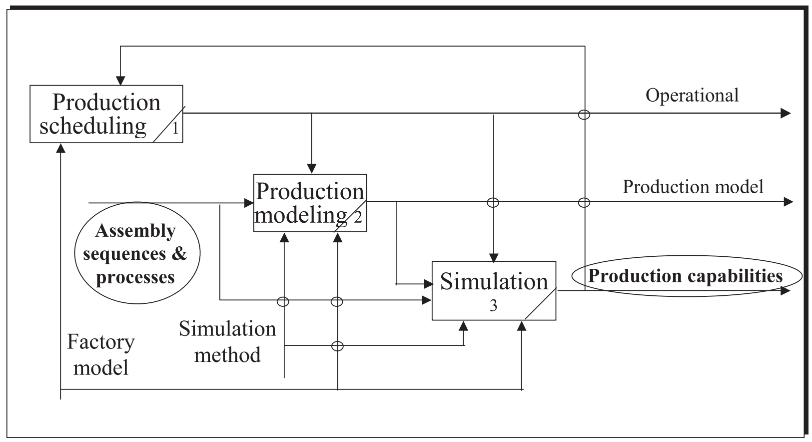


Figure 8. Assembly process planning (IDEF0_A12)



process, and production. In this concurrent design process, the three views should be connected to each other and supported by each other. For example, in the production view (figure 9), the production capabilities can be calculated based on the assembly modeling and simulation. Then, production capabilities can be used to support assembly process planning and optimization, as shown in figure 8. In process planning (figure 8), assembly sequences and assembly processes can be generated according to the constraints from the product structure and the production system. The production capabilities and assembly processes can support DFA analysis in structure design, as shown in figure 7.

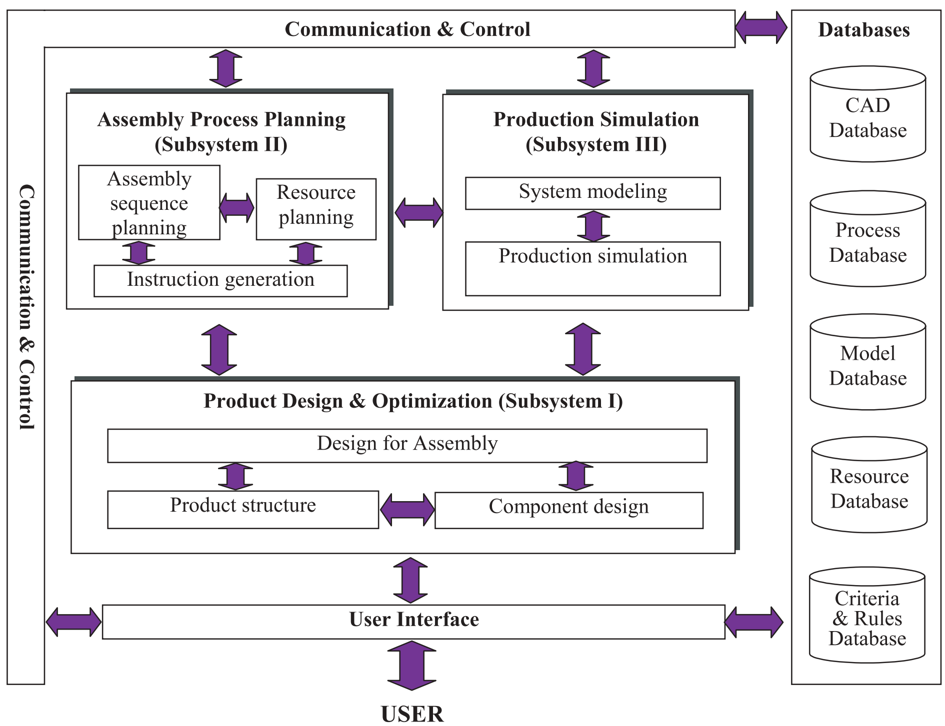
Figure 9. Production Simulation (IDEF0_A13)



Implementation

The proposed AOPDO system is illustrated in figure 10. Based on the IDEF0 models, the framework has been implemented (Su, 1997). A description of the AOPDO system implemented follows. The first version of the system was developed for use in China.

Figure 10. The framework of AOPDO



Subsystem I: Product Design and Optimization

In this subsystem, as shown in figure 11, an assembly model can be created based upon product CAD models. In addition, the product can be evaluated, redesigned, and optimized according to the principles of Design for Assembly (DFA). In this subsystem, the other two subsystems can supply information to support product design and optimization from assembly process and production perspectives, respectively.

Subsystem II: Assembly Process Planning

In figure 12, the optimal assembly sequence can be determined and printed out as assembly process instructions. From the optimal assembly sequence, assembly process properties, such as assembly time, operation difficulty, and assembly design efficiency can be analyzed and calculated. Analysis results, as shown in figure 13, can be sent back to Subsystem I to support evaluating and improving the product design.

Subsystem III: Production Simulation

In Subsystem III, different production planning and resource schedules, such as assembly workstation arrangements and worker deployments, can be simulated, analyzed, and then compared with each other (Su, Lin & Chen, 1996). Analysis results can be fed back to Subsystem II, or directly to Subsystem I, for product improvements.

Supporting Modules

Supporting modules include a database module, a communication and control module, and a user interface module. In the database module, all required data (e.g., CAD data, assembly process data, model data, resource data, and rules and criteria for DFA) are stored. In figure 14, the geometry parameters and assembly parameters are listed. In figure 15, the DFA analysis criteria and the function flowchart is shown to assist the user in analyzing assembly design efficiency.

In addition to the database module, a communication and control module manages the large volume of data and controls data-flows between the subsystems. A user interface is used to facilitate the interaction between designers and the system.

Conclusions

Technical and managerial professionals understand the importance of concurrent engineering and design for manufacturing (Ezell, Brown, Waggoner, 2001). Proper collaboration between manufacturing and the design and development activities of a company can reduce cost, improve quality, minimize investment and speed the launch of new products (Design for Effective Manufacture, 1997). Companies are demanding that designers incorporate more efficient production characteristics into their designs. However, even the best designers have difficulty incorporating all factors and criteria into their designs. This paper describes a design advisor, Assembly-Oriented Product Design & Optimization (AOPDO), which can lead designers to better designs and decision-making.

The AOPDO system realizes the functional requirements of concurrent engineering-based assembly design. The function models of AOPDO are established using the IDEF0 structural analysis method. In AOPDO, three aspects of an assembly planning system, i.e., assembly-oriented product design, assembly processes planning, and assembly production simulation, are integrated into a single framework. Thus, all three aspects can be concurrently considered, and all three aspects support each other for evaluating and optimizing a design.

With AOPDO, users can import CAD models, and the system will evaluate the models and provide redesign suggestions. The system also generates optimal assembly sequences

Figure 11. Assembly model analysis

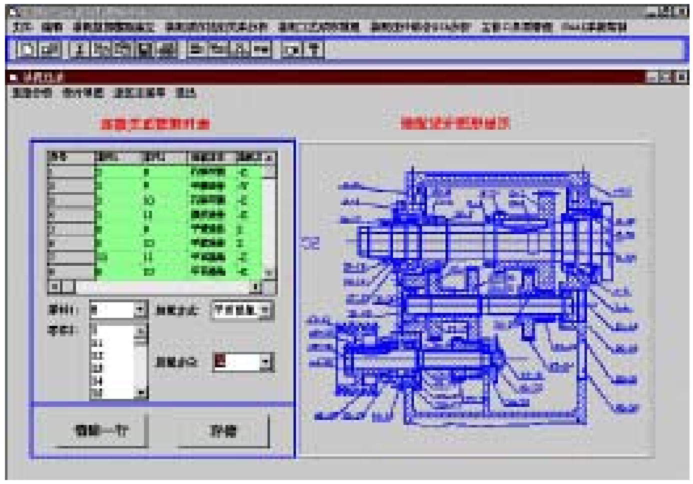


Figure 12. Assembly sequences

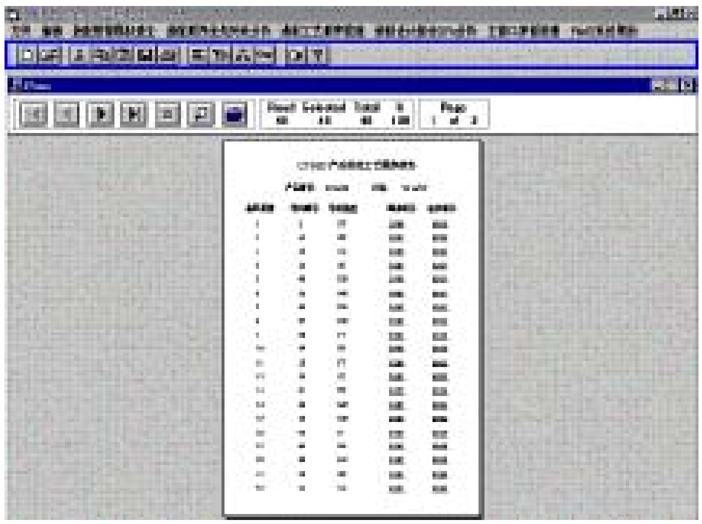
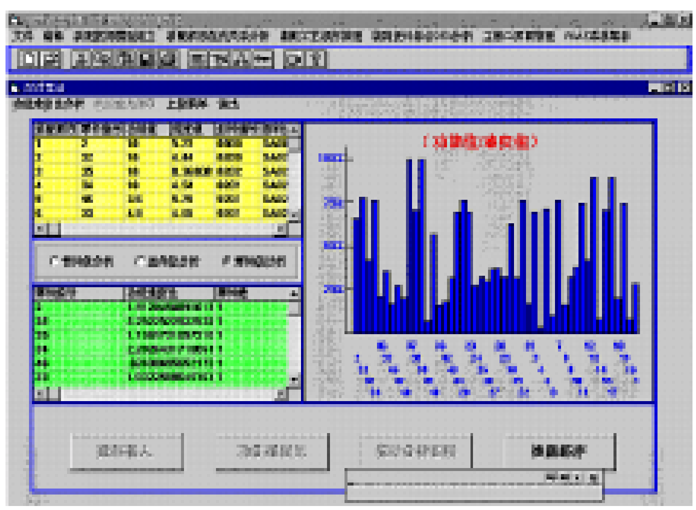


Figure 13. DFA analysis



based on production resources. The framework can also be used as an instructional tool by industrial technology educators to introduce the concepts of concurrent engineering and design for manufacturing.

Figure 14. The CAD data of an assembly

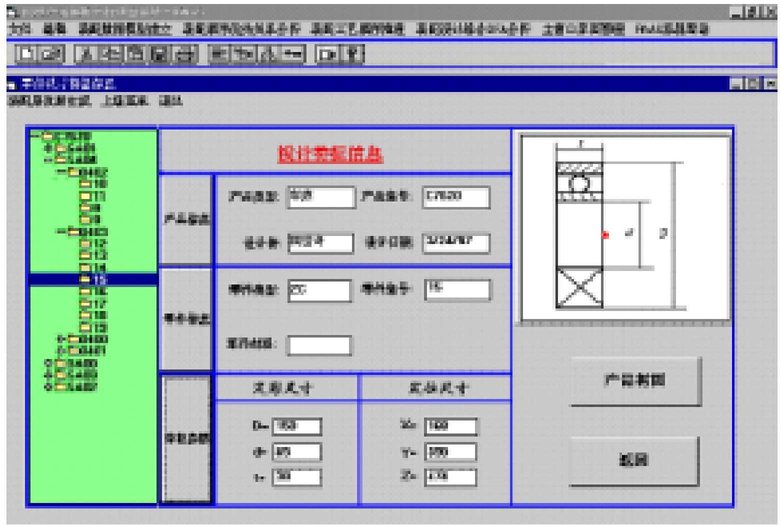
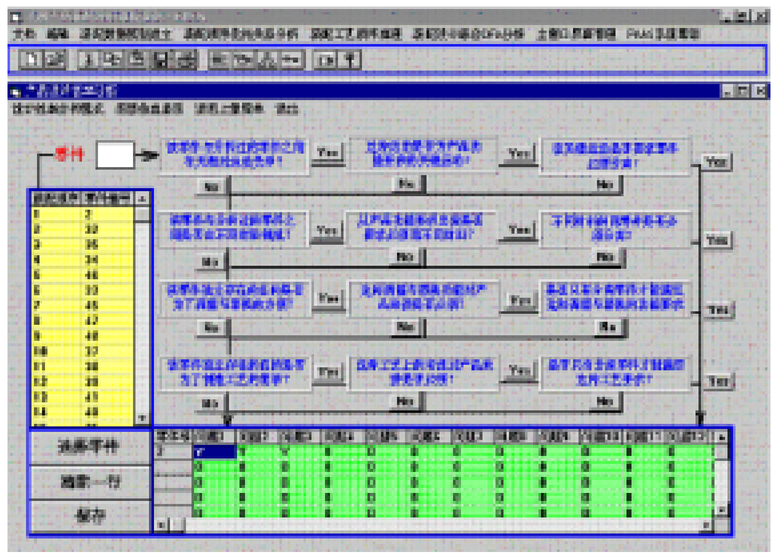


Figure 15. The DFA analysis criteria



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