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Factory Automation and CAD -Product Modelling for Advanced Manufacturing Automation

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요 지

고부가 가치 제품의 소량 생산을 요구하는 새로운 제조 경향에 대처하기 위해서는 공학적인 활동의 유연한 집합체제가 각 활동들의 처리 결과를 동시에 예견하는데 효과적이다.

제품의 모델링은 이와 같은 집합체제의 중요한 구성요소이며 제품 묘사에 대한 여러가지의 기술적 정보를 나타낼 수 있다.

제품의 모델링에 대한 최근의 결과들을 간단히 고찰하고 그의 효용성을 실증하기 위하여 생산자동화에서 몇가지 응용을 제시한다.

1. INTRODUCTION

In order to survive in the severe competition among advanced manufacturing companies, powerful information processing technologies are being actively introduced for producing high-quality value-added products, and for achieving higher productivity and manufacturing flexibility. In spite of the extensive research and development of CAD/CAM and CIM, we still see many important open problems.

In recent years, we see a sharp change of the basic principle of manufacturing in advanced indurstrial countries. That is the shift from mass production of conventional cheap products to small-sized or one-piece production of high-quality value-added products.

In the former years, engineers can rely on their experiences, because products were not changing so rapidly, and functionality and manufacturing methods of products could be gradually improved through mass production processes. But, it is now becoming difficult to make gradual improvements due to the rapid change of technology and products, and small-sized production.

It is now required to have a sound theory for product design and manufacturing preparation, to be able to simulate and predict the functional behaviour and manufacturing constraints of products before actual production. We shall call such pre-production evaluation as ***product realizability***.

Product realizability can be well evaluated through the tight combination of product design and manufacturing preparation activities. It is not enough just to have a feedback from manufacturing preparation to product design, but more intimate integration is desirable. In the ultimate case, we can think of the almost concurrent or simultaneous processing of product design and manufacturing preparation. Recently we call such concept as ***concurrent*** or ***simultaneous engineering***.

For really achieving concurrency of engineering activities to produce innovative products, we need a new framework or infra-structure for engineering information processing. Instead of conventional CAD systems, we need more powerful product information representation which is understandable to both product designers and manufacturing engineers. The central concept for such representation is ***product modelling***.

Product modelling is a modelling framework which can capture and represent all the necessary product information through the whole life-cycle of our products, from initial product planning until maintenance. Now, we can see so many research and development works concerning to product modelling, for example [Sata85, Spur89]. Most of them are dealing only with the representation of products, but are not dealing with the process of how to generate such product information from the initial requirements for products. For achieving efficient product design, it is necessary to have such representations as requirements, functionality, behaviour, decisions and justifications to determine product description, etc. A dynamic and powerful framework for dealing with such information is not yet well established.

In this paper, important key concepts are first discussed for advanced manufacturing automation to cope with new demands from the market, and a framework for the flexible integration of design and manufacturing process is introduced, which is based on product modelling. Then basic roles and functionalities of product modelling are considered, and some examples of manufacturing automation via product modelling are considered, and some examples of manufacturing automation via product modelling are explained. These examples are only at a research stage, and future problems for practical applications are discussed.

2. KEY CONCEPTS FOR ADVANCED MANUFACTURING AUTOMATION

As discussed above, in the former years, product design and manufacturing processes could be gradually optimized through long range mass production stages. But, in recent years, such gradual optimization is no more feasible due to the rapid change of products and small butch production. Therefore, it is vitally necessary to precisely predict the defects of products before actual production, and to promptly realize prototype products for verifying the design decisions. Manufacturing information generation by computerized product and production models can facilitate the designers and manufacturing engineers to predict the behaviour and characteristics of their products and production methods efficiently. Rapid prototyping by physical production can prove and enhance the prediction results by modifying the computer internal models. If the required volume of production is very small, the production lines should be constructed based on the knowledge acquired by prototyping. In order to operate the whole manufacturing processes consistently, we need some kind of integration mechanism.

The major key concepts are briefly enumerated with respect to three aspects of manufacturing automation : manufacturing information generation, physical manufacturing and integration.

(1) Manufacturing Information Generation :

All the technological information necessary through the whole life cycle of products should be dealt with.

* Concurrent Engineering : Based on the common representation of products and related data, as many engineering process as possible should be carried out concurrently for flexible and efficient product design and manufacturing processes.
* Virtual Manufacturing : All the necessary physical production processes should be modelled in computer, and manufacturing characteristics should be predicted.
* Engineering and Manufacturing Simulation : Based on the precise models of products and production processes, large scale simulation is now possible by use of powerful computers, such as super computers.
* Organization of Engineering Knowledge and Data : Common knowledge, such as mathematics and physics, should be implemented in computer, as well as

application-dependent expert engineering knowledge.

* Design by Customers : The requirements from customers should be rapidly and flexibly reflected to products.
* Tutoring or Advising of Engineering Knowledge : The system should be able to flexibly accept new knowledge, and to inherit it to novice engineers.
* Electronic Warehouse : If we can represent and manipulate enough information for reproducing the spare parts in computer, we do not need to store real physical parts.

In summary, the target is to construct the computer environment where we can simulate actual design and production process.

(2) Physical Manufacturing :

Based on the manufacturing information generated by the above-stated activities, real production processes are carried out by using manufacturing devices.

* Verification of Virtual Manufacturing Processes : Manufacturing process model in computer should be verified by the feedback from actual experiments.
* Rapid Prototyping : Innovative processes should be developed for efficient rapid prototype creation.
* Intelligent Manufacturing Control : According to the production requirements, intelligent management and control of production facilities should be performed. Recognition of real situation of production facilities are relly necessary.
* Reconfigurable Factory Architecture : In parallel with the product design, factory or production installation should be designed, which reflects the requirements of versatile production methods.
* Preventive Maintenance and Renewal of Manufacturing Facilities : It is necessary to keep the production facilities very up-to-date.

In summary, the target is to realize flexible and effcient prototyping facilities.

(3) Integration :

Integration mechanism is necessary to construct a consistent manufacturing system.

* Self-Organizing and Distributed System : Centralized systems cannot cope with the previous requirements. But, practical methods for distributed system design are not yet known.
* Standardization of Product and Production Data Description : For interfacing many subsystems over different companies and countries, it is necessary to establish the true international standard.

In summary, the target is to identify the methodology to support the integrated system construction.

3. FLEXIBLE INTEGRATION FOR EFFICIENT PRODUCT DESIGN

To cope with the new trend and requirements discussed above, it is quite necessary to have a new flexible framework for efficient product design and manufacturing preparation through the thorough evaluation of functionality and produceability of products with the aid of computer technology. To really think of the new trend of manufacturing it is important to consider the economical, social and psychological aspects of manufacturing, but here we just think of technological issues.

3. 1 Flexible Integration of Engineering Processes

Here we investigate the general framework for flexible integration of engineering processes, and clarify the roles of product models which represent all the necessary aspects of engineering information about products.

In the conventional manual practice, there is an intimate human communication via conventional drawings and technical decuments. The manual working methods are not formally specified, but there is a lot of interactions between design and manufacturing sections.

When we introudce CAD/CAM systems, if we neglect such interactions which are not explicitly specified or oranized, we will have rather rigid inflexible systems which invalidate the former friendly communication.

According to the above considerations, we need to introduce the very flexible framework for CAD/CAM integration, as shown in fig. 1.

Here a product model plays a central role for realizing mutual transparency among respective activities. Within a product model we can see several models of different nature. An object model contains the information which represents various kinds of information of products during designing. Not only descriptions of objects, but also any relevant information about products should be kept, such as functional requirements for products, history of generation of products, etc. The evolutional process of such object model information is further elaborated in the next section.

A function model contains pertinent enviromental model data, where object models exhibit their performance to achieve their functions. A factory model is a model of production facilities which constitute a real factory. The necessity of those two models is recognized, but we have not yet sufficient works about those topics.

During product design and manufacturing preparation activities, object models act just like a workbench. Each process is watching the workbench, and, if it can find out some material that it can process, then the process can start to work, and evolve the model data. By such a working method, flexible control of concurrency of processes can be realized.

If the representation of object models can be made understandable to human engineers, they can freely intervene in modelling processes, and can make various decisions which cannot easily be automated. We shall call such integration as *flexible integration*, where human engineers play essential roles, and have initiatives to manipulate the total processing.

3. 2 Simultaneous Processing of Engineering Activities

One of the practical approach to efficient product design is to introduce the simultaneous or concurrent processes of engineering activities, as shown in fig. 2. If we look at manufacturing processes superficially, they seem to proceed sequentially, that is, from initial product planning, product design to production planning. But, as already well-known, in actual practice, those engineering activities are more or less processed concurrently.

By taking into account of such concurrency, we can achieve high precision product design which realizes maximum performance of products under severe manufacturing constraints.

Concurrency does not just mean feedback from the later stages, or prediction of the further activities, but it gives means to identify freedom and interdependence among various activities.

By supplying adequate means to communicate each other, each engineering process can know the effects of its own and also of other processes, and then it can have freedom to make its own decisions. In such a situation, we say that related engineering processes are mutually *transparent* each other.

To realize such situations, it is necessary to explicitly represent all the related product information, and to let each process access to it. By use of product modelling, we can the previous subsection.

As we shall discuss later, various kinds of information are necessary to be represented in product models. Perhaps design intent is one of the most important product model information during concurrent processing. By design intent, product designers express their original objectives of the design, and manufacturing engineers can well understand the process of product design to attain good manufacturability without invalidation the performance of products. If a product modelling framework cannot hold the original design intent, and just can keep the final description of product definition, then it becomes difficult to capture the original intention of product design, and to improve the design without violating the original intent. By the investigation of practical examples, we understand that, by the term design behabiour, funcctions, etc. And it is not easy to rigorously classify them.

4. PRODUCT MODELLING FOR MANUFACTURING AUTOMATION

In this section, we elaborate the contents of object models, which is central in fig. I and is a basis for simultaneous processes of engineering activities.

An object model in fig. I corresponds to the so-called product model in the narrower sense [Sata85], and it should represent all the pertinent product information throughout the whole product life cycle. But, many of the existing product modelling systems can just represent current results of modelling porocesses, and cannot keep the past history of modelling processes. During the course of model development, target requirements or specifications are given, and much data are added according to the decisions given byhuman engineers or other processes. Sometimes, in the following stages, the reasons or origins of some data difficult from the standpoint of information processing to keep all such justification information, but it is vitally necessary to keep it for the purpose of realizing concurrency.

Some of model developing processes can be represented as shown in fig. 3. At each stages of design and manufacturing preparation processes, the iteration cycle of fig. 3 should be repeated to construct a consistent and complete description of a product model which exactly specifies the object that we wish to produce by physical manufacturing processes. A history of such iteration should be recorded in the oibject model, and it will represent the major part of design intent of the product.

Requirements, specifications and objectives are the information concerning to the desired property of products to be designed. Description is the information which unambiguously determines the product for specified application processes. Property and behviour are the derived information from the description to exhibit product characteristics. Function is a very complicated concept, and is an interpretation of behaviour of ppoducts with respect to product requirements of specifications. As discussed in the previous section, it is not easy to define design intent precisely. The items appearing in fig. 3 or some interdependence of those items can be considered to depict design intent in many cases. Real semantics of design intent depend on respective application, and can not easily be gen eralized.

In fig. 4, some of the typical technological information in a product model is illustrated. Various kinds of product structure are necessary to be represented in the context of product functionality, assembly, manufacturing, etc. The respective attributes of component parts should be represented, such as drawings, dimensions and tolerances, materials, etc.

Process-related information during product manufacturing or operations is also necessary.

Currently we still do not have satisfactory methods to fully represent and manipulate all the above information in a consistent manner. There have been many trials. and the combination of predicate logic and an object oriented method seems to be very effective.

5. EXAMPLES OF MANUFACTURING AUTOMATION BASED ON PRODUCT MODELLING

In this paper the technical details of the representation framework for product modelling are not discussed, but application examploes for manufacturing automation are shown for demonstrating the effectiveness of product modelling. These examples are only experimental ones. The difficulties for real practical applications will be discussed in the final section.

5. 1 Design of Optical Structure for Copying Machines [Kimura89a]

There have been many works concerning object repersentation of engineering products, but it is still fairly difficult to deal ith dunamic evaluation of object models from initial conceptual modelling to final detailed description of products.

Precise description of object shape can be well treated by the conventional geometric modelling methods, but more vague, initial functional descripion of products cannot be conbeniently dealt with. for such purposes, we have been investigating to use logical constraints [Kimura87, 89b]. Especially, for dealing with the so-called routine or variational design works, constraint-based approach is very useful for representing functional structure of products.

Here we introduce a method to describe basic functional structures of products by a set of logical constraints. Then the actual meaning of constraints or manipulation of constraints can be given by a set of rules, which are also described by logic expressions.

Generally, we can describe generic knowledge by a set of rules, such as physical laws, etc. Also we can store our past design examples and routinized design procedures by a set of logical constraints, which are often product specific.

We utilize constraint logic programming as a basis for implementing constraint solving. CLP is one of the good language for this purpose.

By the above methods, we can accumulate our design knowledge in generic and also product-specfic ways.

In order to show the usefulness or structural modelling with logical cnonstraint solving, we take an example of variational design of rather standardized products. Here we treat design of optical structure of plain paper copiers. The similar methods can be applicable for other kinds of products.

As is well known, automation or computer-aid of conceptual design is quite difficult in general. But it is very important and interesting to introduce computer processing to conceptual design. As the first step, it is feasible to think or the well standardized products whose conceptual design is just to select several alternatives of the predefined functional structures.

Even for such standardized situations, flexible modelling framework is necessary to represent basic functional structure of products. Here we represent structural models by collection of logican constraints which corresponds to design requirements or specification. If we determine the basic functional structure, then we elaborate the models gradually by incorporating precise models which are based on conventional modelling methods, sucg as geometric modelling.

In fig. 5, two typical examples or optical structure of plain paper copiers are shown. At the scanner part, a ray is projected on a face of a copy source sheet, and then the ray is directed by mirrors and lens to a drum surface to constitute a latent copy image. 6-mirror type is simple in its operation, but needs more space and parts. 4-mirror type requires less parts and space, but needs precise control of mirror angle when magnification factor is changed.

According to design requirements, one of two types is to be selected. Therefore it is desirable to represent the basic structures in a uniform manner, and to easily change from one structure to another. For such purposes, structural modelling based on logical expressions is very effective.

For representing the models of fig. 5, several predicates are prepared for dealing with relationships among mirrors, lens and rays. Simple optical calculation rules are encoded by use of CLP. Those rules are generic, such as to determine out-going ray with given incomming ray and mirrors, or to determine mirror angles with given incoming and outgoing rayts, etc. Configuration of mirrors and lens is described by specifying their relationships by apporpriate logical predicates. Those descriptions are specific to optical structure of copying machines. If we prepare enough generic rules about optical calculation, it is fairly easy to define new types of optical structure.

Actual design will proceed as shown in fig. 6. At the first step, designers specify major dimensions, allocation of major components, or design parameters, such as magnification factors. Then, following the step 3 and 4, fundamental optical structure can be determined introduced to define the fine details of compomnent shape. Some results of deign are shown in fig. 7.

5. 2 Producibility Evaluation of Machine Parts

[Rata9] In a machine design process, a designer has to go through vaerious requirements in order to refine a product description into a final realizable product. Among those requirements, the ones concerning with manufacturing processes have the strongest effect on the final production cost. If the designer is not aware of the manufactuing technology, the producibility difficulties are noticed only during process planning or manufacturing processes. This may lead to an expensive and time consuming iteration of the design and manufacturing preparation processes. In order to overcome these problems, the product designer needs advice on the manufacturing viewpoint, that producibility evaluation.

The architecture of an experimental producibility evaluation system is shown in fig. 8. The designer constructs a product model by using modelling operatrions of the product modelling module. At any moment, the user can activate the producibility evaluation module to obtain suggestions for improving the machinability of ther product.

The producibility evaluation is attained by the following two steps. Initially, a process planing expert system with rules for machining type assignment and machining process determination invoked fig. 8. (1)). This system applies rules on the product specfication avalable at that moment, and determines partial process plan information. The dependency between the generated machining information and the product information referred to in the generation is very important for simultaneous update of the process plan and for the producibility feedback.

In the second step, the producibility feedback system is activvated. It prepares various diagnostic rules and procedures to detect any problems with the featerures of the machining process information. Examples of these potential problems are excessive cutting directions and tool changes, usage of special machining tools, and the requirements of high accuracy cutting. Thew problems are usually caused by the critical and/or special product specifications on form featurs. The producibility feedback system tries to detect such causes by using the recorded data dependency, and suggests a design modification to attain higher producibility (Fig. 8(2)).

The user decides whether proposed changes can be executed without causing loss of product functionalities. When the user erases some product information according to the advice, the ATMS(Assumption-based Truth Maintenance System) atomatically erases the corresponding machining information(Fig. 8 (3)). When some new product infomation is added, the process planning systerm is simultaneously activated. It applies rules only on the part upon which the process planning information is not yet determined (Fig8. (4)). The regenerated process plan is used for the further producibility evaluation.

Fig. 9 displays the initial design of an example part which was evalated in order to detect manufacturing problems. The process plan and producibility warnings are also shown in the figure. Fig. 10 shows the refined product and updated process plan after design modificatons

5. 3 Variational Process Planning [Kimura89c]

Process planning is recognized as an essential bridge between design and manufacturing activities. Much research and practical work has already been done to realize Computer Aided Process Planning (CAPP) systems. Computerized process planning can be generally classified into two major classes; variant process planning and generative process planning.

Most of the process planning in actual manufacturing are for the parts which are very similar to the already manufactured products. In this sense, the variant approach is most suitable for the practical application than the generative one. However, in the variant apporach, a certain amount of modification must be manually done on the referred plan to derive one for the new product.

In order to solve the problem of variant process planning, we propose a new approach, named as variational process planning, which is the combination of variant and generative approaches. The basic idea is shown in fig. 11. Frist, a completely new product is given for process planning, and the system generates a process plan in the generative manner (fig. 11(a)). A product model corresponding to the given part is stored in the database, and the system applies process planning rules on the product model to determine a part of the process plan. During this plan generation process, the system detects the dependency between the product information and a part of the process plan using the product information. The TMS is used to record such data dependency.

When a similar machine part is given for process planning afterwards, the process planner invokes the product modeling system and modifies the prior product information to be the same as the new part. According to the product model modification, the ATMS automaticallt erases the part of the process plan that depends on the modified product information. Then, process planning rules are applied again on the part upon which the necessary maching iformation is not yet determined, and the system regenerates a new process plan fig. 11b)). Thus, by using the dependency between the product description and the process plan, efficient variational process planning can be realized.

6. CONCLUSIONS

In order to cope with new manufacturing

trend of small-sixed production of high-quality value-added products, flexible integration of engineering activities is proposed to be effective. Pre-production evaluation of product functionality and manufacturablity is desirable, and the tight integration or almost concurrent executiuon of all the necessary engineering activities is becoming very popular, which is called as concurrent engineering or simultaneous engineering.

Product modelling plays an essential role for realizing such flexible integration and concurrency of engineereing activities. By product modelling, it is not enough to represent final detailed initial conceptual design to fial manufacturing operations. We still do not have powerful and flexible representation framework to be able to represent diversity of products and their processing information.

Several examples of product modelling applications for manufactring automation are shown, but they are still too simplified from the standpoint of practical applications. The reasons for this simplicity may be two-fold : Real engineering activities are too complicated, and existing product modelling representation frameworks are too weak for representing such complexity. We need to develop far more powerful representational frameworks, and to analyze deeper the engineering activities by use of the frameworks. For instance, feature modelling is one the key technologies, but current works are still too primitive for practical applications [Pratt88].

ACKNOWLEDGEMENT

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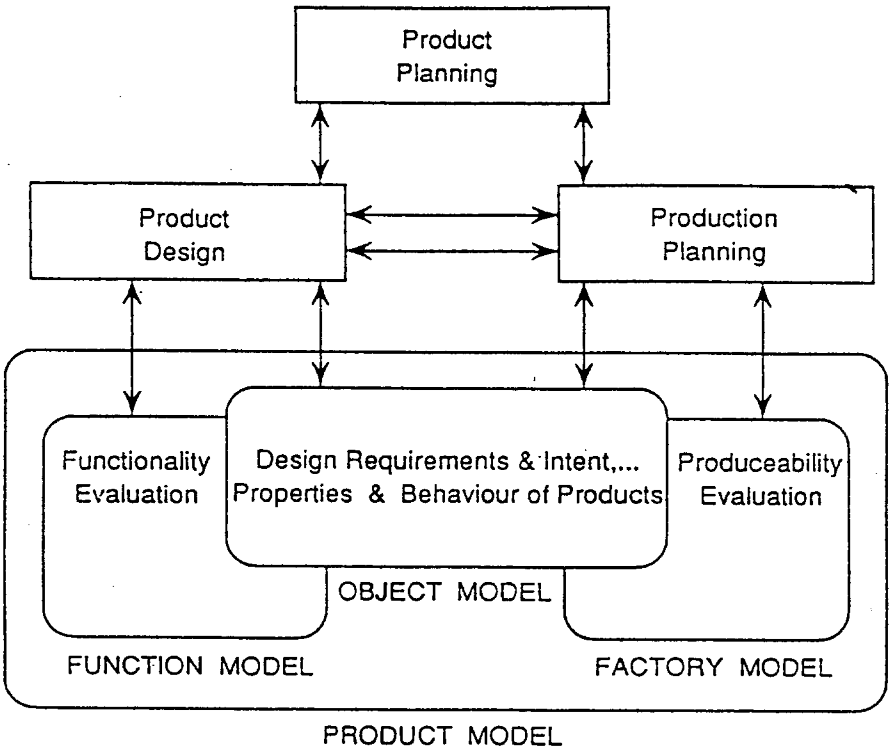


Fig.1. Flexible Integration of Production Processes

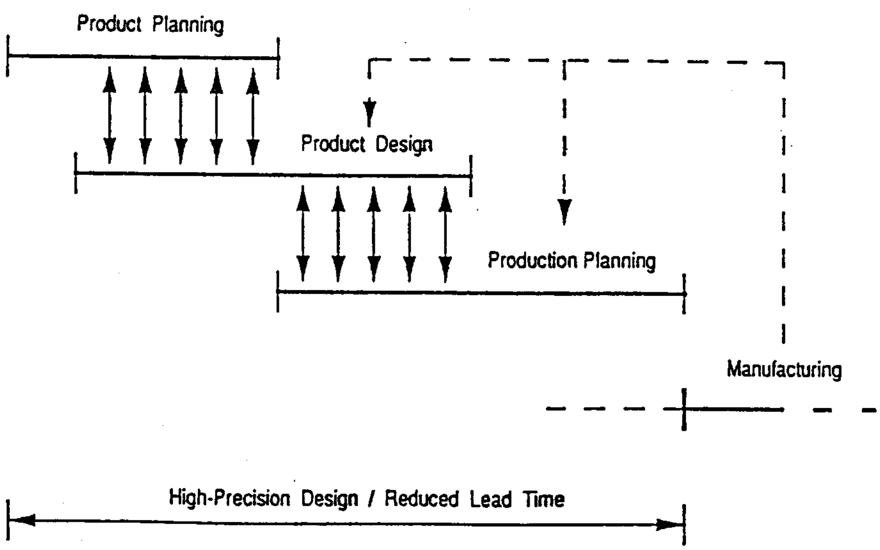


Fig.2. Simultaneous Process of Engineering Activities

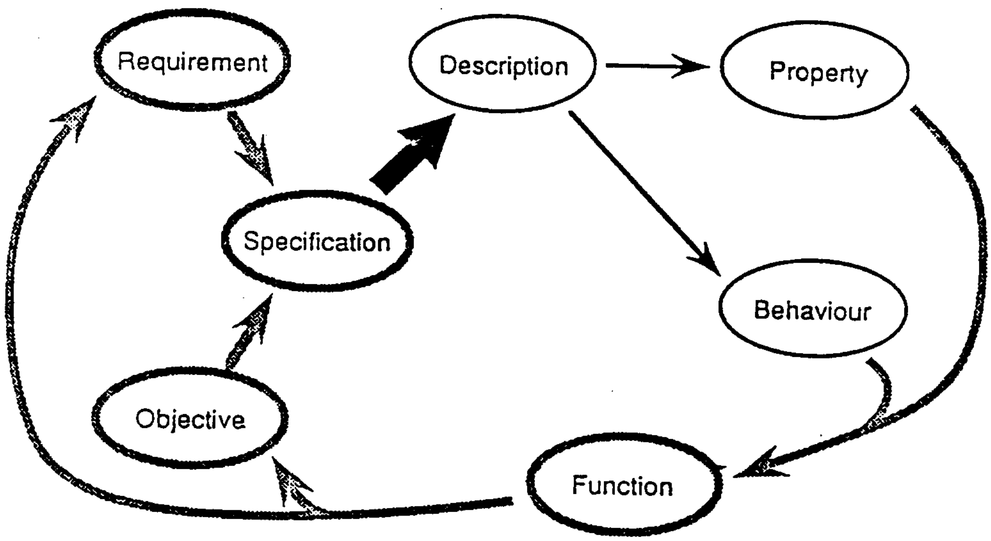


Fig.3. Product Modelling Processes during Product Development

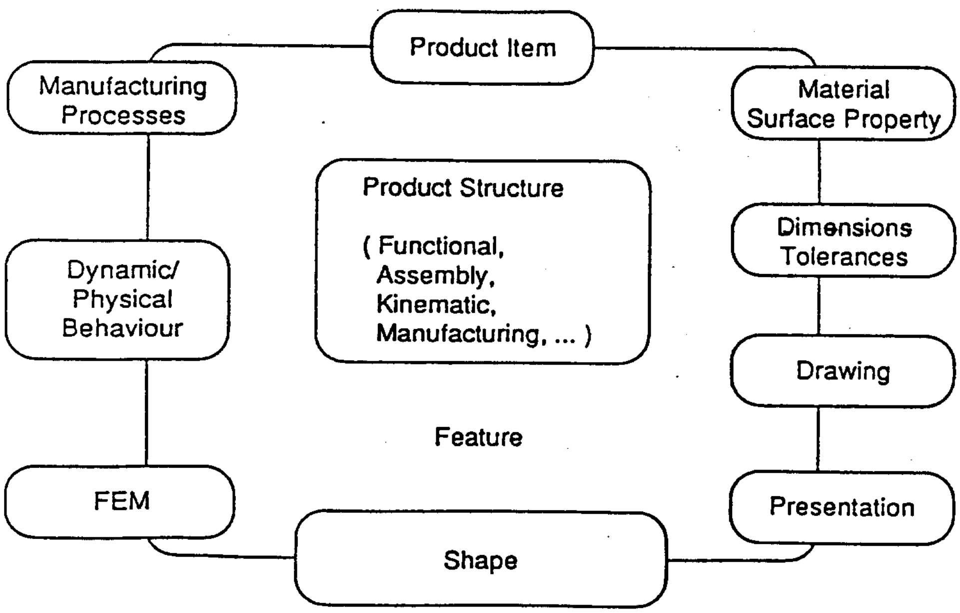


Fig.4. Technological Information in a Product Model

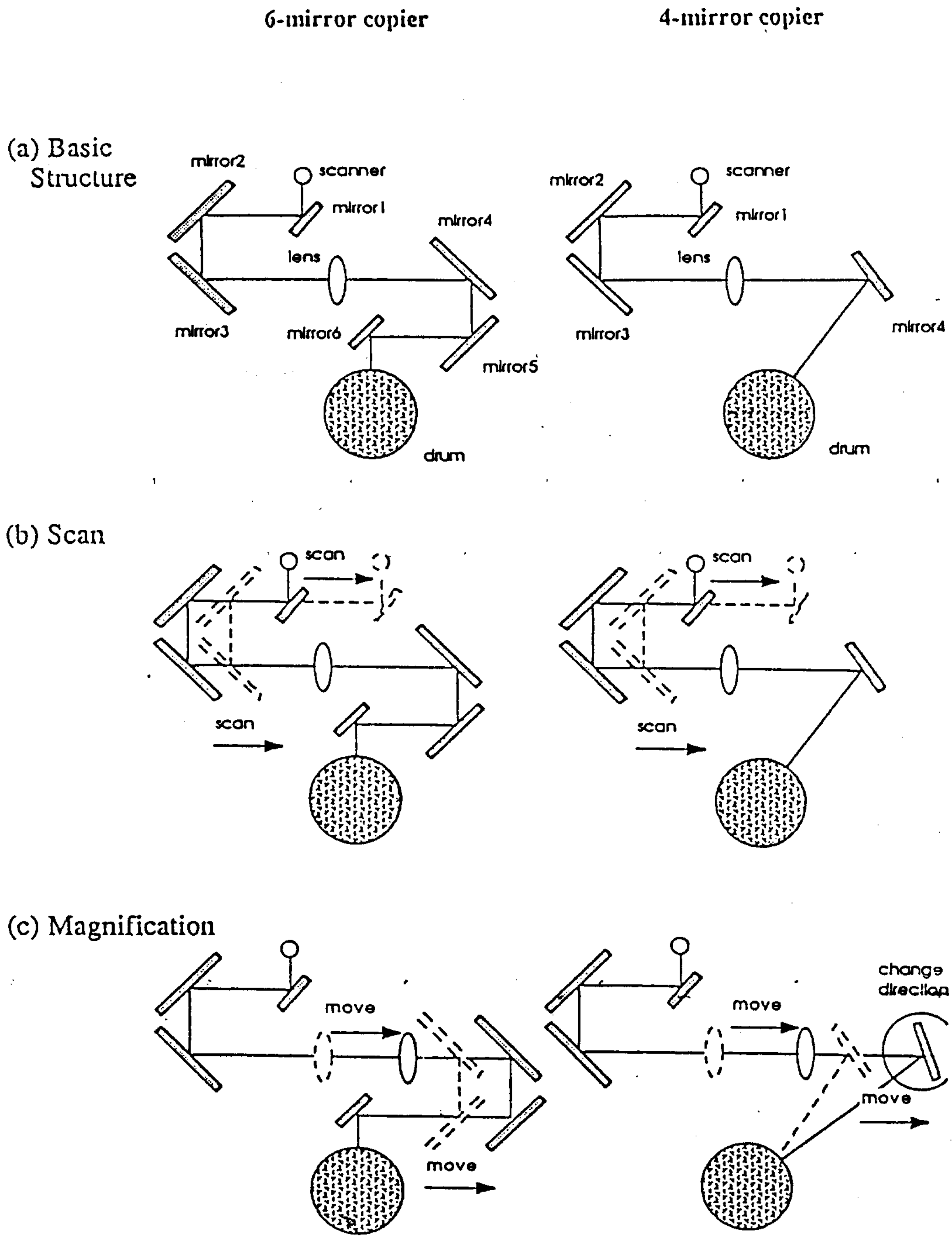
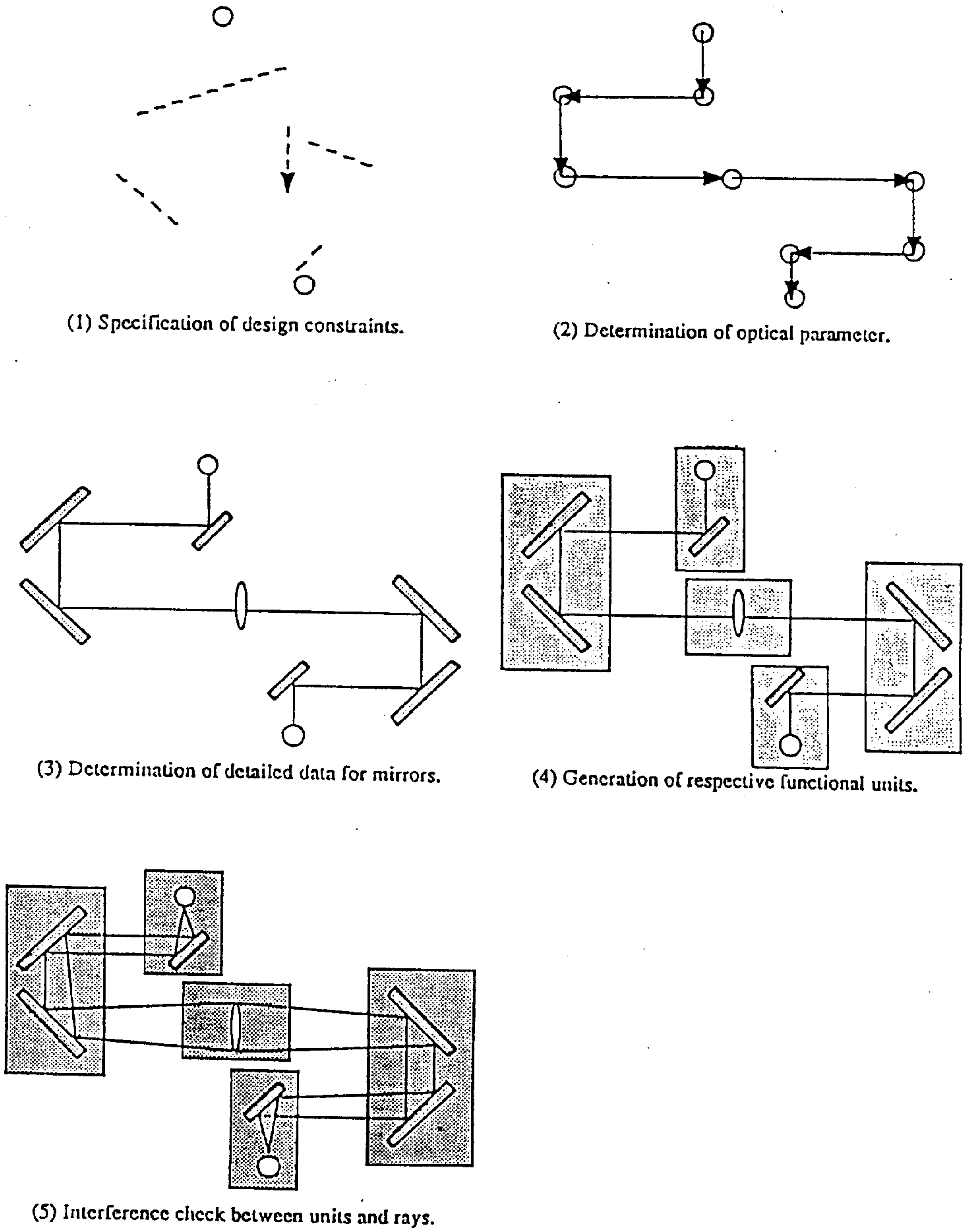


Fig.5. Examples of Optical Structure for Copying Machine



(1) Specification of design constraints.

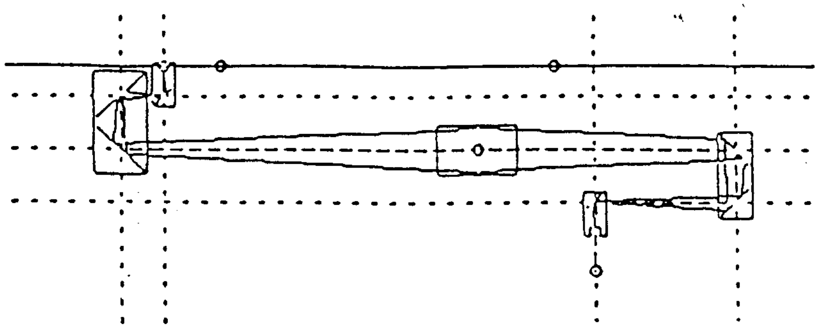
(2) Determination of optical parameter.

(3) Determination of detailed data for mirrors.

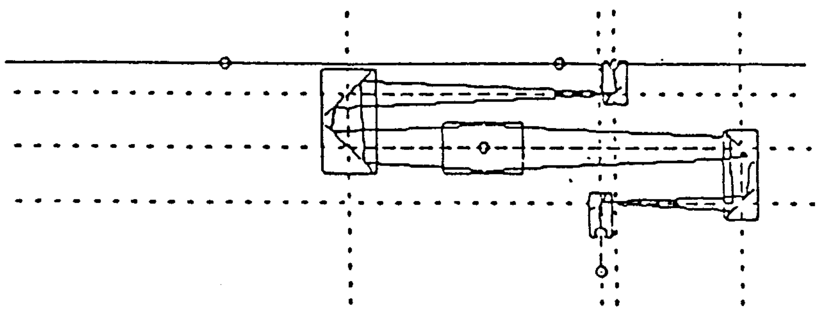
(4) Generation of respective functional units.

(5) Interference check between units and rays.

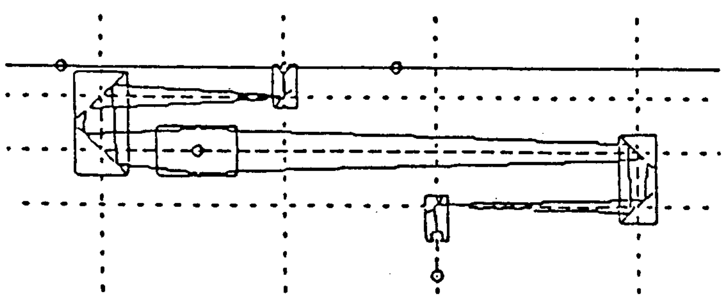
Fig.6. A Design Procedure of Optical Structure



(a) Home position for equi-size copy.

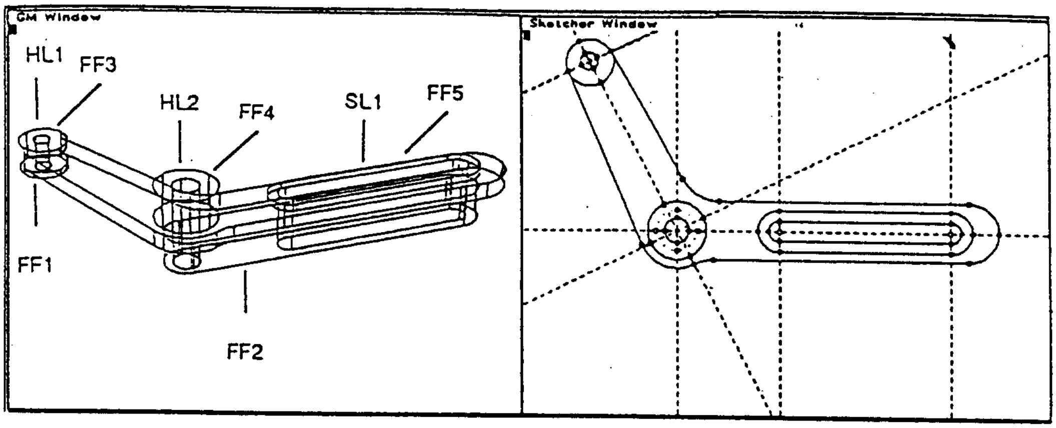


(b) End of scan for equi-size copy.



(c) End of scan for magnification copy.

Fig.7. A Design Example of Optical Structure



Phase:1 Workpiece Orientation: Z-
1. ROUGH FACE-MILLING on (FF1 FF2).
2. FINE FACE-MILLING on (FF1 FF2).

Phase:2 Workpiece Orientation: Z+
1. ROUGH FACE-MILLING on (FF3 FF4 FF5).
2. FINE FACE-MILLING on (FF3 FF4 FF5).
3. CENTER-DRILLING on (HL1 HL2 HL3 HL4 HL5 HL6 SL1).
4. 5mm ROUGH DRILLING on (HL3 HL4 HL5 HL6).
5. 8mm ROUGH DRILLING on (HL1).
6. 12mm ROUGH DRILLING on (HL2 SL1).
7. 10mm FINE DRILLING on (HL1).
8. 15mm FINE DRILLING on (HL2).
9. ROUGH END-MILLING on (SL1).
10. FINE END-MILLING on (SL1).
11. M6 TAPPING on (HL3 HL4 HL5 HL6).

Phase:3 Workpiece Orientation: Z-
1. VERY-FINE FACE-MILLING on (FF2).

WARNINGS:
1. (FLAT-FACE FF1 AND FF2 SHOULD HAVE SAME HEIGHT.)
2. (FLAT-FACE FF3 AND FF4 SHOULD HAVE SAME HEIGHT.)
3. (FLAT-FACE FF5 AND FF4 SHOULD HAVE SAME HEIGHT.)
4. (TOO DEEP END-MILLING IS REQUIRED ON SLOT SL1.)
5. (DIVIDE FLAT-FACE FF2 FOR HL2 AND FOR SL1.)
6. (VERY-FINE MACHINING REQUESTED ON FF2 IS REALLY REQUIRED?)
7. (ALIGN CENTER-LINE FOR SL1 TO OUTER CYLINDRICAL SURFACE.)

Fig.9. An Example Product

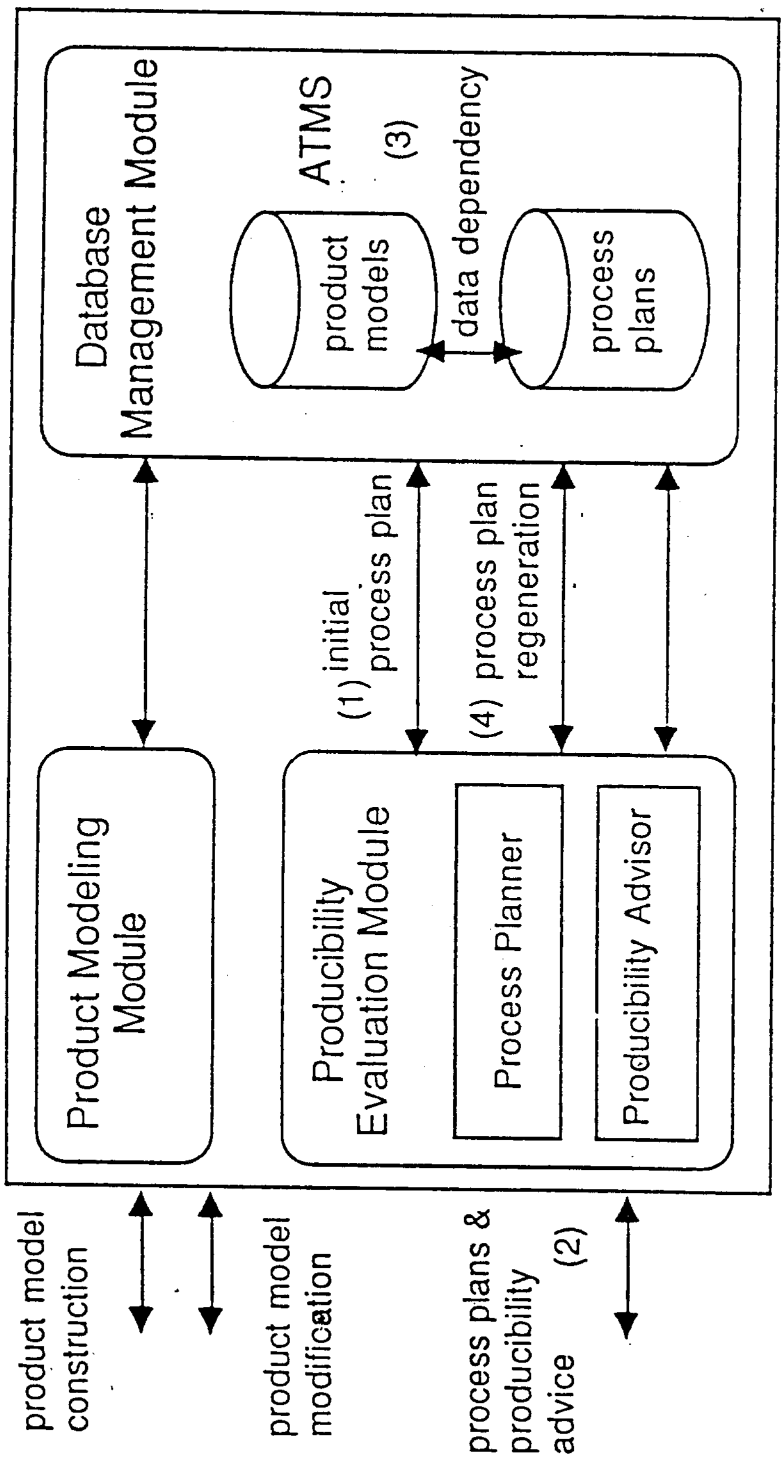
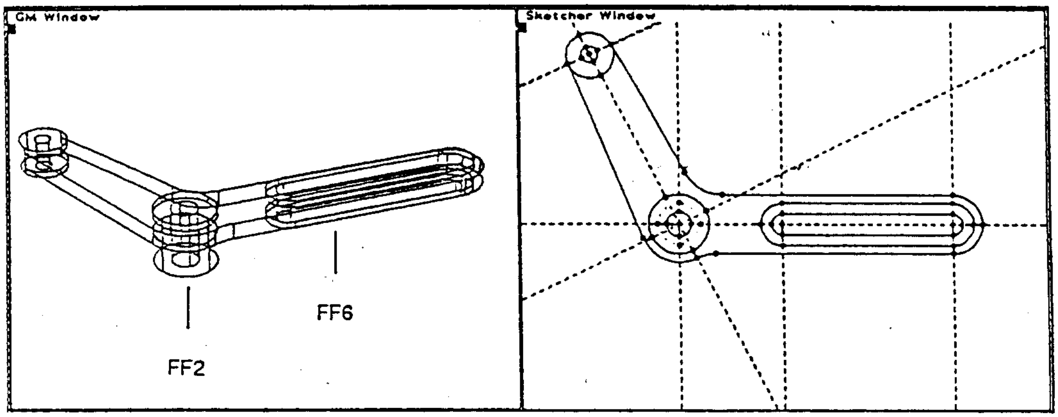


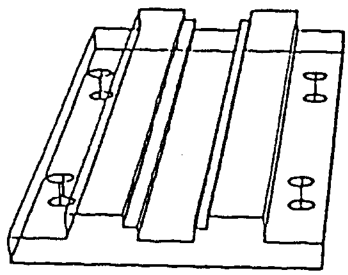
Fig.8. Producibility Evaluation System



Phase:1 Workpiece Orientation: Z-
1. ROUGH FACE-MILLING on (FF1 FF2 FF6).
2. FINE FACE-MILLING on (FF1 FF2 FF6).

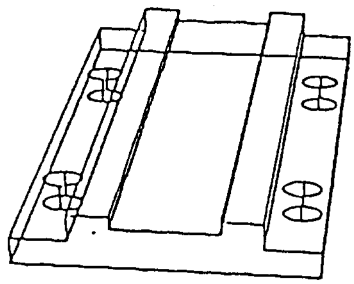
Phase:2 Workpiece Orientation: Z+
1. ROUGH FACE-MILLING on (FF3 FF4 FF5).
2. FINE FACE-MILLING on (FF3 FF4 FF5).
3. CENTER-DRILLING on (HL1 HL2 HL3 HL4 HL5 HL6 SL1).
4. 5mm ROUGH DRILLING on (HL3 HL4 HL5 HL6).
5. 8mm ROUGH DRILLING on (HL1).
6. 12mm ROUGH DRILLING on (HL2 SL1).
7. 10mm FINE DRILLING on (HL1).
8. 15mm FINE DRILLING on (HL2).
9. ROUGH END-MILLING on (SL1).
10. FINE END-MILLING on (SL1).
11. M6 TAPPING on (HL3 HL4 HL5 HL6).

Fig.10. A Modified Example Product



FIXING WORKPIECE Z+ DIRECTION
RESTING FACE FF1
1. ROUGH FACE-MILLING F-FACE (FF2 FF3)
2. FIN FACE-MILLING F-FACE (FF2 FF3)
3. ROUGH END-MILLING STEP (STP1 STP2)
4. FIN END-MILLING STEP (STP1 STP2)
5. ROUGH END-MILLING GROOVE (GRV1)
6. CENTER-DRILLING HOLE (HL1 HL2 HL3 HL4)
7. ROUGH END-MILLING GROOVE (GRV2)
8. FIN END-MILLING GROOVE (GRV1)
9. DRILLING HOLE (HL1 HL2 HL3 HL4)
10. FIN END-MILLING HOLE (HL1 HL2 HL3 HL4)
11. FINE END-MILLING HOLE (GRV2)

(a) Initial product model and process plan.



FIXING WORKPIECE Z+ DIRECTION
RESTING FACE FF1
1. ROUGH FACE-MILLING F-FACE (FF2 FF3)
2. FIN FACE-MILLING F-FACE (FF2 FF3)
3. ROUGH END-MILLING STEP (STP1 STP2)
4. FIN END-MILLING STEP (STP1 STP2)
5. CENTER-DRILLING HOLE (HL1 HL2 HL3 HL4)
6. ROUGH END-MILLING GROOVE (GRV1)
7. DRILLING HOLE (HL1 HL2 HL3 HL4)
8. FIN END-MILLING HOLE (HL1 HL2 HL3 HL4)
9. FIN END-MILLING HOLE (GRV1)

(b) Modified product model and regenerated process plan.

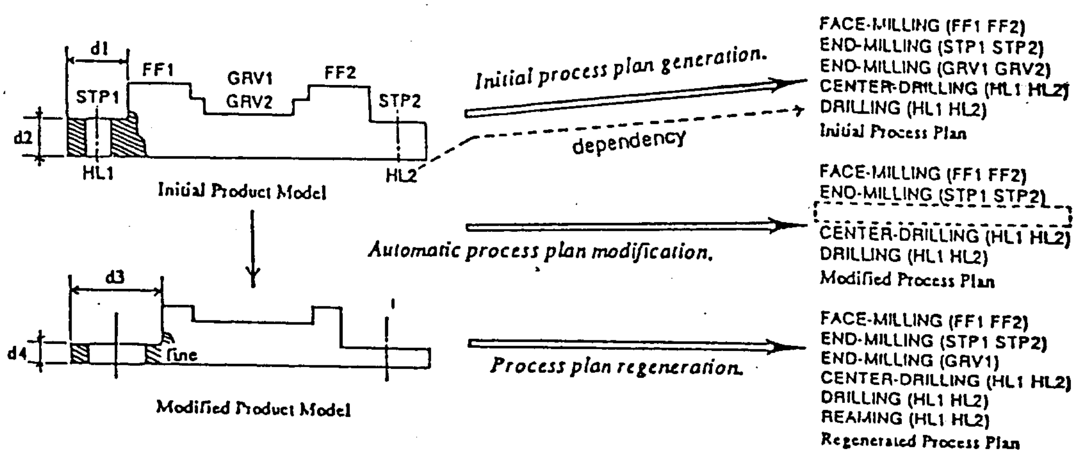


Fig.11. An Example of Variational Process Planning