Design for mass production of small lotsize mechanical systems

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Design for Mass Production

of small lotsize mechanical systems

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Design for Mass Production

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Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Eindhoven,
op gezag van de Rector Magnificus, prof. dr. J.H. van Lint,
voor een commissie aangewezen door het College van Dekanen,
in het openbaar te verdedigen op vrijdag 8 mei 1992 te 14.00 uur

door

JOHANNES WILHELMUS MARIA KRIKHAAR

geboren op 14 februari 1957 te Nijmegen

Dit proefschrift is goedgekeurd door de promotoren:

prof.ir. J.M van Bragt

en

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SUMMARY

By the increasing market demands on product innovation, the industry requires a fast product creation process. Part of this process is the development of production tools. Production tools contain many mechanical components, each in small lotsizes. Because of the fast changes in product types, there are hardly even re-orders for these production tools. Therefore, the lotsizes of mechanical components for this kind of applications are reducing.

In Design conventionally, the designer and draftsman define the geometry of components. The workshop defines the manufacturing procedures (machine tool, set-ups, sequences of operations, tools etc.). The application of numerically controlled (NC) machine tools in manufacturing of the mechanical components in small lotsizes is hardly justifiable because of the high NC programming costs.

By reconsidering the goals of Mechanical Design, a new working method for Design is defined in this study, in which method the manufacturing process planning is merged into Design. By the use of CADCAM techniques, the NC programming has been automated, by which the use of NC machine tools become economically justifiable for small lotsize mechanical components. This working method puts aside the conventional design procedures, avoids drawings and brings back manufacturability considerations to the designer. Good results are only possible by a high degree of standardisation and automation (technology, manufacturing methods, palletizing systems, tool changing device, tool management, Manufacturing Families). The new design approach also has a great influence on the manufacturing organisation. It leads to a manufacturing process of small lotsize mechanical parts, which has the characteristics of mass production. The results of this study are based on proven applicability in a pilot project at Philips Lighting Eindhoven.

The new working method, to be called DfMASS (Design for Mass production), is illustrated by a comparison with conventional practice in Fig. 0.1.

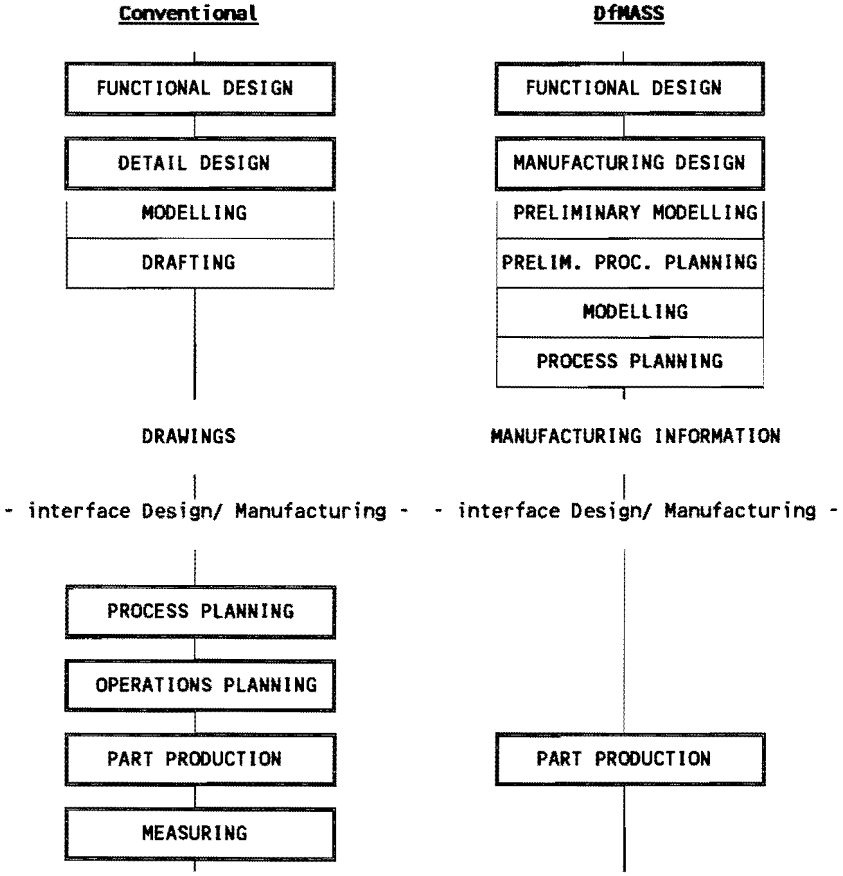

Fig. 0.1: The difference between conventional practice and DfMASS

The differences between the two schemes of Fig. 0.1 are following.

> Conventionally, component design contains modelling of components on a drawing board and creating two dimensional drawings of the components. The interface to Manufacturing is technical drawings. Process planning and operations planning [1] are executed in the workshop environment before part production on the machine tool can be started.

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[1] By operations planning is meant the decisions taken on tool choice, speeds and feeds and the the definition of tool pathes. In NC production, operation planning entails the activities to create a NC program from the process plan.

In DfMASS, the process planning is merged into geometric modelling. This new activity is called Manufacturing Design. Manufacturing Design is divided into preliminary modelling, based on the Functional Design; preliminary process planning based on the preliminary model; final modelling and final process planning. NC programming is automated. The output of Manufacturing Design is manufacturing information, from which the components can directly be produced on a NC machine tool. Hence, in DfMASS all technological decisions on manufacturing have been brought back to Design.

By the merging of process planning into geometric modelling, this new design activity has become more complex. By the same token, the complexity of Manufacturing has decreased. To restrict the increase of complexity of Design, Manufacturing Families have been introduced. A Manufacturing Family prescribes manufacturing limitations and supplies a standard process plan. Designing a component, belonging to a Manufacturing Family, is restricted to these limitations. By designing within a Manufacturing Family, defining a process plan has become redundant.

The DfMASS method was applied, for 9 months in a pilot environment at Philips Lighting. In this period, over 6000 hours of manufacturing production was done, already obtaining a profit of 11% in manufacturing costs. An additional savings of 25% is achievable by building experience with this working method.

DfMASS has been found to having the following advantages compared to conventional. DfMASS:

- supplies an economically justified transition from drawing-based Design to an integral drawingless application of CADCAM (Chapters 4 and 7),
- enlarges the applicability of NC machine tools for small lotsize mechanical systems (Chapter 7),
- reduces leadtime (Chapter 6),
- reduces costs (Chapter 7),
- enables a single sourcing information (Chapter 4),
- suffices a limited set of machine tools for manufacturing the majority of components (Chapters 5 and 7),
- stimulates modularity of designs (Chapter 4).

SAMENVATTING

Door de groeiende marktvraag naar produktinnovatie, vraagt de industrie een snel produkt creatie proces. Een deel van dit proces is de ontwikkeling van produktiemiddelen. Produktiemiddelen bevatten een grote hoeveelheid mechanische onderdelen, elk onderdeel echter in een kleine aantal. Tevens wordt er door de snelle veranderingen in produkttypes nauwelijk meer copien van dergelijke produktiemiddelen gevraagd. Daardoor worden de produktie-aantallen van dit type onderdelen steeds kleiner.

In het conventionele ontwerpen bepalen de ontwerper en de tekenaar/ constructeur de vorm van de onderdelen. De werkplaats bepaalt de manier waarop het onderdeel wordt gemaakt (machinekeuze, opspanningen, volgorde van bewerkingen, gereedschappen, etc.). Het toepassen van numeriek bestuurde (NC) machines in het fabriceren van mechanische onderdelen in kleine series is nauwelijks te verantwoorden ten gevolge van de hoge NC-programmeer kosten.

Na heroverweging van de doelen van Werktuigbouwkundig Ontwerpen, is een nieuwe werkmethodiek gedefinieerd waarin de werkvoorbereiding opgenomen is in het Ontwerpen. Door toepassing van CADCAM technieken is het NC programmeren geautomatiseerd, waarmee de inzet van NC machines voor het fabriceren van enkelstuks en kleinserie mechanische onderdelen ecomonisch verantwoord is geworden. Deze werkmethode schuift conventionele werkprocedures aan de kant, vermijdt de noodzaak van tekeningen en brengt maakbaarheidsoverwegingen terug in het ontwerpproces. Goede resultaten zijn alleen mogelijk door een hoge graad van standardisatie en automatisering (technologie, fabricage methoden, pallet systemen, gereedschapwisselsystemen, gereedschapbeheer, fabricage families). The nieuwe ontwerpaanpak heeft een grote invloed op de werkplaatsomgeving. Het leidt tot een fabricage proces voor kleinserie onderdelen dat de characteristieken van massa produktie heeft. De resultaten van deze studie zijn gebaseerd op aangetoonde toepasbaarheid in een proefomgeving bij Philips Lighting in Eindhoven.

De nieuwe werkmethode, DfMASS genoemd (Design for Mass production), wordt in Fig. 0.1 geillustreerd door vergelijking met de conventionele praktijk.

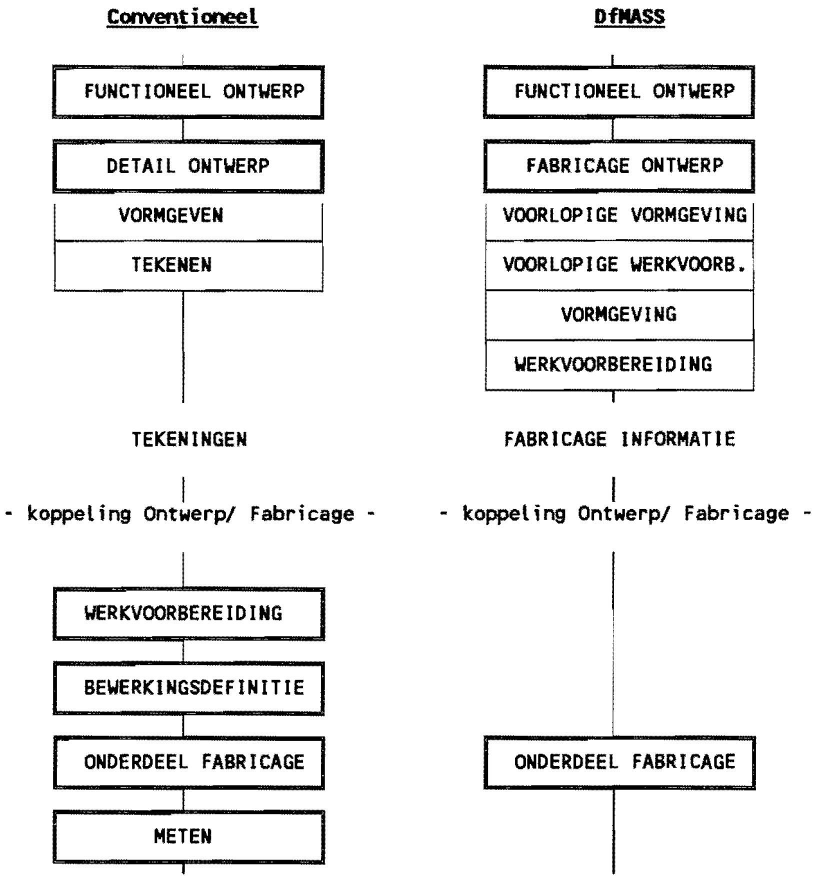

Fig. 0.1: Het verschil tussen de conventionele practijk en DfMASS

De volgende verschillen zijn aanwezig tussen de de twee schema's in Fig. 0.1.

Het ontwerpen van onderdelen bestaat conventioneel uit het vormgeven van het onderdeel achter een tekenbord en het maken van een twee-dimensionale tekening van het onderdeel. De koppeling naar het fabricage proces bestaat uit technische tekeningen. Werkvoorbereiding en het definieren van de bewerkingen[1] worden in de werkplaatsomgeving uitgevoerd, voorafgaand aan het daadwerkelijk fabriceren van het onderdeel.

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[1] Definitie van de bewerkingen bestaat uit gereedschapskeuze, toerental, voeding, gereedschapsbewegingen. Bij NC bewerking, omvat het definieren van de bewerkingen alle activitieiten om vanuit de werkvoorbereiding te komen tot het NC programma.

In DfMASS is de werkvoorbereiding opgenomen in de vormgevingsfase. Deze nieuwe activiteit wordt Fabricage Ontwerp genoemd. Fabricage Ontwerp is opgedeeld in voorlopige vormgeving, gebaseerd op het functionele Ontwerp; voorlopige werkvoorbereiding, gebaseerd op de voorlopige vormgeving, definitieve vormgeving en definitieve werkvoorbereiding. Het NC programmeren is geautomatiseerd. Het resultaat van Fabricage Ontwerp is fabricage information waaruit het onderdeel rechtstreeks kan worden gefabriceerd. In DfMASS zijn alle technologische fabricage beslissingen teruggebracht in het Ontwerp.

Door de opname van werkvoorbereiding in het Ontwerp, is deze nieuwe ontwerp activiteit complexer geworden. Gelijkertijd is het fabricage traject minder complex geworden. Om de complexiteit van het Ontwerpen te beperken zijn fabricage families geïntroduceerd. Een fabricage familie schrijft fabricage beperkingen voor en verschaft een standaard werkvoorbereiding. Het ontwerpen van een onderdeel, behorende tot een familie, moet binnen deze beperkingen plaatsvinden. Voor onderdelen behorende tot een fabricage familie, is het maken van een werkvoorbereiding overbodig geworden.

De DfMASS methode is 9 maanden lang toegepast in een proefomgeving bij Philips Lighting. In deze periode zijn meer dan 6000 uur aan onderdelen gefabriceerd, waarbij al een kostenreductie van 11% is gerealiseerd. Een additionele kostenreductie van 25% wordt verwacht door de toename van ervaring met deze methode.

DfMASS heeft getoond de volgende voordelen te hebben ten opzichte van conventioneel. DfMASS:

- verschaft een economisch verantwoorde overgang van tekeninggeöriënteerd ontwerpen naar een integrale tekeningloze toepassing van CADCAM (hoofdstukken 4 en 7),
- vergroot de toepasbaarheid van NC fabricage machines voor enkelstuks en kleinserie mechanische onderdelen (hoofdstuk 7),
- verkort doorlooptijd (hoofdstuk 6),
- reduceert kosten (hoofdstuk 7),
- maakt een unieke eenduidige informatiebron mogelijk (hoofdstuk 4),
- vraagt slechts een beperkte hoeveelheid machine-types voor de fabricage van de meerderheid van onderdelen (hoofdstukken 5 en 7),
- stimuleert modulair ontwerpen (hoofdstuk 4).

CONTENTS

APPENDICES

1. INTRODUCTION

1.1 Why doing this study

From rock to disk

In the prehistoric age, man tried to secure information by cutting symbols in rock. Communication changed considerably when people used sheets of skin and lateron sheets of paper. When the art of printing was invented, man was able to copy information much more easier than by rewriting. This has leaded to a great change in communication. In the last decades, information is becoming more electronic, by which another great change in communication has been initiated. Opportunities of electronic communication also influences the design process, for which the existing working procedures need to be adjusted to this new medium.

From individual to company

Another tendency is the exponential increase of technological know how. Just a hundred years ago, a single man could construct a machine and execute the manufacturing of it. For instance, agricultural machines, cars and airplanes were designed and manufactured under direct control of a single man. Today, companies have large research divisions to develop new products. Also, the design and manufacturing process has become a complex

operation with a lot of specialization. In this process, drawings have become very important. The drawing now operates as a legal document between Design and Manufacturing for ordering parts and for Assembly. The following disadvantages are implied in this drawing-based working method:

- the workshop follows the drawings exactly, without considering the real function of the component,
- the designer describes the entire geometry in detail, not only functional geometry, although for nonfunctional geometry an alternative shape may be easier to produce,
- the designer is expected to consider manufacturability, although he hardly gets feed back from the workshop.

Breaking down this drawing-based interface by a computer aided design method is a challenge.

Numerically controlled machine tools

During the sixties, numerically controlled (NC) machine tools have been introduced in Manufacturing. For mass production they are well introduced. For small lotsize components with complex shapes, CADCAM is a efficient tool to create NC programs, because the tool paths can be generated automatically. There are even products, which can hardly be manufactured without CADCAM and NC tools.
For small lotsize mechanical component however, the application of NC tools is still less successful, because of the topology of mechanical components. These components consist of a complexity of simple shapes, for which a lot of technology (tool selection, feeds and speeds) needs to be defined to create a few manufacturing instructions. Generally, this time consuming effort of NC programming is not cost-effective for small lotsize mechanical components. To make NC machine tools successful in this area, the programming costs need to be limited substantially.

Computer aided

During the seventies, new Computer Aided (CA) functionalities have become available as a tool for Design and Manufacturing:

- Computer Aided Design (CAD),
- Computer Aided Manufacturing (CAM),
- Computerized information: retrieval of electronic data.

By CA systems a lot of opportunities are to be gained in Mechanical Design. Unfortunately, many implementations of CA systems automate the existing activities ("the things they did") and suboptimize activities within the walls of an organizational unit ("island automation"). For example, a lot of CAD applications, even CADCAM applications use drawings as interface between Design and Manufacturing, because they are used to working with drawings. This often leads to inefficient use. Even today, although CA vendors claim success stories, most CADCAM applications are still not cost effective. Especially in Mechanical Design and Manufacturing of small lotsize mechanization, cost effectiveness is difficult to achieve.

Continued investment in CA systems is often based on belief and excused by strategic reasons. Consequently, a slow down of CA implementations can be foreseen for the near future. Only by a break through in working procedures ("Throw away conventions") a new acceleration may happen.

1.2 Specification of the study

Hypothesis
For small lotsize mechanization, the integral application of CAD, CAM and NC is generally not economically justifiable. Cost-effectiveness is lacking because the design methods have not been adapted to the new opportunities. A new approach on Design and Manufacturing will justify the integral application of CAD, CAM and NC in small lotsize mechanization.

Aim of the study
Aim of the study, presented in this thesis, is to achieve:

- a new working method for Design and Manufacturing of small lotsize mechanical systems, with optimal use of new CA functionality and NC machine tools. This working method contributes to quality improvement, shorter leadtimes and cost reduction.
- proven applicability, social feasibility and costeffectiveness of this working method in practice (at Philips Lighting Mechanisation departments).

Scope
The scope of work for which this study has been executed, can be defined by following aspects:

- engineer-to-order/ small lotsize,
- specific solutions,
- milling parts.

The design activities of small lotsize mechanical systems are mainly driven by customer orders (engineer-to-order). The manufacturing orders follow from the design. There are hardly ever re-orders for these designs. The work concentrates on purchase parts and specific components manufactured in small and single lotsizes. Examples of such systems are tailor-made production units for consumer products (audio, video, domestic appliances, lighting). Mechanisation projects for those kind of specific purposes do not generally lead to hughe lotsizes of copies. Even when a copy is required, a redesign is made due to changes in the product, the experiences in practice with the production unit and the ongoing technology enhancements.

There is also a limited possibility of using standard solutions, because of the specific requirements of each system to be designed. Even group technology is hardly feasible because of the wide differentiation in required design solutions.

The scope of the manufacturing components is limited to milling parts, mainly consisting of a complexity of simple shapes (holes, slots, pockets), with less complex shapes.

CADCAM system

The design method has been implemented using the Unigraphics II version 8 CADCAM system of Electronic Data Systems[1]. The wire frame modeller has been used instead of solid modelling, because the required computer resources are still too expensive and/or too slow for a full implementation of solid modelling in assembly design of mechanical systems. This is expected to change in the near future.

Relevance

The relevance of this study to the practice of CADCAM in Mechanical Design is high, given the aims of increased quality, decreased leadtime and reduced costs. Mechanical Design techniques can use an impulse [1, 2] to modernize their working methods.

As a part of the study, an investigation of working practices at Fokker, DAF and Volvo in the Netherlands, at General Motors, Caterpillar, Pratt & Whitney and Mc Donnell Douglas (civil and defense aircrafts) in the USA and at different CAD/CAM suppliers Unigraphics, Computer Vision, Intergraph and CADMES has been done, as well as discussions with several companies. Overall, one can say that total integration of Design and Manufacturing by CA technology for small lotsize mechanical systems, has not yet been achieved on the industrial level.

A lot of scientific studies in this area aim to optimize the process planning (CAPP) and NC programming of the manufacturing activities [amongst others 3, 4 and 5]. This approach does not cover the problem of low manufacturability of designs, because the designer is not confronted with the manufacturing consequences of his design. Lately studies start to aim for total integration [6]. The study presented in this thesis comprehends a solution on total integration and the proven applicability of the solution.

NC machine tools have hardly been applied in small lotsize mechanical components, because of the cost of ownership of these machines and the effort required in NC programming. By the approach of the present study, a cost- effective use of NC machine tools in this area has been proven.

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[1] Previously owned by McDonnell Douglas

Exclusions from the study

The study does not primairily focus on:

- planning of design processes, workshops and acquisition,
- Functional Design,
- workshop optimization [7, 8],
- optimization of Assembly,
- optimization of NC datasets,
- optimization of fixturing,
- optimization of logistics,
- organisation of innovation [9],
- design features instead of manufacturing features.

Explanation of used terms/ abbreviations

A list of used terms and abbreviations has been added in Appendix A.

2. RESTRUCTURING

Introduction

The present chapter (Fig. 2.1) starts with a global description of the conventional Design and Manufacturing, while a detailed description is presented in Appendix B. By use of the Systematrix method of C. Jäderlund [16], this process has been analysed and problem areas have been detected. By restructuring of this process, a new design and manufacturing process has been developed. The aim of this restructuring effort is to decrease the logistic complexity between the activities by changing the primairy process. The new approach is called:

"Design for Mass Production" (DfMASS)

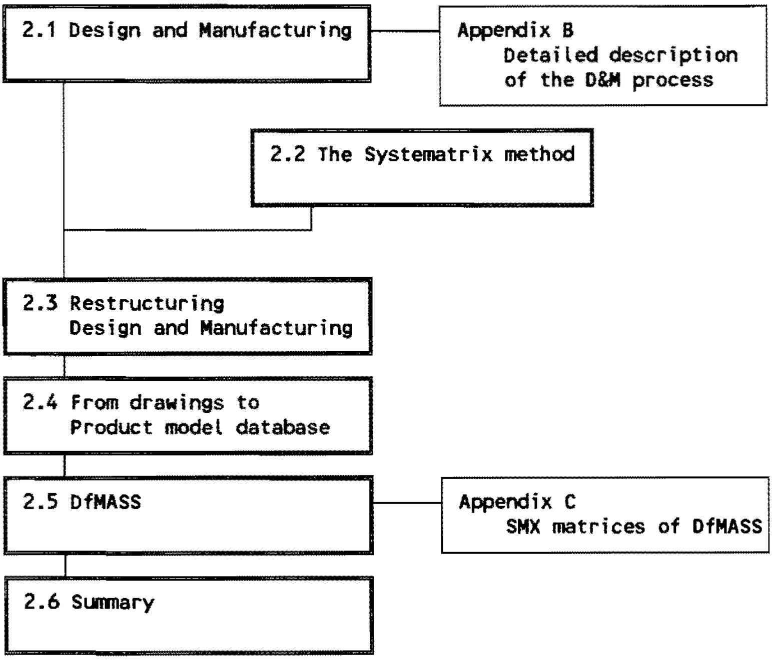


Fig. 2.1: The structure of this chapter

2.1 Conventional Design and Manufacturing

In the creation of complex mechanical systems, a well defined procedure for Design and Manufacturing is important for achieving the best results. In literature a lot of information can be found on design and manufacturing procedures.

Van den Kroonenberg [10] has defined a general design procedure consisting of four phases: investigation of the needs, problem definition, generation of solutions and structure definition, detail design.

Rodenacker [11] distinguishes task definition, functions structure, physical behaviour, construction characteristics and assembly design.

Pahl c.s. [12], as another representative of the German design school, defines "embodiment design" as the phase between Functional Design and Detail Design, where Detail Design completes the final instructions and documents. Clarity and simplicity of Design by a systematic approach of Design, leading to unambiguous interfaces is a main message of his book. Lacking full CADCAM functionality (in 1984), he needs to insert Detail Design to supply information for Manufacturing. Later on in this chapter, it will be illustrated that Detail Design is redundant, using CADCAM functionality.

Dandy c.s. [13] define 4 steps in planning and design of engineering systems: problem formulation, feasibility study, preliminary planning and design, detailed planning and design. They approach the technique from a planning point of view. They do not mention CADCAM as a tool in Design.

Beitz [14] makes a split-up of the total problem in sub-problems, until the level of basic problems ("Einzelprobleme") has been reached. A basic problem can not be split up anymore.

Philips Lighting [15] uses a projectprocedure for splitting up Design and Manufacturing in separate steps with a controllable output (Fig. 2.2).

Besides literature, experiences in mechanical design and manufacturing environments, especially within Philips Lighting, has been used as input for this thesis.

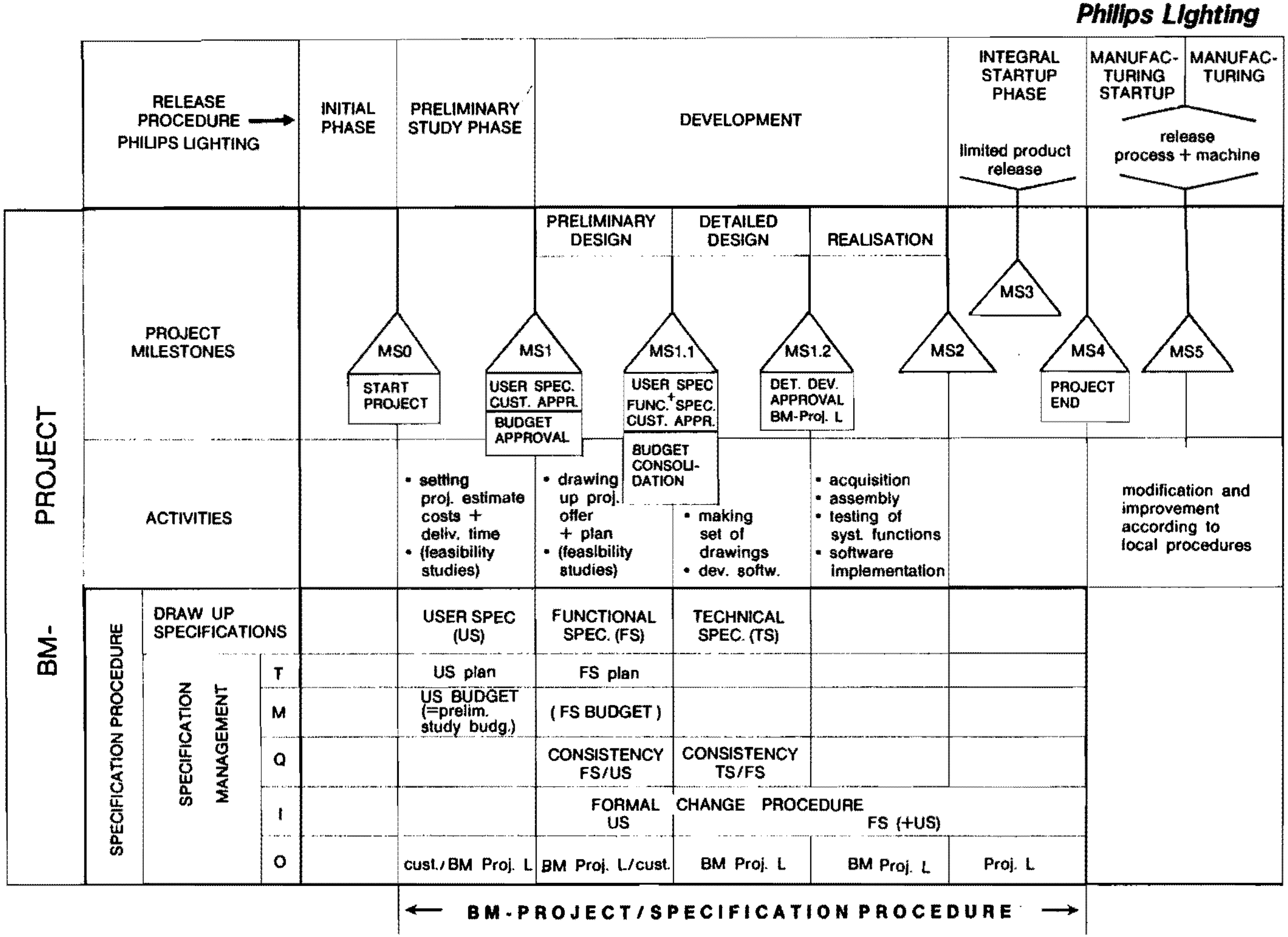


Fig. 2.2: The project procedure of Philips Lighting

A compilation of aforementioned ideas is presented in the scheme of Design and Manufacturing in Fig. 2.3. A detailed description of the different activities is given in Appendix B.

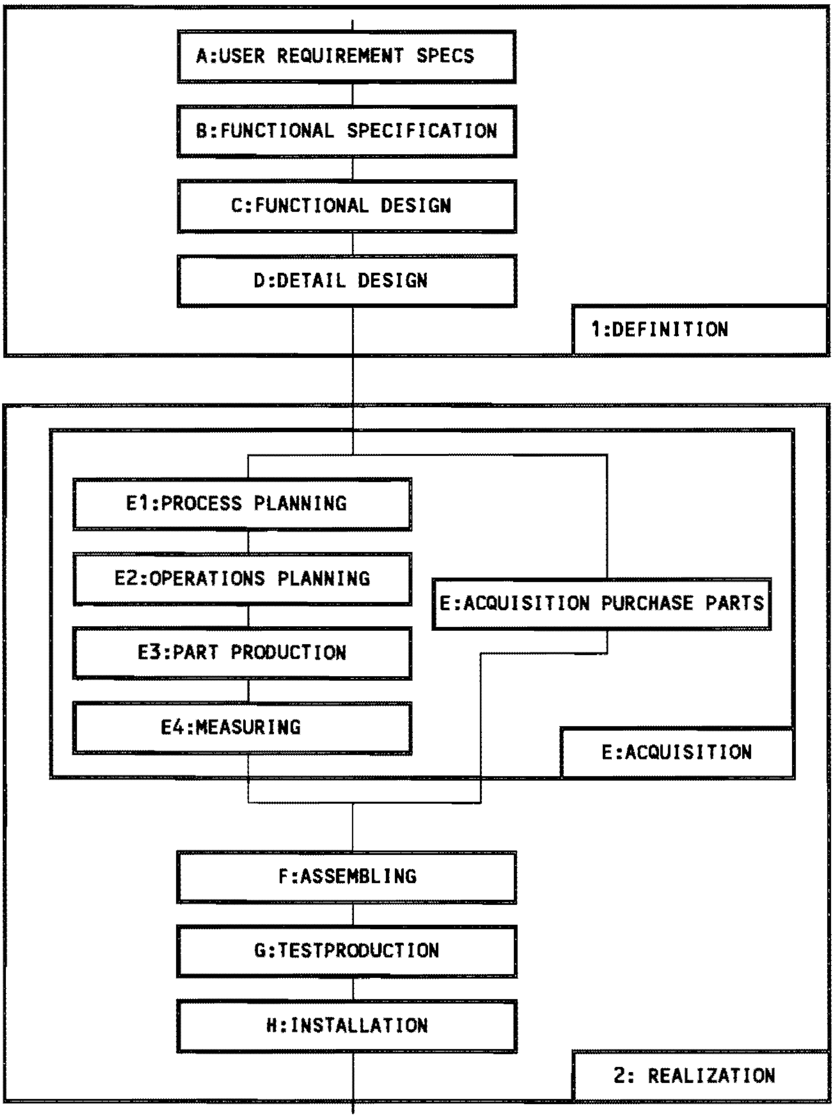


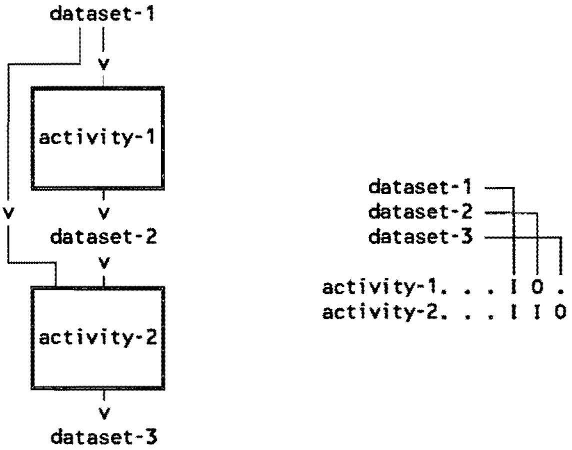
Fig. 2.3: A scheme of Design and Manufacturing

2.2 The Systematrix method

For analysing and restructuring of the design and manufacturing activities, the Systematrix method of C. Jäderlund [16] has been used. The Systematrix (SMX) method provide us with a technique for analysing activities, data sets and the relations between them. The results are documented in SMX matrices.

Software engineering is a young discipline. After a period of uncontrolled growth with sometimes disappointing results, a lot of effort has been done in structuring working procedures [17, 18, 19]. A software project usually starts with analysis of the present situation; secondly a restructuring of the process concerned is executed; finally software tools are generated for the restructured process.
The techniques used in software development fit perfectly in the goal of restructuring Design and Manufacturing process. Software development techniques gather functions and datasets and analyse the relations between them. Some techniques, like SADT [20], are focussed on the functions; others, like INFOMOD [21], concentrate on the data relations. SMX clarifies the relation between functions and datasets and supplies a graphical view on problem areas. This is exactly what is needed to restructure Design and Manufacturing.

The systemmatrix is a representation of activities and their inputs and outputs. Besides activities, inouts and outputs, SMX can document control functions, this part of SMX is not used in the present thesis. How a SMX matrix should be read, is illustrated by the example of Fig. 2.4.



(A) (B)

Fig. 2.4: A process presented in a flow scheme (A) and in a SMX matrix (B)

The matrix consists of rows for the activities and columns for the datasets. An element of the matrix represents the relation between the activity in the row and the dataset in the column. An element can have the value ., I or O, representing respectively no relation (.), the dataset is input for the activity (I) and the dataset is output of the activity (O).

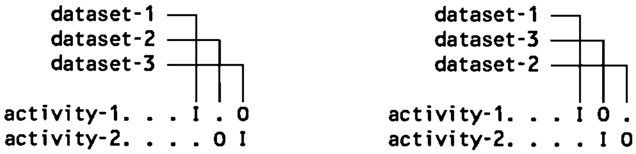
A matrix is created by collecting the activities and datasets of the process involved and relating the activities and datasets by defining input and output relations. By analysis of the matrix one can derive problem areas. These problem areas may be:

- wrong sequences,
- omissions, redundancy,
- feed back loops,
- unbalanced levels of detail.

These problem areas may be caused by a wrong analysis of the process, or there may be a problem in the process itself. In the first case, the analysis must be corrected; in the last case a restructuring of the process is required. Both cases will lead to a new matrix. These problem areas are illustrated in the following explanations.

Wrong sequences in a matrix

An example of a wrong sequence is given in Fig. 2.5 A.



(A) (B)

Fig. 2.5: A wrong sequenced SMX matrix (A) and the resequenced version (B)

The sequence of dataset-2 and dataset-3 in Fig. 2.5 A is wrong, because dataset-3 is required to create dataset-2. This can be recognized in the second row of the matrix where an I is at the righthand side of an O. After the datasets are resequenced, the right matrix appears (Fig. 2.7). In Fig 2.5 B, this matrix has been resequenced.

Omissions/ redundancy in a matrix

Omissions and redundancies may appear in activities or in datasets:

Activities

If an activity does not have an input, or does not have an output, there is an omission in the matrix. If no ommission can be found, there is something wrong with the activity, for instance the activity may be redundant.

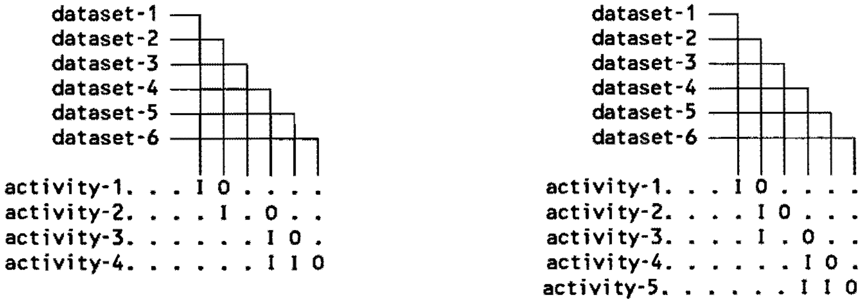
Datasets

If a dataset is not output of any activity, there is an omission in the matrix (e.g. an activity may be forgotten). If a dataset is not input for any activity, there is an omission, or the dataset is not relevant for the process described. Evidently, there is an exception at the beginning and the end of the process described:

- the process starts with datasets which are only input(s) at the beginning of the process; these datasets are output of a previous activity which does not belong to the involved process,
- the process ends with datasets which are only outputs; these datasets are relevant for succeeding processes.

For all other datasets, there must be both input and output relations.

In Fig. 2.6 A, one can see a problem with dataset-3, because there are no input or output relations. Another example is shown in Fig. 2.6 B, where dataset-3 has no input relation. In both figures dataset-1 has only an input relation, because it is output of a previous process. Dataset-6 is the final result of the present process, required for a succeeding process.



```
dataset-1
dataset-2
dataset-3
dataset-4
dataset-5
dataset-6

activity-1. . . I O . . . .
activity-2. . . . I . O . .
activity-3. . . . . . I O .
activity-4. . . . . . I I O
```

(A)

```
dataset-1
dataset-2
dataset-3
dataset-4
dataset-5
dataset-6

activity-1. . . I O . . . .
activity-2. . . . I O . . .
activity-3. . . . I . O . .
activity-4. . . . . . I O .
activity-5. . . . . . I I O
```

(B)

Fig. 2.6: Redundancy in matrices

Feed back loop in a matrix

A loop in a matrix is illustrated in Fig. 2.7 B. Activity-1 needs dataset-1 to produce dataset-2 and activity-2 needs dataset-2 to produce dataset-1. An example of a loop is the chicken-egg problem in Fig. 2.7 B: for breeding a chicken an egg is needed; for producing an egg a chicken is needed.

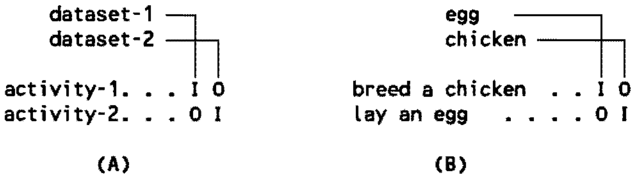


Fig. 2.7: A loop in a matrix

In most cases, loops in a matrix can be broken by redefining contents of activities and/or data sets. In some cases a loop is unavoidable. In those cases the remaining loop(s) must be covered by a good working method.

Unbalance in level of detail

Finally the level of detail between the different activities and datasets must be checked. This can be done by comparing the contents of the activities and the related datasets. In case one desires to go in further detail for a specific activity, a separate matrix for this activity may be made.

2.3 Restructuring Design and Manufacturing

Restructuring is based on the desire to decrease the logistic complexity of Design and Manufacturing. Reduction of complexity can be achieved by:

- decreasing the number of process steps,
- sequencing activities and datasets,
- decreasing feed back loops,
- decrease interaction between activities (decoupling),
- clear interfaces (clarity of data).

SMX is used as a tool for the analysis and optimization of Design and Manufacturing. The following aspects have been taken into consideration, when defining the new activities:

1. Application of CADCAM technology

   DfMASS has been designed for a cost effective implementation of CADCAM technology. Drawingless CADCAM applicability has been taken as criterium to find out whether a new, innovative approach for Mechanical Design based on CADCAM will harvest obvious economic results in business.

2. Data explicitness

   In conventional practice, the designer commonly produces the main lines of a design. A lot of decisions are implicitly given in sketches and documentation. The draftsman in his turn has to make them explicit during the detailing phase. Not always the draftsman understands the intentions of the designer. This leads to feedback loops and often to mistakes. In the following restructuring process, data explicitness has been a criterium in the clustering of activities.

From the analysis of Design and Manufacturing, a SMX matrix has been produced (Fig. 2.8). This matrix is based on CADCAM utilization, where the CADCAM file contains the design information (functional model, detailed model).

DATASETS

User specifications

System & assembly level

Functional system model
Functional assembly model
Critical purchase parts

Component level

Purchase part interface geometry
Functional component model
3D detailed component model
Additional purchase parts
Additional purchase part interface geom
Process plan
NC dataset
Component

System & assembly level

Assembly
Mechanical system

ACTIVITIES

	User specifications	Functional system model	Functional assembly model	Critical purchase parts	Purchase part interface geometry	Functional component model	3D detailed component model	Additional purchase parts	Additional purchase part interface geom	Process plan	NC dataset	Component	Assembly	Mechanical system
System & assembly level														
Functional system design	I	O	.	.	.	.	.	.	.	.	.	.	.	.
Functional assembly design	I	I	O	.	.	.	.	.	.	.	.	.	.	.
Selection of critical purchase parts			I	O		.	.	.	.	.	.	.	.	
Component level														
Add purchase part interface				I	O	.	.	.	.	.	.	.	.	.
Functional component design			I	.	I	O	.	.	I	.	.	.	.	.
Detailed modelling			I	.	I	I	O	.	I	I	.	.	.	.
Select additional purchase parts							I	O	.	.	.	.	.	.
Add additional purchase part interface								I	O	.	.	.	.	.
Process planning							I	.	.	O	.	.	.	.
Operations planning (NC programming)										I	O	.	.	.
Part production							I	.	.	.	I	O	.	.
System & assembly level														
Assembling of components			I	.	.	.	.	.	.	.	.	I	O	.
Mounting of assemblies		I	.	.	.	.	.	.	.	.	.	.	I	O

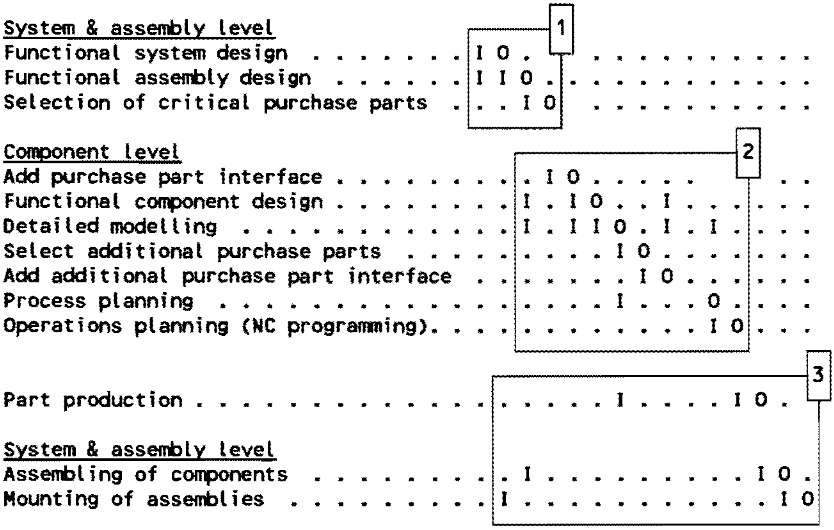
Fig. 2.8: SMX matrix of Design and Manufacturing

After analysis of the matrix of Fig. 2.8, the following six conclusions have been drawn.

Conclusion 1. **There are three main clusters of activities**
The matrix of Fig. 2.8 is split in three clusters of activities, mainly based on data explicitness (clear interfaces) between the clusters. These clusters are called:

1. Functional Design
2. Manufacturing Design
3. Realization

This clustering is based on the theory of Bertrand c.s. [22], who use production units (PU's) to divide Manufacturing in logical units. He clusters by the criteria: limited complexity between PU's, similar resources within a cluster. This principle is extended in this study to Design; resources have been translated in technology, experience, working procedures and tools, and skill. The clusters are presented in Fig. 2.9.



```
System & assembly level
Functional system design . . . . . . . I O .   . . . . . . . . . .
Functional assembly design . . . . . . I I O . . . . . . . . . . . .
Selection of critical purchase parts . . . I O   . . . . . . . . . .

Component level
Add purchase part interface . . . . . . . . . I O . . . . .       . .
Functional component design . . . . . . . . I . I O . . I . . . . . .
Detailed modelling . . . . . . . . . . . . I . I I O . I . I . . . .
Select additional purchase parts . . . . . . . . . I O . . . . . . .
Add additional purchase part interface . . . . . . . . I O . . . . . .
Process planning . . . . . . . . . . . . . . . . . I . . . O . . . .
Operations planning (NC programming). . . . . . . . . . . . . I O . . .

Part production . . . . . . . . . . . . . . . . . . I . . . . I O .

System & assembly level
Assembling of components . . . . . . . . . I . . . . . . . . . . I O .
Mounting of assemblies . . . . . . . . . I . . . . . . . . . . . I O
```

Fig. 2.9: Design and Manufacturing clustered

Functional Design (cluster 1) is a high level job for highly experienced, innovative designers. Selection of critical purchase parts is clustered in Functional Design for leadtime reasons, because Functional Design supplies the information for ordering these parts, while critical parts (specialties, small lotsizes, expensive) may take a long leadtime. Therefore, immediately after the Functional Design has been finished, ordering of these parts can already take place.
Manufacturing Design (cluster 2) requires another type of designers. Manufacturing designers do not invent functional solutions. They construct manufacturing com-

ponents by using the functional assembly model. During construction, they consider standardization, manufacturability and assembling rules. For splitting the functional assembly model into different manufacturing components, the designer needs to consider manufacturability. Therefore the activity "functional component design" has been assigned to Manufacturing Design. Adding the interface-geometry of purchase parts is clustered in Manufacturing Design, because the manufacturing designer knows which information of the purchase parts is needed for constructing the manufacturing components. The process planning is highly interrelated which detailed modelling and therefore integrated in Manufacturing Design.
Part production and Assembling are clustered, because they require workshop resources.

Conclusion 2. <u>Combine functional component design and detailed modelling</u>
In the first conclusion, functional component design has been assigned to Manufacturing Design and not to Functional Design. Apart from process planning information needed for detailed modelling, functional component design and detailed modelling use the same information (Fig. 2.10).

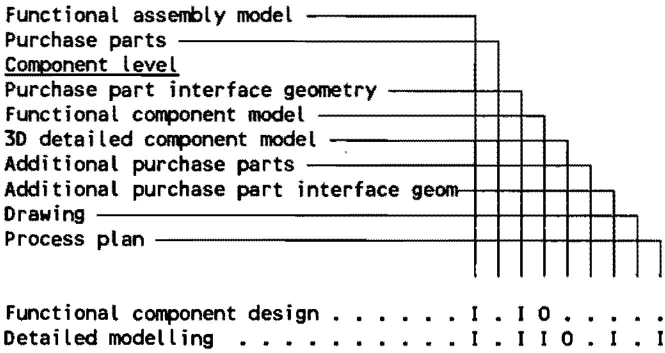
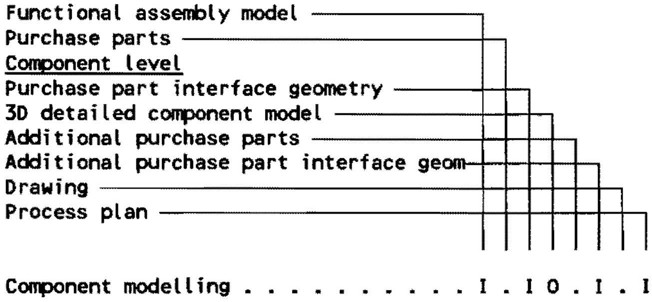


Fig. 2.10: The matrix before combining functional component design and detailed modelling

It is hardly possible to define a distinction between functional component design and detailed modelling: they are highly interrelated. Therefore functional component design and detailed modelling are combined in component modelling (Fig. 2.11).



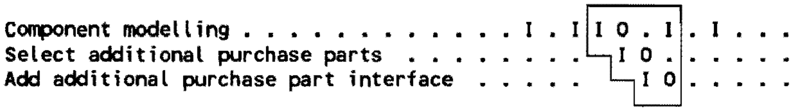
```
Functional assembly model
Purchase parts
Component level
Purchase part interface geometry
3D detailed component model
Additional purchase parts
Additional purchase part interface geom
Drawing
Process plan

Component modelling . . . . . . . . . . . I . I O . I . I
```

Fig. 2.11: Component modelling replaces functional component design and detailed modelling

Conclusion 3. Component modelling and selection of additional purchase parts are in a loop

For component modelling one needs to know the details of purchase parts (eg. bolts, axes). For selecting these purchase parts, one need to know the component model. Conclusion: selection of additional purchase parts is in a loop (Fig. 2.12). These activities are highly interrelated and therefore they must be executed by a single designer.

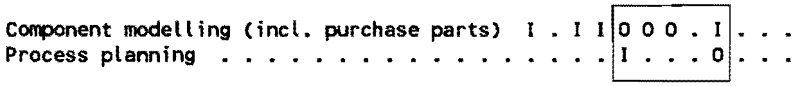


```
Component modelling . . . . . . . . . . . . . I . I I O . I . I . . .
Select additional purchase parts . . . . . . . . . I O . . . . . .
Add additional purchase part interface . . . . .    I O . . . . .
```

Fig. 2.12: The loop in selecting in additional purchase parts

Conclusion 4. Component modelling and Process planning are in a loop

For component modelling, considering manufacturability, one first needs to have the process plan, otherwise one can not consider the set-up configuration, stock material, machine tool characteristics during modelling. For creating the process plan, one needs to know the detailed geometry model. Hence, there is a loop between component modelling and process planning (Fig. 2.13).



```
Component modelling (incl. purchase parts)  I . I I O O O . I . . .
Process planning . . . . . . . . . . . . . . . . . I . . . O . . .
```

Fig. 2.13: The loop between component modelling and process planning

This loop can be avoided by splitting up the activities in sub-activities. This restructuring of modelling and process planning is the most important aspect of the present thesis. By defining the activities preliminary modelling and preliminary process planning, the loop is broken (Fig. 2.14). These activities are highly interrelated and therefore they must be executed by a single designer.

```
Preliminary modelling . . . . . . . . . . . . I . I I O . . .
Preliminary process planning  . . . . . . . . . . . I O . .
Modelling . . . . . . . . . . . . . . . . . . . . . . I O .
Process planning  . . . . . . . . . . . . . . . . . . . I O
```

Fig. 2.14: The new situation: preliminary modelling, preliminary process planning, modelling and process planning

Conclusion 5. Operations planning (NC programming) can be avoided
If the process planning is known and the component model has been defined by standard shapes for which NC datasets can be generated automatically (see form feature functionality in Chapter 3), NC programming is no longer a human activity.

Conclusion 6. Measuring can be minimized
In drawing-based practice the dimensions of the produced part need to be checked, because the manufacturer may have made mistakes, while interpreting the drawing. In DfMASS, the NC dataset is directly generated from the design model without interpretation. Therefore, the only remaining reasons for measuring are:

- interference between operations (vibrations, bending),
- plastic deformations during part production,
- operator errors.

In most cases, supported by proven technology, one can be confident that the produced part meets the requirements without measuring. The quality assurance of automated NC programming normally appears to be high enough to reduce measuring to a minimum. Only in special cases, one needs to measure (intermediate) results.

2.4 From drawings to "Product model" database

The DfMASS approach intends to replace drawings by electronic datafiles. This change of information-medium has a great influence on the working methods[1].

Four restricting characteristics of paper-based designs did have a great influence on the conventional working methods:

1. Paper is located on one single place

   To make drawings available on different places, copies are made. It is hardly feasible to replace all copies of a drawing, in case of changes somewhere in Design. This problem is tackled by complex engineering data management systems.

2. Papersize is limited

   To keep paper manageable, the maximum size of paper is restricted (normally maximum A0 size). Another restriction is the minimum linewidth on the paper. A line width of less than 0.2 is hardly drawable. Scaling is used to overcome these restrictions. If information does not fit on a single sheet, the subject is divided over more sheets. One has to collect all sheets, to get an overview of the total subject.

3. Paper allows only a two dimensional representation

   A drafting procedure has been defined to represent 3D subjects on 2D paper. For experienced people it is easy to read these drawings, however it still takes time to interpret the views and people make mistakes in reading drawings. In Design, Manufacturing and Assembling, drawings are read many times by a lot of people. Each drawing consultation leads to a translation process in the human brain.

4. Changing drawings is timeconsuming

   Drawing changes often require a lot of scratching out and redrafting. Sometimes, designers avoid this activity and adjust their design to a

---

[1] An analogy to illustrate the difference in approach by changing the medium is the introduction of advertisements on television. It has had a great influence on the marketing of products.

minimum of scratching. It may be evident that this practice does not support the primairy design goals.

Replacing drawings by electronic datafiles avoids these restrictions. In the meantime the following advantages are gained:

1. Single sourcing, with multi-entry possibilities

   All people involved use the same source of information. Information changes are immediately available to all its users.

2. Information (entities) can have mutual relations

   All information is available for consultation in different queries, because the total product data is available in relational databases[1].

3. Three Dimensional model of the design

   CAD supplies a better model of the reality than drawings. Geometry is defined in three dimensions. The designer can "walk around" the subject from each viewpoint.

In Functional Design, the 3D model consists of functional entities linked together in a system layout. In Detail Design, all geometry details are added to the 3D model. During process planning, the process plan is added to the 3D model. In fact all these datasets are views on the same database: the "Product model" database:

The "Product model" database consists of related computer files, storing all product information. It contains the functional system model, the functional assembly model, the purchase part interface model, the functional component model, the preliminary process plan, the 3D model and the process plan.

---

[1] Total system overviews without details, all details of components, relations between entities, design sketches, purchase information, manufacturing instructions, maintenance procedures, this information can all be stored in a single electronic source.

2.5 DfMASS

From the conclusions drawn in Section 2.3, a new flow scheme of Design and Manufacturing is derived, which is presented in Fig. 2.15.

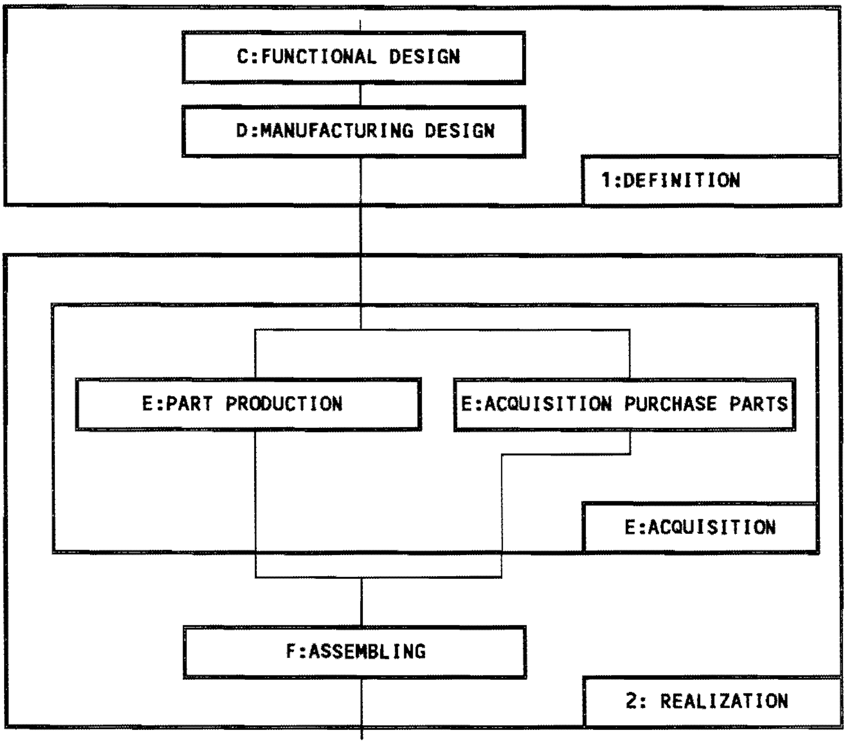


Fig. 2.15: The new scheme of Design and Manufacturing

The approach has been named 'Design for mass production', which is explained by the following statement:

> To realize mass production[1] in Manufacturing, all technological decisions are removed from Manufacturing and re-assigned to Manufacturing Design. Consequentially, Manufacturing is transformed into a production process, having the aspects of mass production.

[1] Mass production is producing in quantity, usually by machinery. In DfMASS the term is used when large quantities can be produced (manufactured) without human intervention in the primary manufacturing process, except for preparation of material and tools and activation the input data at the start of the process.

In Fig. 2.16 a comparison is presented between Design conventionally and by the DfMASS approach. Comparing Design conventionally and DfMASS, Functional Design generally keeps the same contents, although Functional Design in DfMASS is executed by CAD techniques. Conventionally, Detail Design contains modelling and drafting. DfMASS replaces Detail Design by Manufacturing Design, consisting of modelling and process planning.

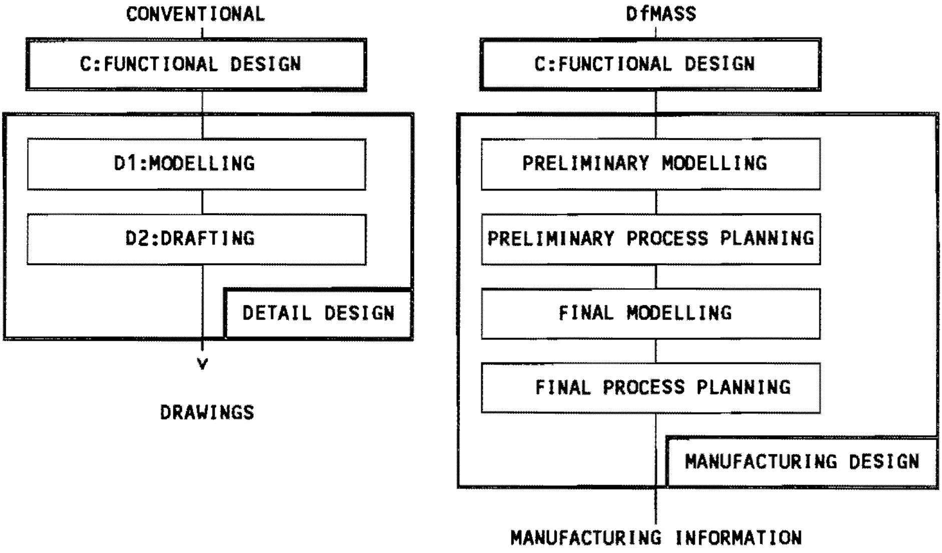


Fig. 2.16: The difference between Design conventionally and DfMASS

In Fig. 2.17, the difference between Manufacturing conventionally and Manufacturing by DfMASS is presented. This difference has major consequences for Manufacturing, which is discussed in Chapter 6.

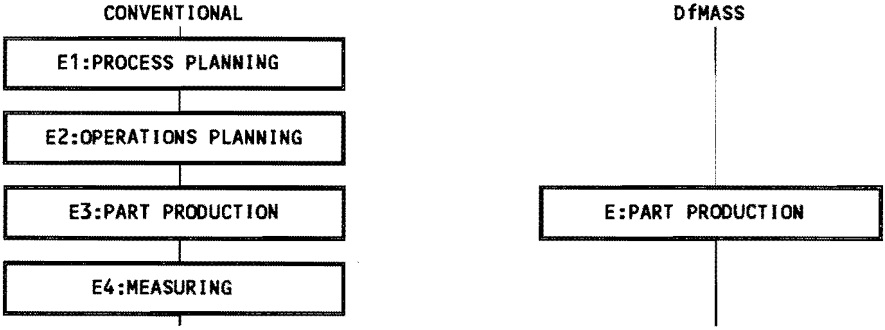
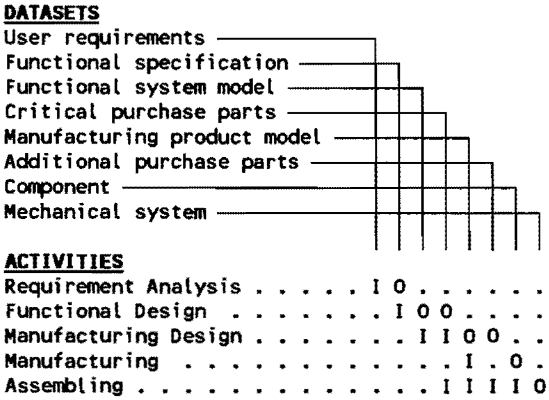


Fig. 2.17: Manufacturing conventionally and Manufacturing by DfMASS

SMX has been used to describe in detail the activities and datasets of DfMASS. In Fig. 2.18 the SMX matrix of the overall process is given. In Appendix C, the SMX matrices of the underlaying activities are described.



DATASETS

ACTIVITIES	User requirements	Functional specification	Functional system model	Critical purchase parts	Manufacturing product model	Additional purchase parts	Component	Mechanical system
Requirement Analysis	I	O	.	.	.	.	.	.
Functional Design		I	O	O	.	.	.	.
Manufacturing Design			I	I	O	O	.	.
Manufacturing					I	.	O	.
Assembling				I	I	I	I	O

Fig. 2.18: SMX matrix of the overall DfMASS process

2.6 Summary

Based on the flow scheme of Design and Manufacturing conventionally (Section 2.1), using the analysis method SMX (Section 2.2), a restructuring of the design and manufacturing activities have been taken place in Section 2.3. The result is a new, drawingless design and manufacturing approach, which is described in Section 2.5.

For this new approach, a new working method is developed, which is described in Chapter 4. This working method require supporting software tools, which are firstly described in Chapter 3.

3. FAST-CADCAM

Introduction

For implementing DfMASS, extra software functions, called FAST-CADCAM, have been developed, because they are not yet available in commercial CADCAM packages. The greater part of FAST-CADCAM has been realized by application software written by the Philips Lighting CADCAM group [23]. Some functions however have not been programmed in software, because of the high costs involved, or because it can only been realized by the source owner of the CADCAM system[1]. For the time being, they are replaced by working methods. Without FAST-CADCAM functions, process planning and NC programming would have been complex and timeconsuming. In Fig. 3.1 the structure of the present chapter is illustrated.

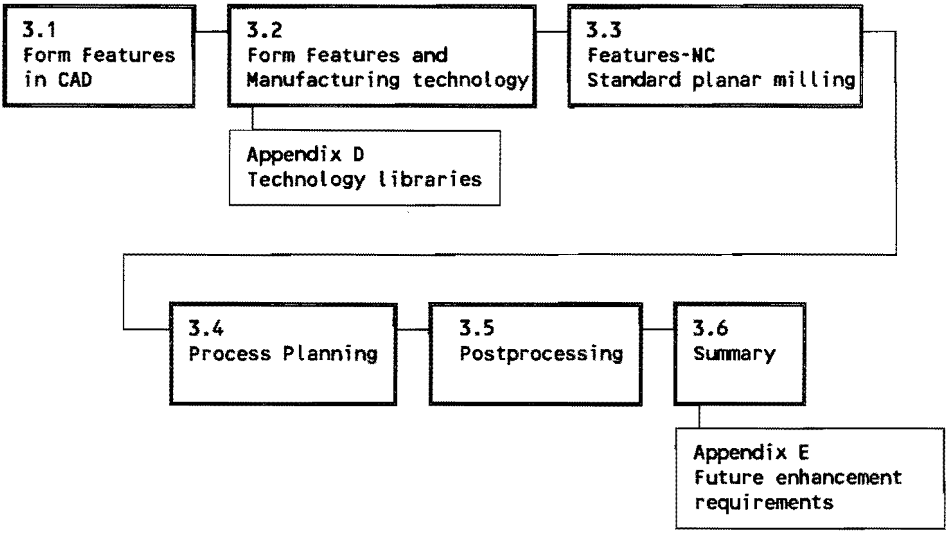


Fig. 3.1: Structure of this chapter

---

[1] Discussions have been started with the source owner to bend CADCAM development in the direction of FAST-CADCAM [24, 25]. There are indications, that the CADCAM vendors will supply these type of functions (machinable form features, technology databases, automated NC programming) in the near future. They will be forced to do it, because all new functionality in CADCAM systems will increase the possibilities, but on the other hand, it will also increase the amount of information needed to specify NC operations. If this new functionality is not companioned by generators for standard solutions and automatic data generation, CADCAM will become a very complex and timeconsuming activity.

A lot of studies present a theory on the automation of manufacturing activities in small lotsize environments.

Delbressine [6] gives a good impulse on the integration of Design and Manufacturing by designing with manufacturable objects. It is based on the idea of bringing back manufacturing decisions to the designer. This theory covers the design activities starting at the level of component design and ending with a NC dataset.

Hummel c.s. [26] describes an architecture of an automated process planning system, based on feature recognition by the process planning system.

Ferreira c.s. [27] describes a model of activities, which should be adressed by a process planning system and the relationships between them. This model is to serve as a reference in development efforts. The activities are Part Understanding, Process Selection and Ordering, Machine Tool Selection, Set-up Planning, Operation Planning

From 1975, Philips has been involved in writing software for feature manufacturing [28]. Partially successful, it lacks the complete functionality for integral implementation. Extending it to a complete CADCAM system requires to many resources.

Van 't Erve [3] has created a software package for automatic process planning. Again the ideas are good and have been considered in this study, but an implementation in practice is still a big problem. He does not actually ask the designer to consider manufacturability. Therefore the manufacturability will stay within the limits of the already designed geometry, without a feed back from manufacturing considerations.

His successor in research, Van Houten [5] succeeded in building an extensive implementation, however, still its applicability is restricted to a very small area of manufacturing components.

Chang [29] has built an expert process planning system. Again the manufacturability restricted by the defined geometry. There is no feed back on manufacturability to the designer.

Nolen [30] gives an overview of the state of the art, with promising try outs. He introduces part families in Design, which already have a process planning, but he does not start with process planning during Design.

Goodman [31] describes the RAMP project at the US Naval Supply Systems Command, which stands for Rapid Acquisition of Manufactured Parts. The aim of RAMP is the electronic storage of designs, which can be retrieved rapidly. The format of the geometry is based on features.

Some of the aforementioned studies also contain a worked out software package to prove the theory, but these software packages do not cover the total required CADCAM functionality for an industrial implementation from Design to Manufac-

turing. The commercial CADCAM packages on the other hand do not supply enough functionality to implement these kind of theories.
Therefore DfMASS is based on a commercial CADCAM package and completed with the required functions. The mentioned studies have been used as input for specification of these extra DfMASS functions.

The strategy will be shown to the reader in this chapter. The results are supported by the results of the restructuring process in Chapter 2. It has been chosen to merge process planning into geometric modelling and not to use feature recognition systems or process planning generators, but to introduce manufacturability considerations directly in Design.

3.1 Form features in CAD

In the early days of CAD for Mechanical Design at Philips (1987), we have been trying to increase cost-effectiveness by standardisation of design methods and by libraries of standard parts (Fig. 3.2). Success was limited, because the new design methods did not decrease design and drafting costs sufficiently. The standard libraries functioned (and still do), but a lot of non-standard components are needed to meet the design requirements. Another approach was needed to increase the applicability of CAD.

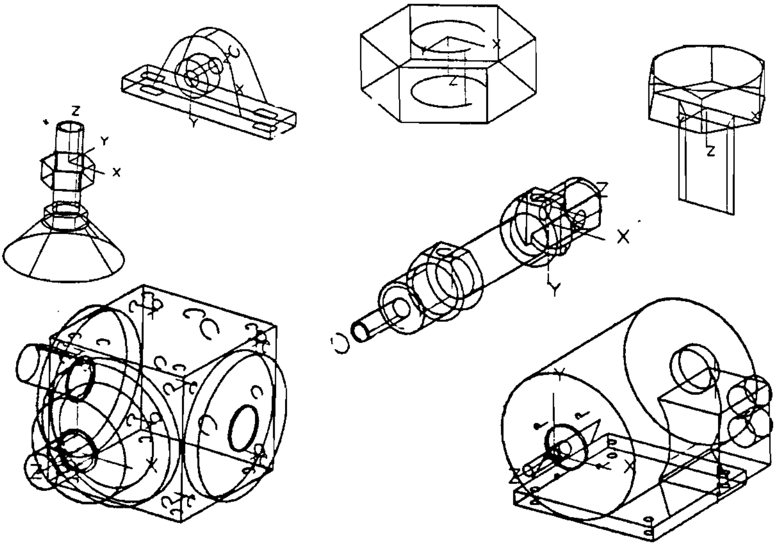


Fig. 3.2: Standard components

A next level of standardization, form features, was developed in 1988: "If you can not use standard components, use standard shapes in the components". The first set of form features, which was developed, were holes. A hole is a manufacturing shape, which is mainly manufactured by rectalinear operations (drilling, boring). The geometry of a hole is defined by parameters. Asymmetric tolerances are defined by the parameter values. By a menu-driven user interface, the designer can choose a hole type, he will be asked for positioning the hole in the product model. Next he is asked to add parameter values by which the feature is completely defined. The applied types of holes are shown in Fig. 3.3.

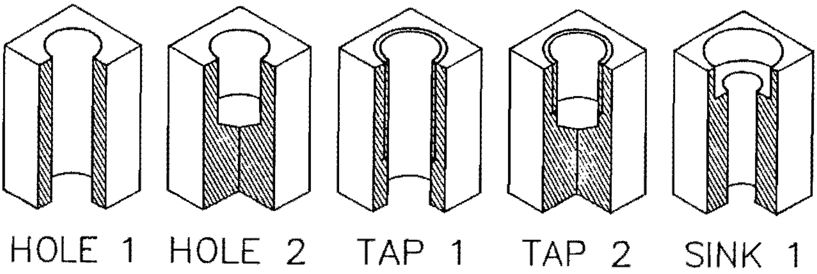


Fig. 3.3: Holes

In first instance, the holes have been applied in geometric modelling. Still working with drawings, the form feature functionality supplied functionality for creating the drafting and dimension entities of the form feature automatically (Fig. 3.4).

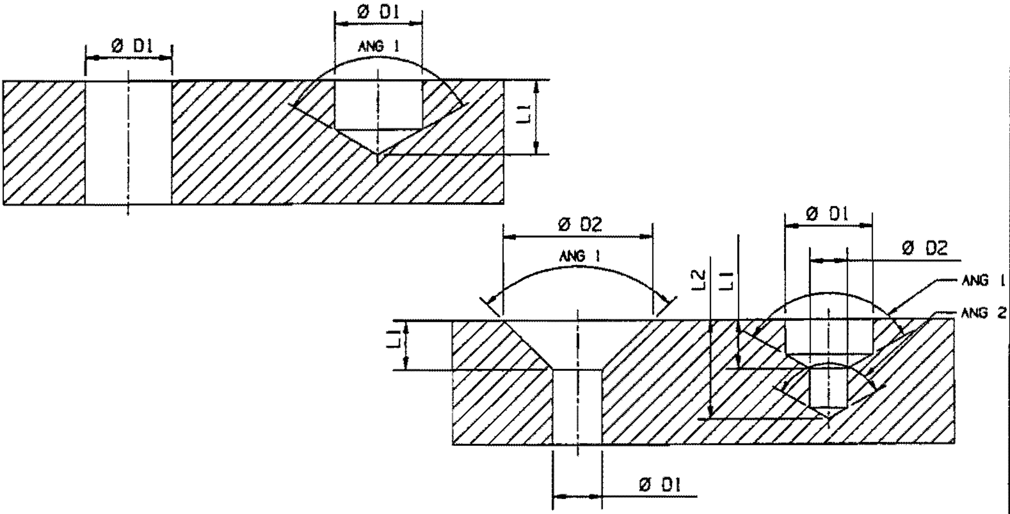


Fig. 3.4: Drawing generation by parameterized form features

A next step in form feature development were pockets (Fig. 3.5).

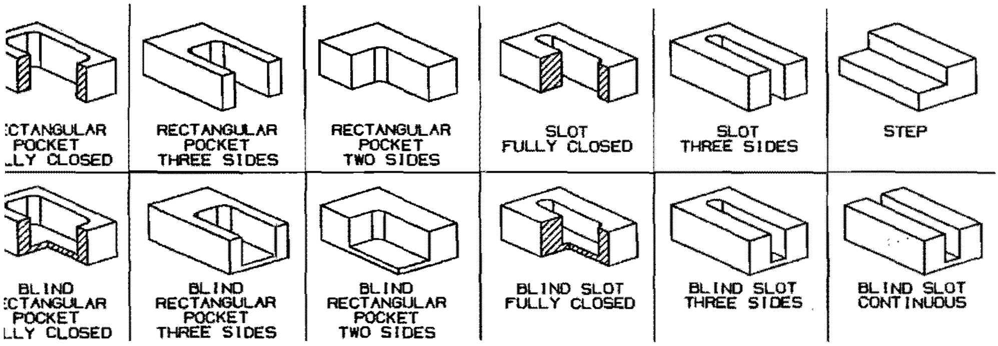


Fig. 3.5: Pocket features

By having holes and pockets, it was possible to construct components by only using form features. In Fig. 3.6 a feature decomposition of a part is illustrated.

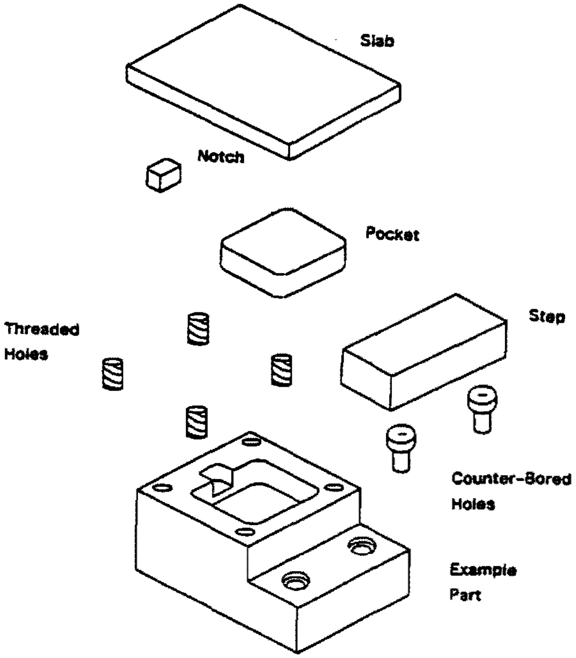


Fig. 3.6: Feature decomposition of a part

The features have been defined from a manufacturing point of view. From the start of form feature development it was intended to extend the functionality to automatic generation of NC-datasets (automatic NC programming). There is a lot of discussion on the way form features should be defined and used [32, 33, 34]. Shah [43] has the opinion that the designer should not be focussed on considering manufacturability. However no commercial CADCAM systems are currently available, which supply a broad CAD and CAM functionality and transform design features into manufacturing features. Besides, it is doubtful whether a designer will produce manufacturable designs without being confronted with the manufacturing consequences of his decisions. Therefore, in DfMASS the set of features has been focussed on manufacturability. The following hypothesis has been formulated: "A limited set of manufacturing features will supply sufficient functionality for modelling mechanical components". Practizing this hypothesis, it appeared that only in exceptional cases it was required to use non-standard geometry. In applying standard values for the feature parameters (length, diameter, etc.), it has also been demonstrated that exceptions were rarely needed to meet the functional requirements. The features parameters have been standardized by offering ranges of default values to the designer by computer menus.

While using the form features, a problem appeared in using the pockets. Complex shapes had to be constructed from a combination of simple features. This appeared to be a difficult way of modelling, compared to free modelling by standard CAD functionality (Fig. 3.7).

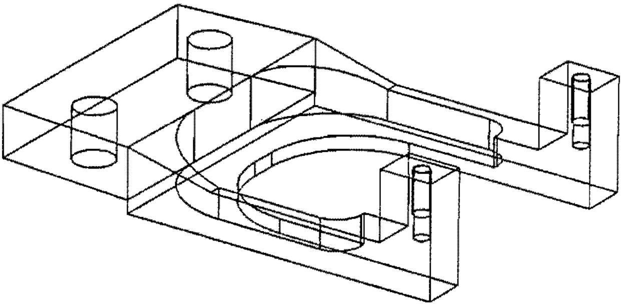


Fig. 3.7: A complex shape, constructed by standard pockets

Besides the modelling problem, a first try-out of a automatic generation NC-datasets from form features [37-1] showed the following problem for complex shapes constructed by standard pockets. For each standard pocket a milling operation was defined to manufacture the shape. In the areas of overlapping pockets, several milling operations were overlapping, which introduced inefficiency in Manufacturing.

To avoid these problems, a more flexible feature was introduced, which has been called the "boundary feature". Standard CAD functionality can be used to construct boundary features. A boundary feature (Fig. 3.8) consists of a boundary and a depth. The boundary lies in a flat plane, the boundary plane. The bottom of the pocket lies in a flat plane, parallel to the boundary plane.

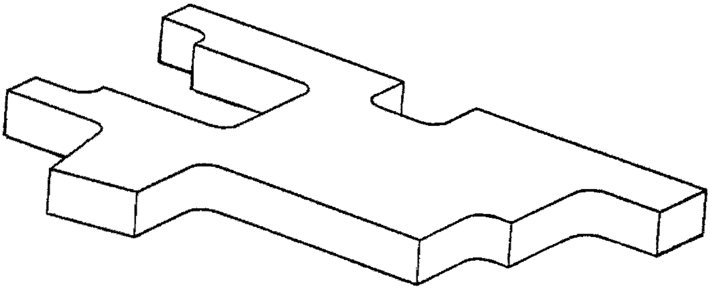


Fig. 3.8: An example of a boundary feature

The boundary[1] of the boundary feature is defined by selecting geometry entities, which have been generated during modelling (lines, arcs, splines). The standard boundary functionality of the CADCAM system is used to define the boundary.

3.2 Form features and manufacturing technology

Although limited to CAD only, form features decreased the modelling and drafting effort substantially. Form features also supplied an efficiency increase in Manufacturing, due to the standardization aspects. However above reductions were not sufficient to reach a cost-effective CAD application.

This problem was mainly caused in the drafting area, where the man hour rate was heavily increased by CAD costs. A lot of effort has been made to increase drafting functionality and to reduce the hour rates of drafting stations. From an investigation in the industry, it appeared that other major companies had the same CAD problems in Mechanical Design of small lotsize systems [48]. It has been concluded that the CAD implementation needed to be extended to CAM. An internal investigation showed the need for integration of CAD and CAM activities [52]. An orientation on

---

[1] A boundary is a chain of entities, lying in a plane.

the implementation of CADCAM in comparable situations (small lotsize mechanical systems) in 1988 [36], supported the idea to extend form feature functionality to CAM, especially to enlarge manufacturability in Design.

A logical step in decreasing costs was avoiding drawings. It was possible by form features, because all information required for Manufacturing has been defined in the form features. An interface was created to transmit CAD data to a CAM system. The CAM system supplied computer aided process planning and computer aided NC programming. This experiment showed another problem. The adjustment of the CAM system to the CAD system was not ideal. A lot of manual input was needed to derive NC datasets from the form features, by which the total system was still too expensive. The interface between CAD and CAM appeared to be a roadblock:

- CAD modelling was not restricted to the constraints of the CAM system,
- changing geometry in the CAD system afterwards, required to re-start the CAM process from the beginning.

Therefore it has been decided to develop an integral solution in which Design covers both the CAD and CAM stages [53]. From a market search on feature based CADCAM systems, no suitable systems were found. Therefore it was decided to develop form feature software (FAST-CADCAM), using the standard CAD and CAM functions of the Unigraphics system. The main objective of FAST-CADCAM functionality was an automatic generation of NC datasets for form features.

To generate NC datasets for the form features, technology and tool data is needed. Software functions have been built for automatical derivation of technology and tools for the manufacturing of the form features. Technology is dependent on the shape, quality and properties of the feature to be produced[1]. Tool data are related to the technology data.

In Manufacturing conventionally, choices are made by the individual craftsman. In many cases it differs per workshop and even per person. Therefore it is seen as a difficult area for automation[2]. However this is an organizational problem. One reason for individualism in technology is the wide range of available machine tools, tools and manufacturing methods. Another reason is the pride of the craftsman, to

---

[1] In cases where the manufacturing of a feature is influenced by another feature, the technology is dependent on both features.

[2] Theoretically the logic of a technology and tool database for automated NC programming is not very complex. In practice however the exceptions dominate the rules. Therefore there are not many systems which operate satisfactory without human intervention.

do things better than his colleague. To be able to automate NC programming, it is essential to convince the organization to introduce standardization in machine tools, tools, technology and standardized quality of the manufacturing components.
The technology libraries contain the technology from which the automatic operations planning of form features is derived. In Fig. 3.9 the different databases and attributes are illustrated. In Appendix D, the basic attributes of the technology libraries are described, as well as the inter-relating structure.

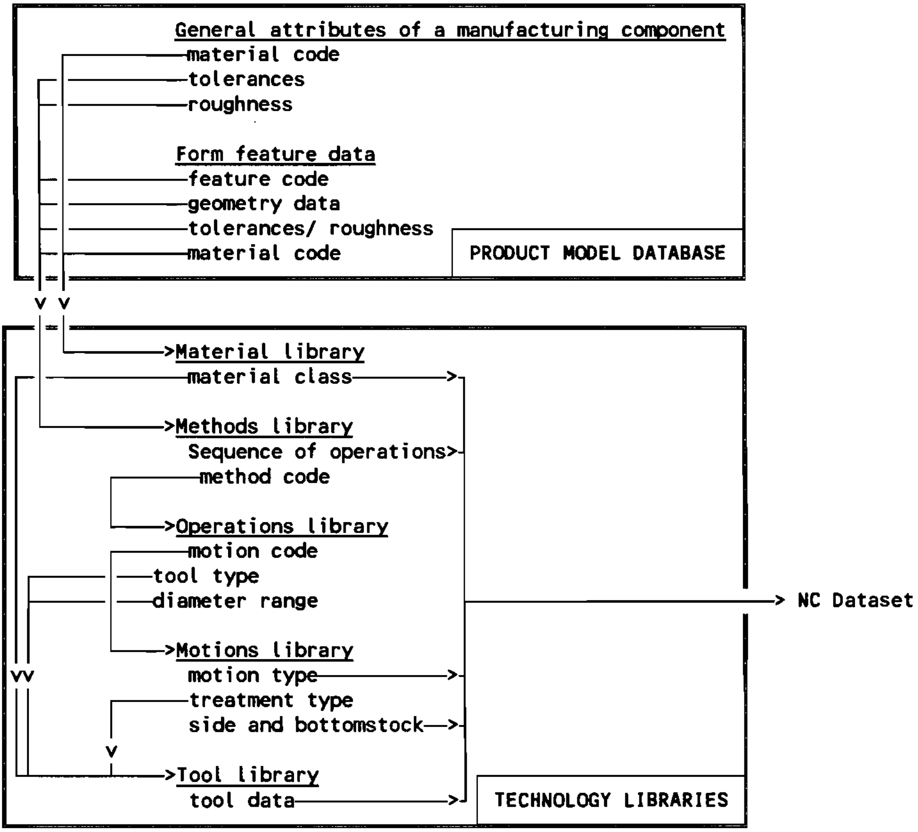
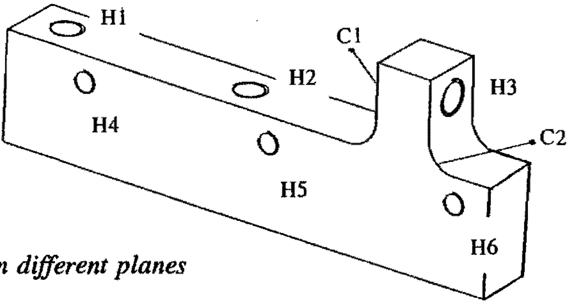


Fig. 3.9: Scheme of the relations between the product model and the described technology libraries

The libraries have been filled by standard technology, derived from literature. Later on it has been speeded up based on workshop experiences. Putting a large effort in optimization of technology appeared to be profitable in the case at Philips Lighting, because each optimalization is fruitful in all future manufacturing operations.

3.3 Automatic NC programming

The automatic creation of NC datasets is realized by three software programs, NC-setup, Features-NC and Standard planar milling [23]. This functionality is automated up to a certain level. Especially the sequence of manufacturing features still requires human interference. From a study on automatic sequencing of features at the Technical University Eindhoven [37-4], quite some problems appeared, especially between related features which lie in different planes (Fig. 3.10).



Before H1 and H2 in the
top surface and H3 in the
side surface can be manufactured,
the contours C1 and C2 in the
front surface need to be produced.

Fig. 3.10: Related features, lying in different planes

NC-SETUP

Before starting to generate NC datasets per feature, the different manufacturing planes must be defined. By the NC-SETUP program, the manufacturing planes are defined. NC-SETUP also adds a view per manufacturing plane to the CAD database. A view is a certain focus on the geometry, set by view coordinates (the direction from which the user looks to the geometry) and a scaling factor. Views are used for displaying the manufacturing plane in the right orientation and scale on the screen. In Fig. 3.11, an example of manufacturing planes is given.

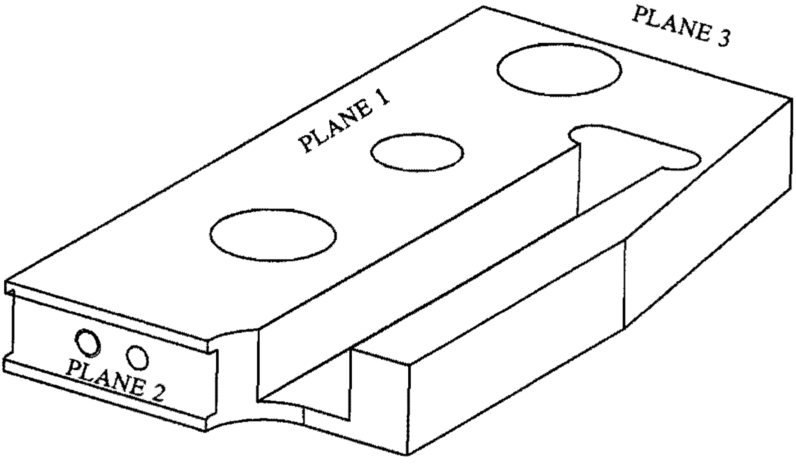


Fig. 3.11: Manufacturing planes of a component

In PLANE 1 of Fig. 3.11 the contour is manufactured and the holes and pockets in the top plane. In PLANE 2, the slot and the two holes are produced. In PLANE 3 the (non visible) holes in the back plane are manufactured.

FEATURES-NC

FEATURES-NC is a software program to create NC datasets for holes. The user is asked by the program to select a set of features (holes). The computer automatically selects tools and calculates the tool paths, using the technology libraries. The NC datasets are sequentially added to the present NC file. By editor functions, the user is able to combine NC files, or change sequences in the NC file by moving blocks of data.

STANDARD-PLANAR-MILLING

The STANDARD-PLANAR-MILLING program generates the operations required for manufacturing boundary features. STANDARD-PLANAR-MILLING uses the technology libraries. First the user indicates the boundary of the feature. Next he enters the depth of the boundary by selecting a line of the side surface of the pocket. The selection of the manufacturing method (follow pocket, profile; rough, finish, face milling) is presently user defined. Further on, the user enters the clearance plane distance. He indicates on which side of the boundary (inside or outside) the feature lies and enters side- and bottom-stock. Side- and bottom-stock values are used to indicate the asymmetric tolerances of the pocket, or to leave material for the next operation. The computer suggests a tool choice and step sizes, which suggestion may be adapted by the user. The selection of the type of motion (zig-zag, clearing, contouring) is entered manually.

Free geometry

If shapes can not be defined by features, standard CAD functions can be used to define geometry. By standard CAM functionality these shapes can be transferred into NC datasets. The existing technology libraries are used to derive technology data.

FEATURES-NC, STANDARD-PLANAR-MILLING and standard CAM functionality can be used in various combinations. By a specific order of combinations, a specific sequence of operations can be achieved, due to the required structure of the manufacturing operations. This subject will be explained in Section 3.4.

3.4 Process planning

Working with form features and deriving NC datasets for them by FEATURES-NC and STANDARD-PLANAR-MILLING, reduced the amount of errors and the required time for NC programming substantially [38]. However in practice, the manufacturability of the designed components was still poor (beginning 1991). The application of form features was a usefull functionality in Design, but still manufacturability was lacking, due to the arbitrary positions of form features in the model. The features were placed, without considering the set-up configuration, even on places where the process planner needed space for fixturing. This lack of considering manufacturability leaded to many set-ups required. A next decision was made, which in fact is the most important one of this study: the merging of process planning into geometric modelling.

The process planning consists of a fixturing configuration and the structure in which the different tasks are executed during Manufacturing. In DfMASS, this structure is called the manufacturing task structure. The manufacturing task structure defines the structure in which the manufacturing tasks will be executed. A manufacturing task itself contains sequences of operations. The manufacturing task structure has a close relation with the stock material characteristics[1] and with the set-up configuration[2]. An example of a manufacturing task structure is given in (Fig. 3.12).

1. Face milling of top plane		1a. rough 0.2 mm bottom stock
		1b. finish 0.0 mm bottom stock
2. Contouring side surfaces		2a. rough 0.5 mm side stock
		2b. finish 0.2 mm side stock
		2c. finish 0.0 mm bottom stock
3. Pocket milling	pocket no.1	3a. rough 0.5 mm side stock
		3b. finish 0.2 mm side stock
		3c. finish 0.0 mm side stock
4. Drilling hole	hole no.1	4a. countersink drill
		4b. drill
5. Reaming hole	hole no.2	5a. countersink drill
		5b. drill
		5c. bore
		5d. ream

Fig. 3.12: An example of a manufacturing task structure

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[1] E.g. if the stock material is too wide, an extra operation is required to cut the side surface.

[2] For instance if a hole in the side surface can not be manufactured by a horizontal operation, because the fixturing devices obstruct it, another set-up is required to manufacture the hole, or another fixturing solution need to be found.

Currently, there is no functionality in the applied CADCAM system to merge task structure information in the product model database. The sequence of tasks can only be entered in CADCAM system by the order in which the tasks are generated. The generation of manufacturing task structure is realized by the sequence of applying FEATURE-NC, STANDARD-PLANAR-MILLING and standard CAM functions. Changing the process plan afterwards can be done in three ways:

a. changing an operation[1],
b. deleting the entire NC file and re-start from the beginning,
c. adding NC statements, which will automatically be placed at the end of the file, secondly moving them by the editor.

Unfortunately, it has not been possible for Philips Lighting to write software to obtain the required functionality, because a change of the internal datastructure of the CADCAM system is required[2]. Therefore, the philosophy of using a manufacturing task structure has been implemented as a working procedure. The designer needs to define the structure on paper. The lack of manufacturing task structure functionality in the CADCAM system is not a fundamental problem. It is expected to be developed in one of the next future releases.

The manufacturing task structure has a close relation to the set-up configuration. A set-up is a fixed position of the material relative to the machine tool. To obtain a fixed position, a fixturing configuration is required, by which fixtures the material will remain at position during manufacturing. To assist the manufacturing designer, and to stimulate him to use standard fixtures, a fixtures library has been built. This library contains the available fixturing tools (Fig. 3.13). Of course if special devices are unavoidable, they must be applied. These devices need to be selected, or specially designed and brought into the product model database.

[1] This can be done by selecting the operation, by entering its number and changing paramater values. The system automatically updates the related NC statements, without changing the order of operations.

[2] The lack of manufacturing task structure functionality in the CADCAM system is not a fundamental problem. It is expected to be developed in one of the next future releases.

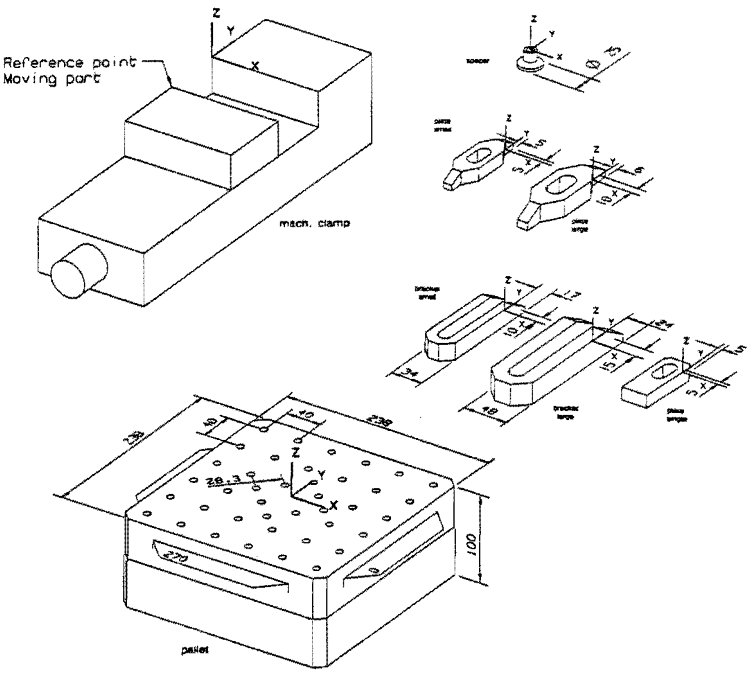


Fig. 3.13: Standard fixtures in the fixtures library

3.5 Postprocessing

The NC file, as generated by FEATURES-NC, STANDARD-PLANAR-MILLING and by standard CAM functions, is a common file, not specific for a type of machine tool. Except, in this NC file already some characteristics of the machine tool configuration have been assumed, like the presence of a horizontal spindle, or a turn table. Main functionality of the post processor is the transformation of NC file into specific machine tool control commands. Besides this main function of the postprocessor, the following functionality improves the functionality and flexibility of the FAST-CADCAM system:

Generate standard headers and trailers for the NC file

The NC file need to be completed with header and trailer statements, like zero-point (de-)activation, start setttings, programmers name, creation date.

Optimization of NC execution

In many situations, it is allowed to resequence the operations of the different tasks as long as the internal order of each sequence of operations of each task is not altered. An example is combining countersink drill operations of the different tasks in a single countersink drill operation. This combination reduces the required number of tool changes. Resequencing is important to optimize the NC dataset, to create minimum tool changes and minimum tool path lengths.

Automatic calculation of turntable rotation and spindle change

(from horizontal to vertical and vice versa)

By the given position of the turn table and the spindle and by the orientation of the manufacturing plane, the CADCAM system is able to calculate the required turn table rotations and spindle changes. Mistakes, which regulary occur in manual calculation of the required turn table rotation, are avoided by this automatic function.

Generate tool changes, turn table rotations

In case an automatic tool changing device is specified, a tool change command must be generated, if another tool is required. In case tool changing is manual, a stop must be generated. In case a controlled turn table is used, a turn table rotation command must be generated. In case a manual driven turn table is used, a stop must be generated.

Optimize tool changes versus turn table rotations

In case a controlled turn table is specified, the sequence of operations must be optimized by minimizing tool changes. In case only a tool changing device is specified (thus no controlled turn table), the sequence must be optimized by minimizing turn table rotations. In last case, a manual driven turn table device can be used to perform the required rotations of the material.

Generation of output formats

The postprocessor is able to generate machine tool dependent NC datasets. It is also possible to generate neutral formats to communicate with other postprocessors. This function is required in sending NC datasets to external workshops which have their own postprocessor systems. A neutral format can be APT or ISO.

The postprocessor as information supplier

Besides the primary functions of a postprocessor, the postprocessor can generate following information in a text file:

- number of set-ups,
- a process sequence list,
- used tools and tool holders,
- number of tool changes,
- cycle times.

This information is used for work shop planning, work shop preparation and manufacturing cost calculation.

3.6 Summary

In the present chapter, the created FAST-CADCAM software is described, required for the DfMASS inplementation. For holes, parameterized features have been developed, which are applied in Design. For pockets, slots, contouring etc. the boundary feature is developed. A boundary feature is formed by selecting geometry from the CAD file. This geometry has been entered in the CAD file during geometric modelling. By technology libraries and CAM programs, NC datasets are automatically derived for holes and boundary features. Finally, the postprocessor adapts the NC dataset to the required format. In Appendix D the structure of the technology libraries is described. In Appendix E future enhancement requirements are presented, which have been defined during development and application of FAST-CADCAM.

4. DESIGN

Introduction

Chapter 2 provided a new structure for the Design and Manufacturing process. Chapter 3 supplied the required software tools. The present chapter describes the newly formulated working method for Design (Fig. 4.1). This method is divided into three phases:

- Requirement Analysis,
- Functional Design,
- Manufacturing Design.

Manufacturing Design is the novel idea of the present thesis, by which activity Design for manufacturability has been realized and Manufacturing has changed in a mass production process. Requirement Analysis and Functional Design are not major subjects of the present thesis, but for a good connection to Manufacturing Design, some aspects of Requirement Analysis and Functional Design needed to be adapted, especially in terms of unambiguous contents of the activities, clearly interfaces and the application of Computer Aided Design techniques.

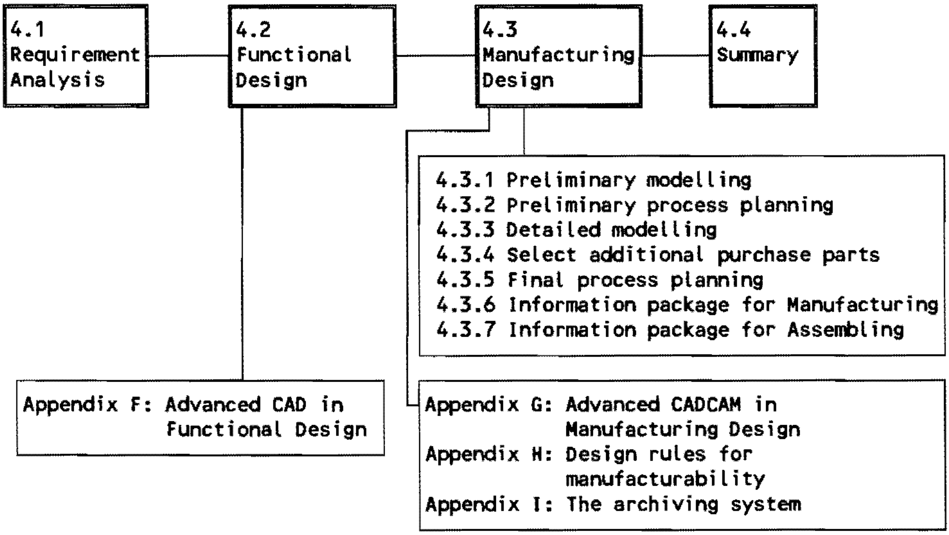


Fig. 4.1: Structure of this chapter

4.1 Requirement Analysis

Before Functional Design can be executed, a Requirement Analysis must be made of the requirements of the client, resulting in functional specifications (Fig. 4.2).

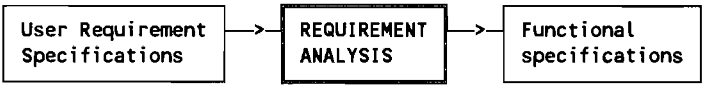


Fig. 4.2: Scheme of the Requirement Analysis

The Requirement Analysis is executed by the following procedure. First, the User Requirements are investigated and checked with the client to ensure that the designer has a correct interpretation of the User Requirements and that the User Requirements really agree with client's intentions. Secondly, the functional specifications are produced. The functional specifications consist of a functional description of the system, a system layout, and sometimes a rough 3-dimensional set-up. CAD can be used to create one or several system layouts and rough 3D set-ups. More alternatives of these layouts can easily be generated by editing the first draft. With some alternative layouts and 3D set-ups, a more profound discussion with the client is possible, also because the CAD information supplies a better insight for the client (Fig. 4.3). Based on the functional specifications, an estimate can be produced on leadtime and costs of the project. At this stage, the client can decide both on the technical contents and the the leadtime and costs of the project.

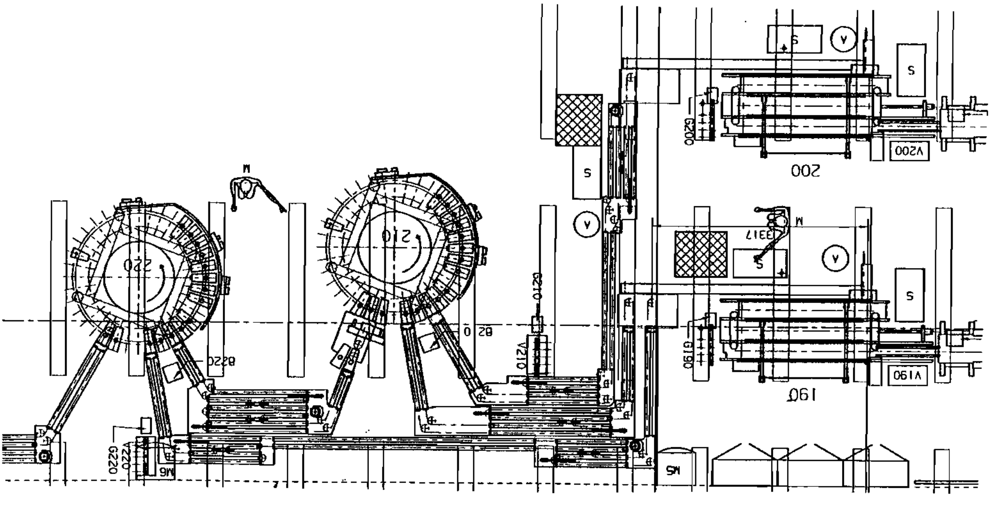


Fig. 4.3: An example of a system lay out

4.2 Functional Design

In the design of a complex system, it is desired to divide the design problem into a set of sub-problems. Van Bragt [39] suggests to continue this division until each problem is a single problem, which can not be divided anymore. The solution of each problem will lead to a separate module of the mechanical system. For each module the space must be defined in which the function has to be realized. This space is defined by interface geometry. The interface geometry describes the borders between the modules. After the interface geometry has been defined, the properties of the input and output must need to be defined. Then, the module itself can be designed, without looking to the problems of the whole system.

It is a basic intention of DfMASS to stimulate modularity in designs, because building up constraints, step by step, from a rough level to detail levels is a practice which is well suited for computer supported techniques (see "The product model database structure" in the present chapter).

Functional Design is a creative process. It is questionable whether a unified methodology can be formulated for this process. The approach of Functional Design is highly dependent on the contents and the level of innovation of the subject. For the present thesis it is not necessary to discuss the contents of the Functional Design working method in detail. However, it is essential to describe the required output structure of Functional Design, to be able to optimize the succeeding activity Manufacturing Design.

From the system layout, the rough 3D set-up and the functional specifications (defined during the Requirement Analysis), the functional designer performs the following activities (Fig. 4.4):

- define the system structure,
- determine the interfaces between the modules,
- define the functions of each module,
- select critical purchase parts,
- design vital details,
- design of critical functions.

It should be noted that in DfMASS, the functional designer must not decide on the division of geometry over the different manufacturing components. It would restrict the freedom in the next design phases to apply manufacturability and Manufacturing Families.

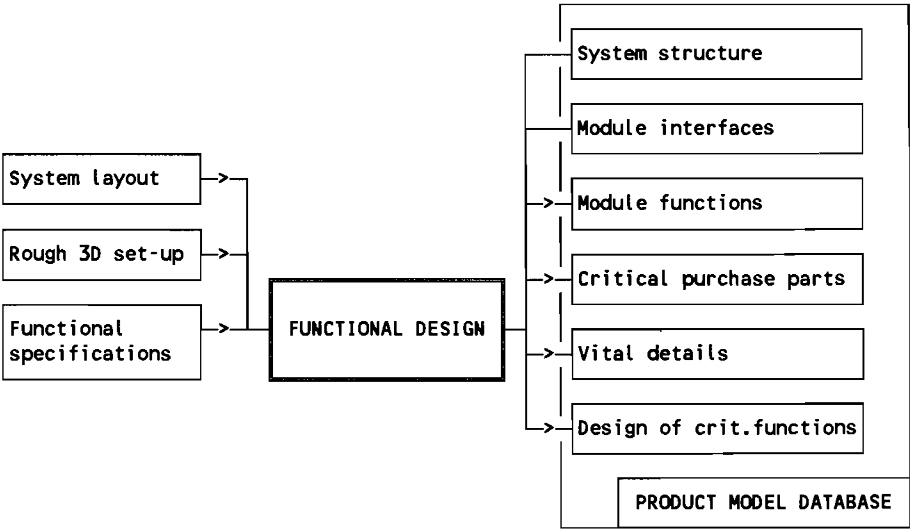


Fig. 4.4: Scheme of the Functional Design

Applying computer supported techniques in Functional Design supplies extra possibilities to improve the design quality (see Appendix F for detailed examples). For DfMASS it is desired to use an electronic database as medium to store the design data. Contrary to drawing based designs, the electronic storage of CAD information in a product model database offers the following advantages:

- it provides a single source of information, supplying data to all users,
- it creates a link between assemblies and components,
- it allows selecting of specific information by viewing techniques.

The structure of the product model database consists of assemblies and single components with mutual relations (Fig. 4.5).

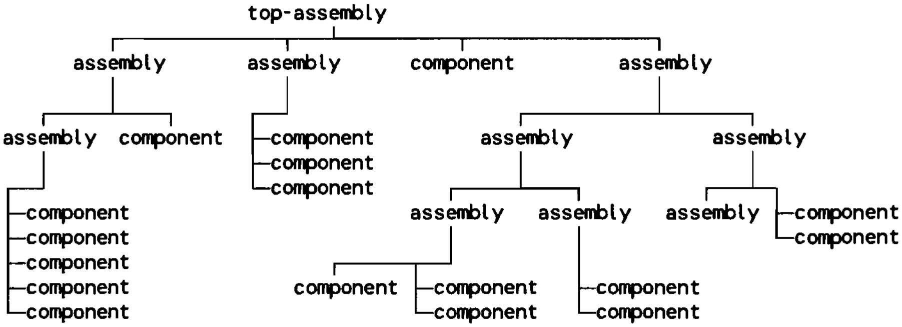


Fig. 4.5: An example of the structure of a mechanical system

For every component, a dataset of detailed information (geometry entities, text, NC datasets, etc.) may exist. From the detailed information and the known structure between components and assemblies, the computer can supply information to the designer in a specified format. This is possible because of the following functions:

a. Assembly and components functionality,
b. Viewing techniques,
c. Retrieval of bill of material information.

a. Assembly and components functionality
In conventional practice, the geometry in an assembly drawing is generated by copying component geometry form the component drawings (or vice versa). If component geometry changes, these changes are not automatically passed through to the assembly drawing. Using a relational product model database, the assembly file itself does not necessarily have component geometry entities[1]. Component files are related to the assembly file, enabling the display of component geometry in the assembly view, without copying the entities to the assembly file.

b. Viewing techniques
Every design activity requires different information. The product model database will often grow into an extensive database of numerous related files. If the entire geometry of all components would be displayed in a single assembly view, a lot of details could confuse the relevant information. By the reference set functionality of the applied CADCAM system, this problem has been solved. In a component file a specific set of geometry entities can be grouped together in a reference set. In retrieving the component information in the assembly view, only the geometry related to the reference set will be available. This functionality can be used across more than two levels of assembly. It is a powerful tool to perform parallel design on different levels[2]. Besides the reference set functionality, other viewing techniques (blanking, group blanking, etc.), it is possible to select only the required information.

In conventional drawing based practice, it often happens that the designer needs to interpret a lot of data to obtain the required information, which is time consuming, confusing and causes mistakes.

---

[1] Except for the case of early design, when no component files are available yet, geometry of future components will be temporarily part of the assembly file.

[2] The designer of the first level defines the interface geometry between different modules; multiple designers of the second level can design single modules concurrently.

c. Retrieval of Bill of Material (BOM) information

The product model database also supplies the following additional information:

- which components belong to which assembly,
- which assembly owns which components.

In conventional practice, people use a paper list of the system structure, which often appears to be outdated, because of the engineering changes. In DfMASS, the BOM information is directly retrieved from the product model database when needed, which ensures an up-to-date status of this information.

In Functional Design, the following six activities have to be executed: i.e. define the system structure, determine the module interfaces, define the module functions, select critical purchase parts, design the vital details, design critical functions. These activities will be explained:

Activity 1: Define the system structure

For modular design, the total problem must be divided into manageable sub-problems. For every sub-problem, the input and output characteristics and the function will be defined. The functional designer defines the system structure up to the module level and leaves the definition of the underlying structure (component break-down) to the manufacturing designer. A typical system structure is shown in Fig. 4.6

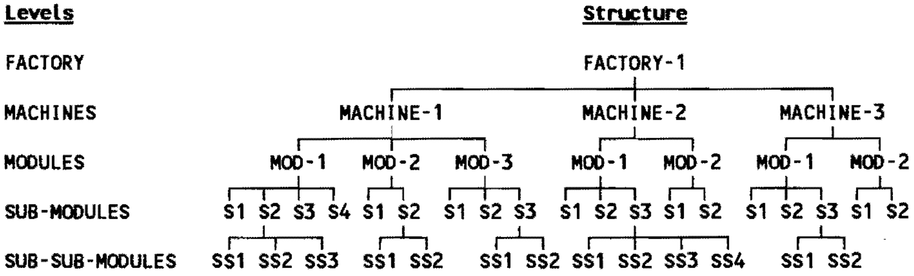


Fig. 4.6: A functional division of a machine structure in different levels

The functional designer must consider whether existing solutions are applicable in the system. Existing solutions may be purchase modules or existing designs. By using existing solutions, the costs and performance are known, which decreases the development risks. In case existing solutions are not suitable, adapting existing designs is the next best solution. Here, Manufacturing Families (Chapter 5) play an important role.

Activity 2: Determine the module interfaces

For existing solutions, the interface geometry of the modules must be described. For the remaining modules the required design space needs to be determined. A remark often heard is, how can one define the interface geometry without knowing all the details of every component. Evidently, one only knows the exact interface geometry after designing all the details. However, without an early split of the system into modules, the module design will be less complex, modular, and the design of each module can be carried out concurrently. It is the skill of the functional designer to perform a close estimation of the interface geometry in an early design stage.

Activity 3: Define the module functions

For the parts of the system, which are not covered by purchased modules or existing designs, the functions must be defined. These functions are described by entering functional geometry entities in the product model database (for instance hinge points of a lever, center and diameters of a roller bearing, movement paths, etc.). Sometimes additional text is required to describe the intentions of the designer.

Activity 4: Select critical purchase parts

Critical purchase parts are chosen during Functional Design. Purchase parts are considered critical, if the leadtime of acquisitioning influences the assembly planning (they need to be defined as early as possible), or if they play an important role in the Functional design of the system.

Activity 5: Design vital details

Functional Design is carried out by highly qualified designers. To control the costs of the Functional Design, the functional design effort must be limited to the essentials. Another reason to restrict Functional design to the vital details, is the requirement to remain maximum freedom to the next design phase to be able to consider manufacturability optimally. Details, which are not needed for defining the functions of the system, will be postponed to the next design phase[1].

Activity 6: Design critical functions

In the design of a critical function, the designer may need to go in extreme detail to prove its feasibility. The functional designer may need to go into details of one or more sub-modules, returning to the a higher level and checking whether the defined details still match with the overall structure. This may be a multi-iteration process.

---

[1] It is difficult to indicate to what level of detail a functional designer must go. It is evidently dependent on the technical contents and the level of innovation of the design. Unfortunately it is also dependent on the individual attitude of the designer involved. The last dependency is hard to recognize.

In Fig. 4.7 an example is given of a rough functional design.

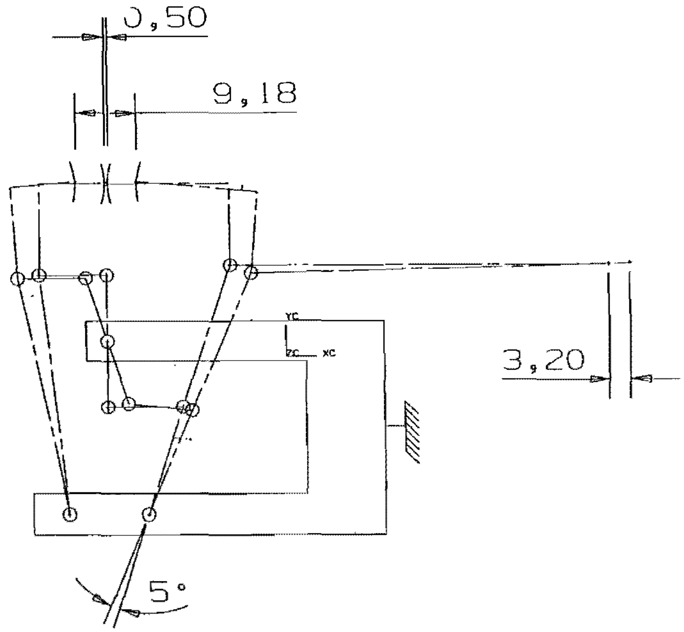


Fig. 4.7: An example of a rough functional design

The product of this design is presented in the detailed assembly drawing of Fig. 4.8.

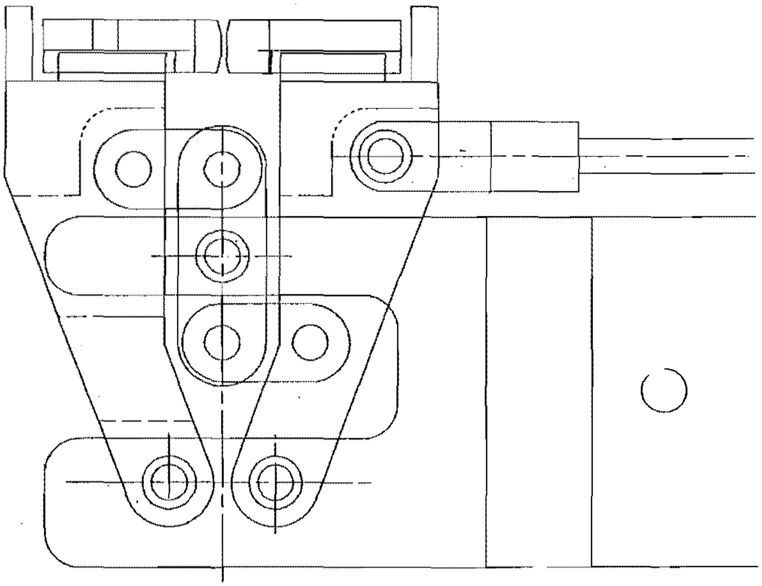


Fig 4.9: The detailed assembly drawing of the design of Fig. 4.7.

4.3 Manufacturing Design

The Manufacturing Design phase consists of all actions required to transform the functional design model into the following datasets:

- complete NC datasets,
- additional information required for part production,
- information for assembling,
- maintenance information[1].

In other words, Manufacturing Design defines the final allocation of geometry to components, completes the geometric model of the components and defines the required operations of the manufacturing process. Manufacturing Design mainly operates on the lowest assembly level and on the level of the associated components[2]. Manufacturing Design is an important activity because it covers more than half the effort of the total design process, by means of leadtime and costs. Compared to conventional methods, Manufacturing Design is the combination of geometric modelling and process planning, using CADCAM techniques, especially the so called form features. The working procedure of Manufacturing Design consists of:

- preliminary modelling,
- preliminary process planning,
- detailed modelling,
- select additional purchase parts,
- final process planning.

These activities are highly interrelated and therefore clustered in a single activity. In the next chapters these activities are described as separate processes, but the reader should keep in mind that they are heavily interrelated.

---

[1] The issue of CA information for assembling and maintenance, is beyond the scope of this thesis. Some ideas are given in 4.3.7.

[2] If the function can not be realized within the defined design space, the interface geometry with the surrounding modules needs to be changed.

4.3.1 Preliminary modelling

Preliminary modelling uses the functional design information, which is on the assembly level, and creates separate component files containing the functional entities of the component. Preliminary modelling consists of the following four activities.

Activity 1: Complete purchase part interface geometry
In Functional Design, purchase parts have been defined and some entities of the purchase part may have been entered in the product model database. The manufacturing designer must complete the interface geometry of the purchase parts, to supply sufficient information for detailed modelling of the surrounding manufacturing components.

Activity 2: Select purchase parts
Apart from the purchase parts already defined, some other functions may be fulfilled by purchase parts. Therefore, it must be considered, which functions can be realized by purchase parts. After this decision, the interface geometry of these purchase parts must be entered in the product model database (on assembly level).

Activity 3: Select family members for manufacturing components
For the design of manufacturing components first an attempt must be made to select a member of a Manufacturing Family (see Chapter 5). In case a family member can be used, next activities of Manufacturing Design do not need to be executed completely, but shrink into control and adjustment of the data supplied by the family database.

Activity 4: Define components interface geometry
The interface geometry of the manufacturing components must be defined in the assembly environment. Note that the interface geometry between assemblies has already been defined during Functional Design. The entities belonging to the interface geometry between assemblies, may be part of the interface geometry of the manufacturing components. Until now, the designer has worked in the assembly environment. For detailing the manufacturing components, it is desired to descend to the component level, where just a single component is present. Thus component files must be created, where the component entities are transferred to.

After this activity the components can be treated separately.

4.3.2 Preliminary Process Planning

In the preliminary modelling phase the functional entities of the component have been stored in the component file. Based on these component data a preliminary process plan can be made. If data is missing, an assumption must be made in the direction of the most simple solution, aiming to restrict the complexity of the final process plan. For example an assumption can be: all features have a Z-orientation: thus all manufacturing operations will be executed in one set-up on a vertical machine tool.
Preliminary process planning consists of the following five activities.

Activity 1: Estimate stock material size
Based on the functional data of the component (interface geometry, the functional entities, vital details) and on the preliminary model a stock material size must be chosen and entered in the product model database. If the material has a material structure, it may influence the manufacturing process (e.g. a laminated material). In that case the structure orientation must be considered and indicated.

Activity 2: Define the minimum machine tool configuration
Dependent on the preliminary model, a certain minimum machine tool configuration can be chosen. For instance, for a cubic product with holes in the top surface and in the side surfaces, a horizontal/vertical machine tool can produce all operations in one set-up. Of course, this component can also be produced on a vertical only machine tool, but then more set-ups are required.

Activity 3: Define manufacturing planes
The manufacturing planes are defined by the NC-SETUP program, as described in Section 3.3. The manufacturing planes are the surfaces on which the manufacturing operations are executed.

Activity 4: Define manufacturing task structure
For considering manufacturability during detailed modelling, the designer must keep in mind the manufacturing task structure[1]. Because the manufacturing task structure is not supported by the CADCAM system, this structure must be described on paper. If the designer enters form features in his design on arbitrary positions, without considering manufacturing, he will frequently cause complex process plans. On the contrary, considering manufacturing consequences during geometric model-

---

[1] The manufacturing task structure describes the way a component will be manufactured by means of the sequence of tasks to be executed. A task contains sequences of operations (see Section 3.4).

ling, will lead to parts, which are more easy manufacturable.

Activity 5: Define fixturing
From the manufacturing task structure, a fixturing configuration can be composed (preferrably from the fixtures library, see Section 3.4).

Result of preliminary process planning
Output of preliminary process planning is process planning information stored in the product model database (stock material, manufacturing planes, minimum machine tool configuration and a fixturing configuration; all in preliminary version). The manufacturing task structure is available on paper (Fig. 4.9).

```
Machine tool with vertical spindle. stock material 200 x 100 x 50
Bottom surface grinded, with two tapped holes (M6) for fixturing
Fixturing by two M6 bolts from the bottom, use extention rings

1. Face milling of top plane
2. Contouring side surfaces
3. Pocket milling (different pockets in the top surface, without interference)
4. Drilling holes (in top surfaces and on the bottom surface of pockets)
```

Fig. 4.9: An example of a preliminary process plan

4.3.3 Detailed modelling

In the detailed modelling phase the geometry of the component must be completed. First, the component will be shaped, preferrably by defining pockets, consisting of a chain of entities in a flat plane (preferrably the manufacturing planes) and a pocket depth. After the component has been shaped, the modelling phase will be completed by defining the hole features. During geometric modelling, the rules for manufacturability in Manufacturing Design need to be considered (see Appendix H).

By Assembly and Components functionality (Section 4.2), related data from surrounding components can be copied by computer functions. By this automated copying, mistakes are avoided. In conventional practice the designer copies entities from an assembly drawing or from other component drawings, by manually measuring the dimensions. By last practice, errors may occur or accuracy may be lacking, which will cause problems later on during assembling.

While completing form features, a check on existing technology for the entered form feature attributes has to be carried out. This is not yet automated (see Appendix G "Check form features on available technology"), but has to be the designer's knowledge of the available technology.

During detailing, it may happen that the functional requirements can not be fulfilled by the present preliminary process plan. In that case, the designer will have to change the preliminary process plan and restart the modelling activity. Existing geometry need to be checked against the new process plan. Only in few cases it will appear that the existing geometry need to be adapted, because normally a new process plan will extend the modelling possibilities and not restrict them.

4.3.4 Select additional purchase parts

After detailed modelling of the manufacturing components, additional purchase parts will be defined (like bolts and nuts for fastening). If an organization has fully implemented electronic data instead of paperbased information, it would be obvious to enter the purchase parts information directly in the product model database. If the assembly workshop is still working with paper based information, it may still be more efficient to use a separate Bill of material database, in which the additional purchase part information will be stored.

4.3.5 Final process planning

As mentioned in Section 4.3.3, in case of major problems with the preliminary process planning during detailed modelling, a redesign of the preliminary process plan has been executed. In case minor problems have appeared with the preliminary process plan during detailed modelling, the manufacturing designer will continue modelling and adapt the process plan after modelling is finished, thus during final process planning. Changes are minor if an adaptation of the process plan does not require changes of the geometry model afterwards. The possible adaptations of the process plan are described in the following nine activities.

Activity 1: Adjust stock material
The present stock material size is checked against the final 3D geometry and adapted if necessary.

Activity 2: Define pretreatments
Related to the chosen stock material, it must be defined, whether pre-treatments are required (turning, add holes for fixturing etc.). In some cases, the pre-treatment will be a complete Manufacturing Design on its own.

Activity 3: Adjust manufacturing planes

The manufacturing planes will be used during the automatic programming of the NC datasets of the features. The existing manufacturing planes are checked against the final model of the component and adapted if required, using the NC-SETUP program (Section 3.3).

Activity 4: Adjust manufacturing task structure, machine tool selection, fixturing configuration

The manufacturing task structure, present on paper needs to be checked against the final model of the component and adapted if required. The machine tool selection and the fixturing configuration need to be checked and adapted if necessary.

After the activities 1, 2, 3 and 4 have been finished, a start can be made with defining boundary features and selecting hole features. First the component shape need to be formed by defining face milling and contouring operations.

Activity 5: Define boundary features

To define the boundary of a feature, geometry lying in a flat plane needs to be selected. Sometimes it is required to add extra dummy geometry to complete the boundary (e.g. if it is an open boundary). Now the STANDARD-PLANAR-MILLING program (see Section 3.3) will be started. STANDARD-PLANAR-MILLING asks to select the geometry entities for defining the boundary. Because the entities are chained (end-point touches start-point) only one entity need to be indicated for selecting the entire boundary. Next, the clearance area, the engage and retract directions and positions are asked for. This is not automated, because it is highly dependent on the shape and environment of the feature. In the area between the material surface and the clearance plane, the tool will engage the material by the engage direction, which vector is asked for. The tool will retract, following the direction of the retract vector. For the hole features these vectors are defined automatically (in many cases the Z direction, perpendicular to the manufacturing plane). For the boundary features a suggestion is made by the computer, but may be altered by the designer, due to functional requirements.

Activity 6: Select hole features

Because task levelling is not part of the FAST-CADCAM functionality yet, the selection of the features need to be done manually sequenced by the manufacturing task structure. For this activity the program FEATURES-NC is used (Section 3.3). For hole features which have the same common values (same plane, same material, etc.) all features can be selected in one session. If a common value changes, the session must be finished and a new session started, by which the computer will ask to adapt the common values.

Activity 7: Define special sequences of operations

For non feature based entities the sequence of operations and the operations itself need to be entered manually. In FAST-CADCAM the computer uses the technology and tool databases to suggest values to the manufacturing designer.

Automatic NC programming

During execution of the previous three activities (5, 6 and 7), the NC file is built automatically. The sequence of operations in this file follows the sequence by which the activities 5, 6 and 7 have been executed. Therefore, dependent on the circumstances, the designer will switch between the three activities. The NC data are generated by automatic retrieval of technology data from the technology database.

Activity 8: Postprocessing

The NC dataset generated by the activities 5, 6 and 7, contains neutral statements, not specific for a machine tool control. This NC file has to be postprocessed to make the statements specific for a type of machine tool.

Activity 9: Define posttreatments

Treatments, to be executed after the total process on the machine tool is finished, need to be defined.

Now, the final process plan is ready (Fig. 4.10)

```
Machine tool with vertical spindle, Stock material 200 x 100 x 50
Bottom surface grinded, with two tapped holes (M6) for fixturing
Fixturing by two M6 bolts from the bottom, use extention rings

      1. Face milling of top plane    1a. rough  0.2 mm bottom stock
                                      1b. finish 0.0 mm bottom stock
      2. Contouring side surfaces     2a. rough  0.5 mm side stock
                                      2b. finish 0.2 mm side stock
                                      2c. finish 0.0 mm bottom stock
      3. Pocket milling  pocket no.1  3a. rough  0.5 mm side stock
                                      3b. finish 0.2 mm side stock
                                      3c. finish 0.0 mm side stock
      4. Pocket milling  pocket no.2  4a. rough  0.5 mm side stock
                                      4b. finish 0.0 mm side stock
      5. Drilling hole   hole no.1    5a. centerdrill
                                      5b. drill
      6. Reaming hole    hole no.2    6a. centerdrill
                                      6b. drill
                                      6c. bore
                                      6d. ream
```

Fig. 4.10: A simplified example of a final process plan

4.3.6 Information package for Manufacturing

After the Manufacturing Design has been finished, the information will be released to archive system (see Appendix I). The released information is input for the manufacturer. The information package supplied to the manufacturer consists of the next seven items, which will be explained in the following description:

- rough drawing of the component,
- pretreatments description,
- fixturing configuration,
- process planning sheet,
- tool list,
- NC file(s),
- posttreatments description.

Rough drawing of the component

A fully detailed drawing is not required for Manufacturing. However some aspects need to be indicated. Tolerances and roughnesses which are beyond the standard quality are indicated on the drawing. In general, exceptional tolerances and roughnesses will not often be defined, because the designer should stay within the standard quality and avoid exceptions. Besides exceptional tolerances and roughnesses, the rough drawing is the medium to communicate the stock material sizes (Fig. 4.11).

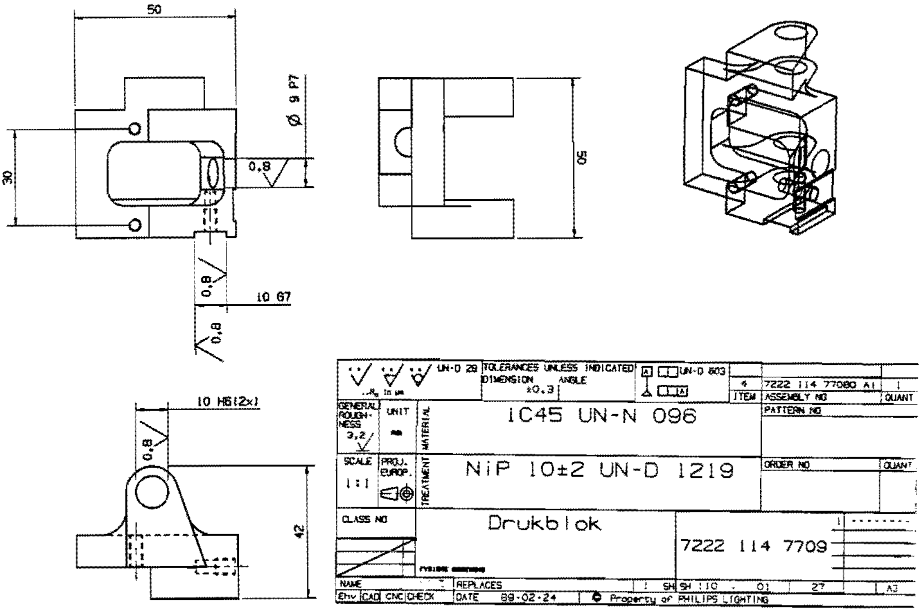


Fig. 4.11: A rough component drawing

Pre- /posttreatments

If pre- and posttreatments are conventional manufacturing processes, the information for pre-/ posttreatments is documented in conventional drawing representation.

Fixturing configuration

The fixturing documentation defines the required stock material and the way teh stock material is fixtured. In Fig. 4.12, an example is given of stock material mounted on a pallet. C4 and D3 indicated the holes in the pallet where the material must be fixtured.

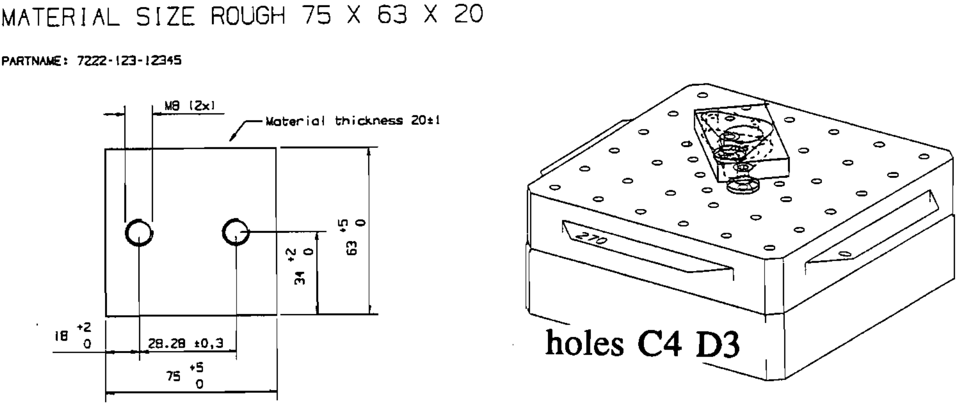
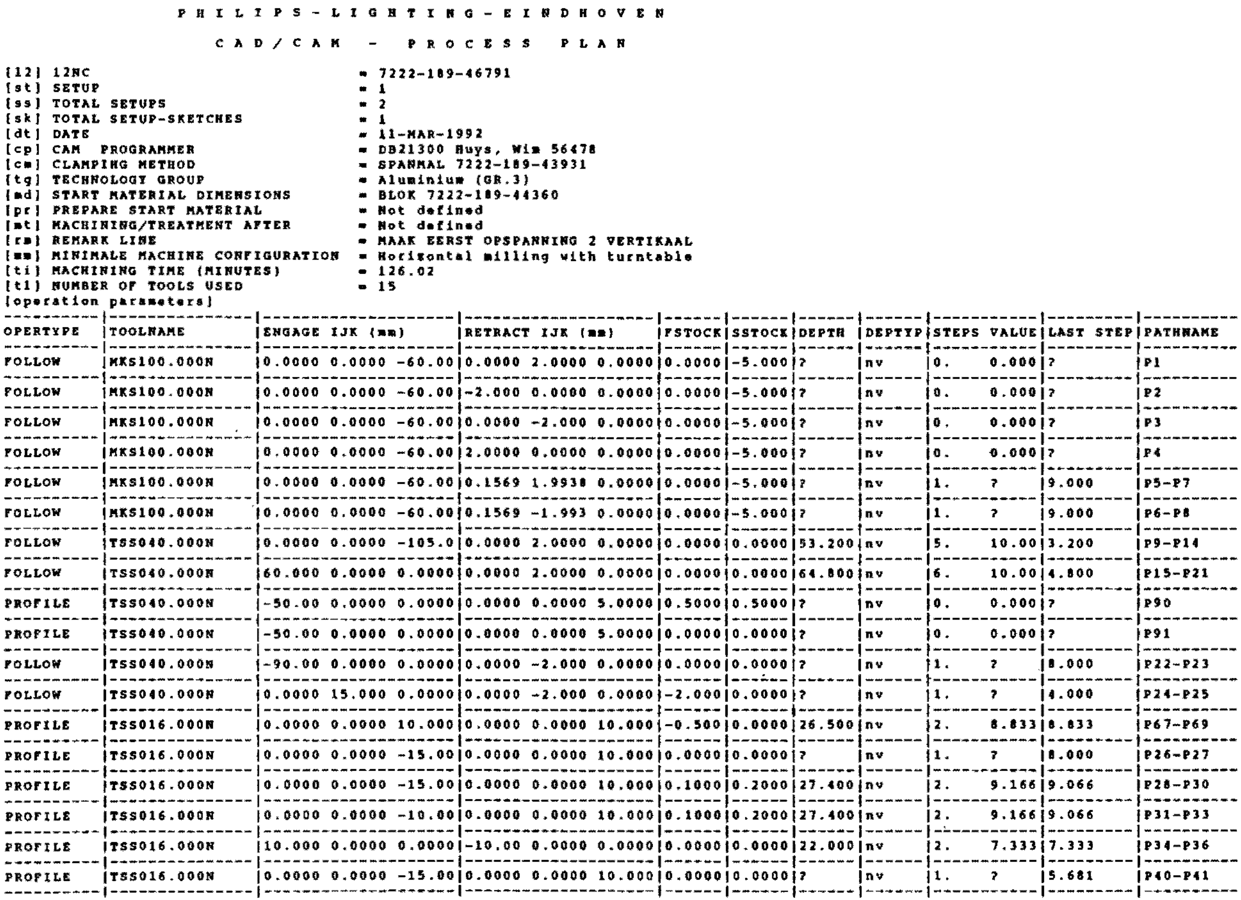


Fig. 4.12: Fixturing documentation

Process planning sheet

The process planning sheet is an automatically created list of the different tasks which are stored in the NC file. By the process planning sheet the operator is supplied with an overview of the manufacturing tasks which will be executed automatically (Fig. 4.13). The process planning sheet also indicates whether and which human interference is required. For enabling human interference, stops are built in the NC file.



```
                P H I L I P S - L I G H T I N G - E I N D H O V E N

                      C A D / C A M   -   P R O C E S S   P L A N

[12] 12NC                              = 7222-189-46791
[st] SETUP                             = 1
[ss] TOTAL SETUPS                      = 2
[sk] TOTAL SETUP-SKETCHES              = 1
[dt] DATE                              = 11-MAR-1992
[cp] CAM  PROGRAMMER                   = DB21300 Huys, Wim 56478
[cm] CLAMPING METHOD                   = SPANMAL 7222-189-43931
[tg] TECHNOLOGY GROUP                  = Aluminium (GR.3)
[md] START MATERIAL DIMENSIONS         = BLOK 7222-189-44360
[pr] PREPARE START MATERIAL            = Not defined
[mt] MACHINING/TREATMENT AFTER         = Not defined
[rm] REMARK LINE                       = MAAK EERST OPSPANNING 2 VERTIKAAL
[mm] MINIMALE MACHINE CONFIGURATION    = Horizontal milling with turntable
[ti] MACHINING TIME (MINUTES)          = 126.02
[tl] NUMBER OF TOOLS USED              = 15
[operation parameters]
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
OPERTYPE  |TOOLNAME        |ENGAGE IJK (mm)      |RETRACT IJK (mm)     |FSTOCK |SSTOCK |DEPTH  |DEPTYP |STEPS VALUE |LAST STEP |PATHNAME
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |MKS100.000N     |0.0000 0.0000 -60.00|0.0000 2.0000 0.0000|0.0000|-5.000|?      |nv     |0.    0.000|?         |P1
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |MKS100.000N     |0.0000 0.0000 -60.00|-2.000 0.0000 0.0000|0.0000|-5.000|?      |nv     |0.    0.000|?         |P2
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |MKS100.000N     |0.0000 0.0000 -60.00|0.0000 -2.000 0.0000|0.0000|-5.000|?      |nv     |0.    0.000|?         |P3
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |MKS100.000N     |0.0000 0.0000 -60.00|2.0000 0.0000 0.0000|0.0000|-5.000|?      |nv     |0.    0.000|?         |P4
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |MKS100.000N     |0.0000 0.0000 -60.00|0.1569 1.9938 0.0000|0.0000|-5.000|?      |nv     |1.    ?    |9.000     |P5-P7
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |MKS100.000N     |0.0000 0.0000 -60.00|0.1569 -1.993 0.0000|0.0000|-5.000|?      |nv     |1.    ?    |9.000     |P6-P8
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |TSS040.000N     |0.0000 0.0000 -105.0|0.0000 2.0000 0.0000|0.0000|0.0000|53.200|nv     |5.    10.00|3.200     |P9-P14
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |TSS040.000N     |60.000 0.0000 0.0000|0.0000 2.0000 0.0000|0.0000|0.0000|64.800|nv     |6.    10.00|4.800     |P15-P21
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
PROFILE   |TSS040.000N     |-50.00 0.0000 0.0000|0.0000 0.0000 5.0000|0.5000|0.5000|?      |nv     |0.    0.000|?         |P90
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
PROFILE   |TSS040.000N     |-50.00 0.0000 0.0000|0.0000 0.0000 5.0000|0.0000|0.0000|?      |nv     |0.    0.000|?         |P91
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |TSS040.000N     |-90.00 0.0000 0.0000|0.0000 -2.000 0.0000|0.0000|0.0000|?      |nv     |1.    ?    |8.000     |P22-P23
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
FOLLOW    |TSS040.000N     |0.0000 15.000 0.0000|0.0000 -2.000 0.0000|-2.000|0.0000|?      |nv     |1.    ?    |4.000     |P24-P25
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
PROFILE   |TSS016.000N     |0.0000 0.0000 10.000|0.0000 0.0000 10.000|-0.500|0.0000|26.500|nv     |2.    8.833|8.833     |P67-P69
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
PROFILE   |TSS016.000N     |0.0000 0.0000 -15.00|0.0000 0.0000 10.000|0.0000|0.0000|?      |nv     |1.    ?    |8.000     |P26-P27
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
PROFILE   |TSS016.000N     |0.0000 0.0000 -15.00|0.0000 0.0000 10.000|0.1000|0.2000|27.400|nv     |2.    9.166|9.066     |P28-P30
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
PROFILE   |TSS016.000N     |0.0000 0.0000 -10.00|0.0000 0.0000 10.000|0.1000|0.2000|27.400|nv     |2.    9.166|9.066     |P31-P33
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
PROFILE   |TSS016.000N     |10.000 0.0000 0.0000|-10.00 0.0000 0.0000|0.0000|0.0000|22.000|nv     |2.    7.333|7.333     |P34-P36
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
PROFILE   |TSS016.000N     |0.0000 0.0000 -15.00|0.0000 0.0000 10.000|0.0000|0.0000|?      |nv     |1.    ?    |5.681     |P40-P41
----------|----------------|---------------------|---------------------|-------|-------|-------|-------|------------|----------|----------
```

Fig. 4.13: A process planning sheet

Tool list

For tool preparation a tool list is supplied (Fig. 4.14). The tool list is an excerpt, automatically generated from the NC file.

T1 MKS063.000N
T2 TSS010.000N
T3 TSS004.000SF
T4 CVB006.000
T5 CVB010.000
T6 SBS003.300SN
T7 SBS006.000SN
T8 SBS006.500SN
T9 SBS012.000SN
T10 SBS025.000SN
T11 SBS006.900SN
T12 KBS025.800
T13 KBS026.000
T14 RMS007.000
T15 TAPM4
T16 SBS002.500SN
T17 TAPM3

MKS: Shell end mill
TSS: Two-flute slot drill
CVB: Countersink drill
SBS: Standard drill
KBS: Boring cutter
RMS: Reamer
TAP: Tap

Fig. 4.14: An example of a tool list

There are two aspects on tools, requiring extra attention.

Minimum flute length

The manufacturing designer assumes a minimum flute length during Manufacturing Design. A tool table is available, presenting the maximum and minimum flute length. Some tools are reduced in flute length after sharpening, therefore the obtained flute length must be checked against the tool table during tool preparation.

Tool holder collision

As said in chapter 3, there is no automatic collision checking implemented yet. The manufacturing designer assumes a certain occupied space for the tool holder. In most cases this will not cause problems in manufacturing. However if the tool holder will approach material very closely, it has to be documented, so that the manufacturer can check, whether the applied tool holder will not cause collision problems.

NC file(s)

The generated NC files are text files containing machine control instructions (Fig. 4.15). Dependent on the procedures, a single NC file contains the NC data for all set-ups, or the data are divided over more files. For the manufacturer there is hardly preference, whether it is stored in a single file or in more files. The NC file(s) can be sent to the machine tool by a network facility, by computer tape or floppy disk. There is no problem to read the file on different computer systems, because the format is standard ASCII, which is well known.

```
%PM
N92534
N1  (MACHINE : MH800C VERTICAL CW)
N2  (CODENO  : 7212-025-08081-99901.CLS)
N3  (T1 MKS063.000N)
N4  (T2 TSS010.000N)
N5  (T3 TSS004.000KF)
N6  (T4 CVB006.000)
N7  (T5 CVB010.000)
N8  (T6 SBS003.300KN)
N9  (T7 SBS006.000KN)
N10 (T8 SBS006.500KN)
N11 (T9 SBS012.000KN)
N12 (T10 SBS025.000KN)
N13 (T11 SBS006.900KN)
N14 (T12 KBS025.800)
N15 (T13 KBS026.000)
N16 (T14 RMS007.000)
N17 (T15 TAPM4)
N18 (T16 SBS002.500KN)
N19 (T17 TAPM3)
N20 M54
N21 G17
N22 G51
N23 (ACTIVATE 0-POINT)
N24(STOCKMAT: 80X40X30)
N25 T1 M6
N26 S500 M13
N27 M8
N28 G0 X113.5 Y-30.5 Z12.
N29 G0 Z-1.
N30 G41 X113.5 Y-30.5
N31 G1 X80. F203
N32 X0. F407
N33 X-33.5 F203
N34 G40
N35 G0 Z12.
N36 G0 X0. Y0. Z100.
N37 T2 M6
N38 S3150 M3
N39 M8
N40 G0 X15. Y-46.75 Z12.
N41 G0 Z-5.2
N42 G1 Y-25.75 F340
N43 X8.25 F680
N44 Y-32.25
N45 X21.75
N46 Y-25.75
N47 X15.
N48 Y-23.25
N49 X5.75
N50 Y-34.75
N51 X24.25
N52 Y-23.25
N53 X15.
N54 Y-19.5
N55 X2.
N56 Y-38.5
N57 X28.
N58 Y-30.5
N59 Y-19.5
N60 X15.
N61 Z2.3 F340
N62 G0 Z12.
N63 G0 X15. Y-46.75 Z12.
N64 G0 Z-9.4
N65 G1 Y-25.75
N66 X8.25 F680
```

Fig. 4.15: A piece of a NC file

4.3.7 Information for Assembling

Because there are no detailed drawings required for Manufacturing anymore in a DfMASS environment, it needs to be considered whether these type of drawings still need to be produced for assembling purposes. It is not a part of this thesis to define a new type of assembling documentation, however some comments are made in this section.

The detailed drawing has been invented for manufacturing purposes, not for assembling. In fact it is not well suited for assembling, but in many circumstances the detailed drawing is sent to the assembly workshop as documentation together with a rough assembly drawing and a bill of material (BOM). A better document for assembling is a detailed assembly drawing on which the position of each component of the assembly is documented (Fig. 4.16). It would be helpful if the designer also supplies an assembly plan, indicating in which sequence the module should be assembled.

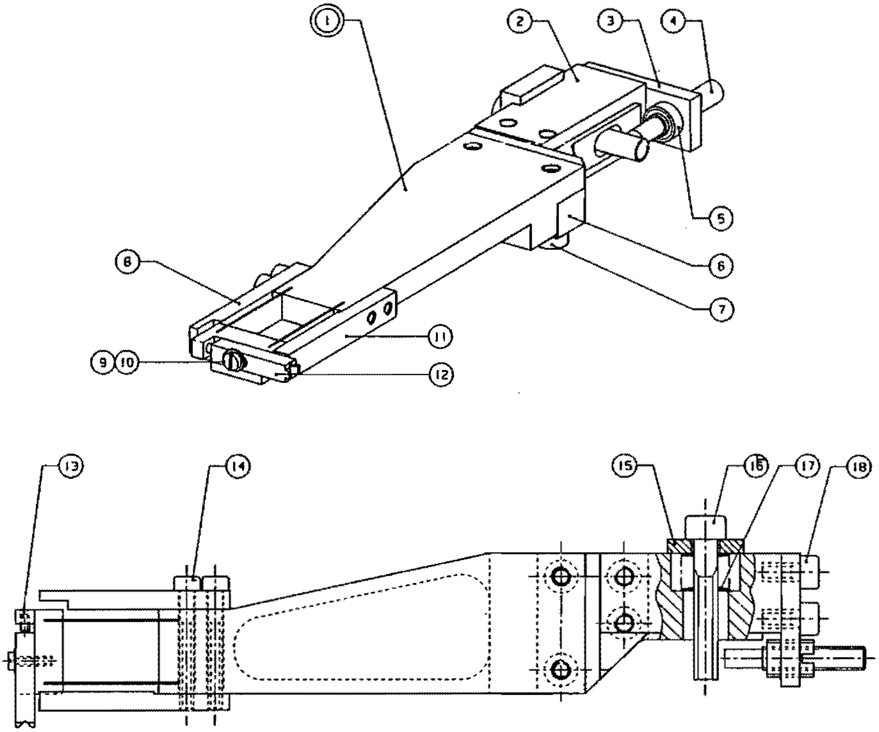


Fig. 4.16: An example of a detailed assembly drawing

Another way of supplying assembling information is an exploded view (Fig. 4.17).

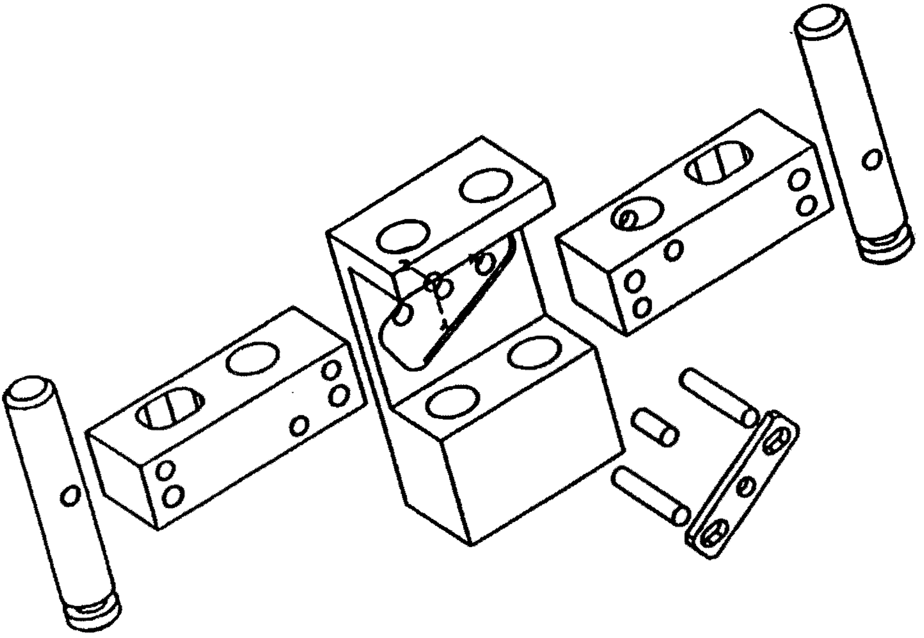


Fig. 4.17: An exploded view

4.4 Summary

This chapter described the working procedure for Manufacturing Design. Manufacturing Design is the combination of detailed modelling and process planning in a single activity. Output of Manufacturing Design is a NC dataset and additional information, by which the manufacturer is able to produce the component without making extra technical decisions.

To be able to execute the Manufacturing Design efficiently, the preceeding Functional Design must define a suitable structure of the product data in the CAD file(s). Therefore, this chapter started with structuring the Functional product data, before describing Manufacturing Design.

The application of CAD supplies extra possibilities to the designer. These aspects are described in Appendices F and G. In Appendix H rules for manufacturability are given. Appendix I describes an archieving system for product model data.

5. MANUFACTURING FAMILIES

Introduction

The complexity of activities in Manufacturing Design have been increased by the DfMASS working method, because process planning has been added to geometric modelling[1]. To simplify the work to be carried out during Manufacturing Design and to avoid errors and ommissions, **Manufacturing Families** have been developed (Fig. 5.1). Design by Manufacturing Families has been a major contribution to the successfull implementation of DfMASS at Philips Lighting (see Section 7.1).

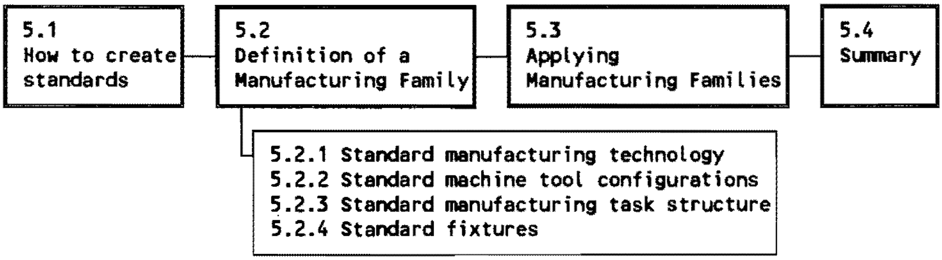


Fig. 5.1: Structure of this chapter

For a number of years, design organizations try to standardize components. By group technology and classification [42, 37-4] families of parts have been developed to increase the degree of standardization (Fig. 5.2). In some sections of industry, families of parts have been a success, especially in companies where the same type of systems are used for different design solutions.

Nolen [30] states on group technology for Design and Manufacturing: "It can serve to focus our technology so that we consistently apply our best practices". He also assumes that group technology is the key to computer aided process planning.

In the design of special machines in small lotsizes, although, the acceptance of group technology is poor, often because the variety of required components is too large and the functions to be carried out by a single group are too limited. This objection is solved by Manufacturing Families, because a single Manufacturing Family supports a larger variety of components, only restricted by the defined manufacturing task structure.

---

[1] In conventional methods all these activities need to be executed as well, but they are spread over three single activities: detailed design, process planning and NC programming.

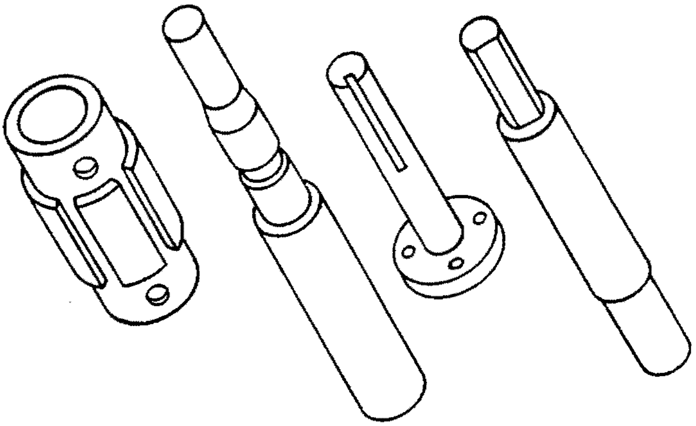


Fig. 5.2: A part family

The difference between group technology and Manufacturing Families is the wider variety of possibilities in designing in Manufacturing Families, by the link between geometric entities and process planning entities (Appendix G) and by having efficient CAD functions in adding and editing geometry. A variant design of a new family member is easily obtainable. Unlike the limited application of group technology, Manufacturing Families are welcomed by the designers.

Other advantages of Manufacturing Families are following:

- To be able to review all manufacturing options, commercially available, the manufacturing designer needs to have a wide and profound manufacturing knowledge. By Manufacturing Families, the manufacturing options have been examined as a predevelopment activity and not during execution of Manufacturing Design[1].
- If manufacturing orders often contain novel manufacturing solutions, Manufacturing requires extra attention to understand these solutions. Novel solutions also require a lot of documentation to prescribe the necessary actions of the manufacturer. Novel solutions also cause high error risks. Manufacturing Families reduce the unneccesary variety of manufacturing solutions.

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[1] This does not imply that an organization should freeze their know how in manufacturing. Evaluating new technologies should be incorporated in the innovation program of the organization. It should not be part of the job of the manufacturing designer, when he is busy realizing the design of a project. See also Section 5.2.1: Standard manufacturing technology.

Therefore, Manufacturing Families are very important. They accelerate the implementation of DfMASS, reducing manufacturing problems and increasing standardization. Extra attention to manufacturability in designing a Manufacturing Family is justified, because the effort is only once and the savings are recurrent.

There are two basic methods of deriving a process plan from existing know how: generative and variant process planning. Variant process planning is based on the retrieval and adaptation of existing process plans. Generative process planning use mathematical models to derive a process planning, often by automated functions [3, 29]. Working with Manufacturing Families could be called hybrid, because it is based on variant design of the basic structure of the process planning, but by use of CADCAM functionality a lot of aspects can be changed, for which new process planning data are generated by CAM functions.

5.1 How to create standards

Manufacturing Families are based on standard solutions. Therefore it is needed to look to the way standardization is achieved. Aim of standardization is to decrease the number of decisions which have to be made by the designer. If standardization leads to activities which can be executed without intervention of the human mind, those activities can be completely automated[1]. In other cases, where human decisions are required, the computer is a welcome tool to suggest possible answers, by consulting standard databases. In conventional practice, the introduction of standardization is often a laborious job. Fortunately standardization is easier achievable in computer environments, because the user can communicate with the computer via menus. These menus offer default solutions. If the presented default values are not satisfying, the designer can enter other (non standard) values.

It is a burden to an organization, if a new system can only be introduced after spending extensive efforts in building standard databases and defining working procedures. Even if the organisation is willing to spend a large amount of money in research, and is willing to wait for a long while, the results of standardization efforts are often poor, because in the meantime the technology has changed, or the available software tools have been improved, or the organization is aiming at new targets.

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[1] A possible pitfall of application of computer technology is the banishment of creative thinking, analytical thought and fuzzy logic of the human mind. This pitfall must be avoided. The computer must act as a tool for the designer and must help him to enlarge his capabilities, not to restrict him. Often, the designer invents new solutions, where standard solutions would have been sufficient, just because he is lacking the knowledge of the available solutions.

Therefore a different approach has been chosen:

ON-THE-JOB-STANDARDIZATION.

In this method, budget and resources are reserved for standardization, but standardization is not executed immediately. Just at the moment demands arise, during execution of a project, a standardization activity is started to supply the required standardized solutions. It is obvious that one cannot start with no standards at all. Therefore, a set of common standards has to be created beforehand. Advantages of on-the-job-standardization are:

- standards are used immediately after developing them and can be adjusted due to project experience,
- no standards are created that will never be used,
- instantaneous return of investment of standardization expenditures.

Disadvantages of this method are the required discipline and extra leadtime in projects, in case additions to the standards are required. In these cases it is tempting to create an ad hoc solution instead of defining a new standard solution.

On-the-job-standardization has been applied at Philips Lighting in building a form features library, several technology libaries, a fixtures library, manufacturing task structures, and Manufacturing Families.

5.2 Definition of a Manufacturing Family

Before starting to describe the ingredients of a Manufacturing Family, the term Manufacturing Family need to be defined. A Manufacturing Family describes a set of manufacturing limitations and supplies a standard process plan. Designing a component, belonging to a Manufacturing Family, is restricted to these limitations. The limitations, which will be discussed in the following sections, comprehend:

- manufacturing technology,
- minimum machine tool configuration,
- manufacturing task structure,
- fixturing configuration,
- a set of standard form features.

Minimum machine tool configuration, the fixturing configuration and the manufacturing task structure have a close interrelation. For building Manufacturing Families, a package of well combined standard solutions on these three aspects must be defined.

5.2.1 Standard manufacturing technology

All Manufacturing Families, generated in the DfMASS project, use the same manufacturing technology. Extensions in the technology databases have been realized in such a way that previously designed families can still be produced by the new technology data (compatibility of technology releases).

First, the database has been filled, using data available from technology handbooks. The contents of the database has been based on the use of two material types (aluminium[1] and tool steel) and on frequently used tools for a set of preferred tool diameters. In this phase, the goal was effectiveness: to achieve a sufficient set of technology data, resulting in good products. At that moment, the purpose was not to have the most efficient technology. Secondly, the technology has been extended, triggered by the requirements of the current jobs. In Fig. 5.3 an illustration of manufacturing technology is given.

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[1] For slim components a special type of aluminium has been used ACP-5080 which remains low tensile stresses during manufacturing.

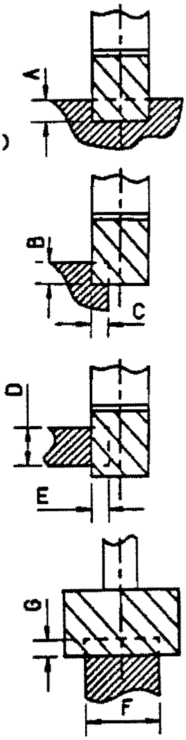
CUTTING CONDITIONS FOR MILLING

FEED/SPEED

	FE400		ALUMINIUM		TOOL STEEL	
	speed /min	feed m/min	speed /min	feed m/min	speed /min	feed m/min
EMT 20	630	160	1200	250	630	100
EMT 16	800	160	1200	300	800	100
EMT 12	1000	160	1600	300	1000	100
EMT 10	1250	160	2000	300	1250	100
EMT 8	1600	120	2500	300	1600	100
EMT 6	2000	100	3000	250	2000	80
EMT 4	2500	100	3000	160	2500	75
EMT 3	2500	50	3000	50	2500	50
EMT 2	3000	40	3000	40	3000	40

Feed in Z-direction = 1/4 * X-Y feed

MAXIMUM CUTTING CONDITIONS (related to mill diameter)



	FE400	ALUMINIUM	TOOL STEEL
	A	A	A
EMT short	1/4	1/2	1/5
EMT long	1/8	1/4	1/10
	B C	B C	B C
EMT short	1/2 1/4	1 1/2	1/2 1/5
EMT long	1/4 1/8	1/2 1/4	1/4 1/10
	D E	D E	D E
EMT short	1 1/5	1 1/2	1/2 1/5
EMT long	1/2 1/10	1/2 1/4	1/4 1/10

EMT: End mill two cutting edges

short: short flute length
long: long flute length[1]

Fig. 5.3: Example of manufacturing technology

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[1] For tools, there is a dimension table a.o. indicating the length of short and long.

Maintaining the technology database is an important, ongoing activity, which pays itself back by an increase of manufacturing efficiency and by better quality of the endproduct. It is carried out, by analyzing the performance of the technology in practice and deciding for which technology it is worthwile to invest in efficiency increase. Priority must be given to the quality of the technology for all manufacturing situations, instead of the best solution for only a part of the situations.

By elimination of the craftsmen, who had a major role in technological decisions, a new specialism must be installed, that takes care of know how on the application of new technology. This specialism gathers information from literature, from manufacturing experience, from experiments and by severe testing in production. New design requirements will also ask for new technology. Using a single technology database for all users, supplies the advantage that these changes will be used for all work, once the technology has been entered in the database.

To avoid a serious problem in tool management, the number of tools in the technology database need to be constrainted to the absolute minimum. Besides, the quality of the endproduct is less predictable by incidental use of special tools. Only tools, which conform to international standards (DIN, ISO), have been applied, because the tools need to be available commercially, preferrably from stock.

5.2.2 Standard machine tool configurations

A good machine tool selection is done, if only a few machine tool configurations are needed to produce the main part of the manufacturing components. In the DfMASS project, it has been chosen to standardize on a single machine tool, the MAHO 800. This machine tool contains a tool spindle, which can automatically rotate from vertical to horizontal. It has a reach of 800 x 600 mm, a controlled turn table and a tool changing device. On the MAHO 800, a lot of components can be produced in a single set-up because of the automatical cahnge from vertical to horizontal operations. Since a substantial part of the manufacturing components, only requires vertical operations a second machine tool type has been selected in addition, the MAHO 600. The MAHO 600 contains a tool spindle which can manually be changed from vertical to horizontal. It has a reach of 600 x 450mm, a controlled turn table and a tool changing device. Besides the difference in functionality, the MAHO 800 and the MAHO 600 are compatible.

Fig. 5.4: The MAHO 800

In a family, a minimum machine tool configuration is defined instead of a required machine tool, because if a machine tool with more facilities is available, it is possible to produce the component on that machine.

In the future, by an increase of the scope of work, more manufacturing organisations could be involved in DfMASS production. Hence, it may be required to be more flexible in machine tool types. To avoid the need to consider a specific machine tool during Manufacturing Design, a classification of machine tool characteristics is required. By defining a machine tool class during Manufacturing Design, instead of a specific machine tool type, the flexibility in Manufacturing increases. Theuws [44, chapter 2.4] has elaborated a classification based on the possible movements of the machine tool.

The classification may be based on

* the relative movements of the workpiece towards the tool spindle (Fig. 5.5):

- X-axis, horizontal movement
- Y-axis, vertical movement
- Z-axis, horizontal movement
- A-axis, rotation around the X-axis
- B-axis, rotation around the Y-axis
- Z-axis, rotation around the Z-axis

* on the reach of the machine tool:

- length
- width
- height

* on efficiency aspects:

- accuracy
- tool changing device
- pallet changing device.

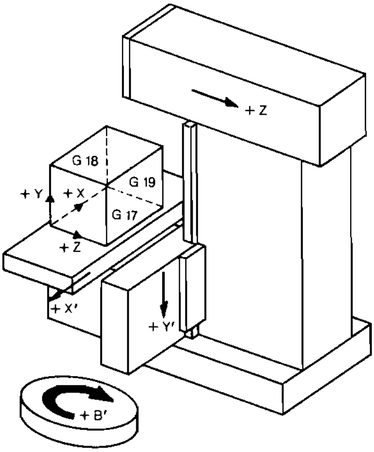


Fig. 5.5: The axis of a milling machine

The required machine tool configuration can be changed to a less facilitated machine tool by the postprocessor functionality. For instance if the tool changing device is missing, stops can be generated by the postprocessor for manual tool change. Another example is the generation of stops for turn table rotation, in case only a manual driven turn table is available. However, dependent on the component to be manufactured, the efficiency may be severely reduced.

5.2.3 Standard manufacturing task structures

The manufacturing task structure (MTS) of a component defines a set-up plan for manufacturing. (See also Sections 3.4 and 4.3.2). The MTS also indicates how the material will be fixed during manufacturing. The MTS assumes a minimum machine tool configuration (turning, milling with only a vertical tool axis, milling vertical/ horizontal, turntable etc.). The MTS is an efficient tool for defining the basic structure of the process plan, before detailed modelling takes place. It is also the backbone of a Manufacturing Family.

In this section three examples of standard MTS's are presented, which have been developed for the DfMASS project.

The vertical MTS

This example shows a MTS for components, which can be produced by vertical operations only. The MTS is illustrated in Fig. 5.6.

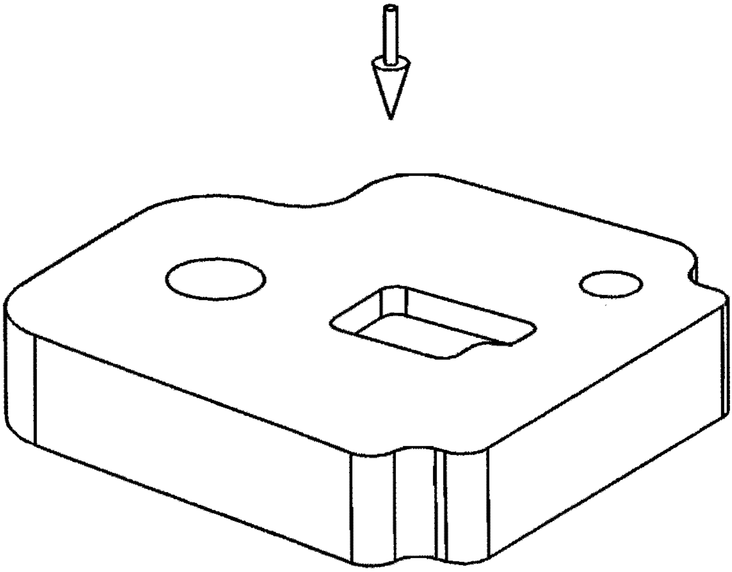
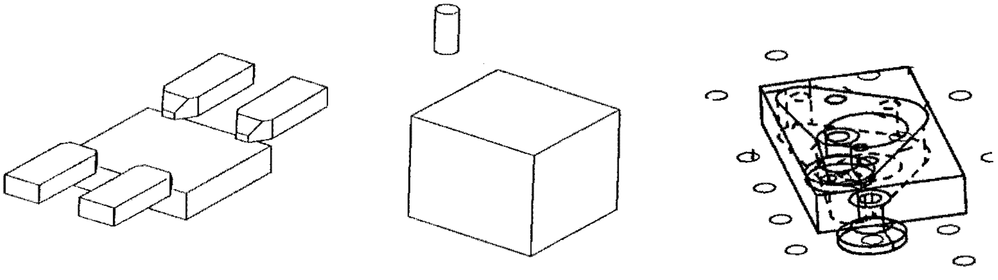


Fig. 5.6: A vertical MTS

The task structure allows holes and cavities in the top surface. Dependent on the way of fixturing and on the thickness of the material, contouring of the side surfaces is also allowed (Fig. 5.7).



Fixturing by clamps,
no contouring possible

Material too thick,
contouring hardly possible

Fixturing by bolts,
contouring allowed

Fig. 5.7: Contouring possibilities in a vertical MTS

The horizontal/vertical MTS

This example shows a MTS for components, which can be produced by vertical and horizontal operations. The MTS is illustrated in Fig. 5.8.

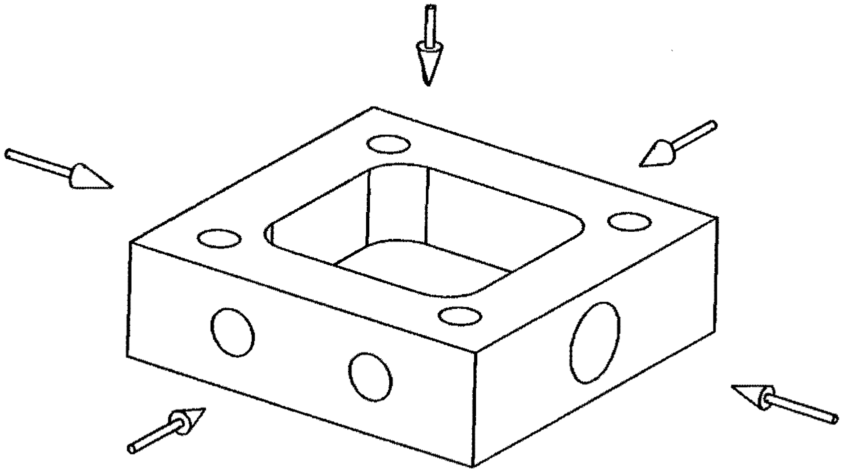
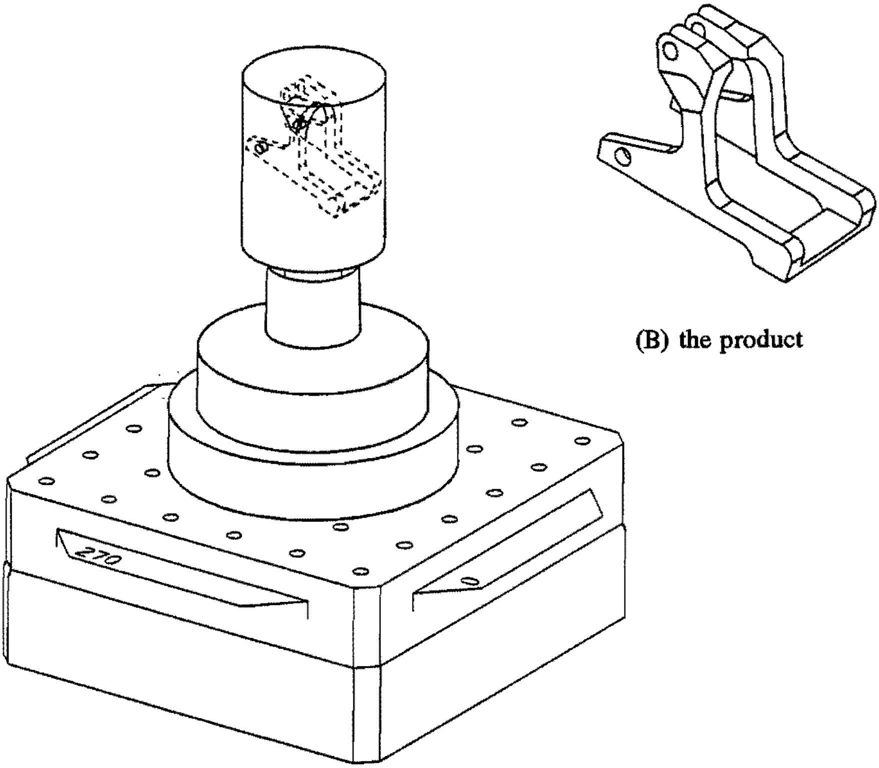


Fig. 5.8: A vertical/ horizontal MTS schematically

The task structure allows holes and cavities in the top surface and on side surfaces. All side surfaces are created by contouring and face milling, by which method no exact positioning is required when placing the stock material on the machine tool.

The sculpturing MTS

By the sculpturing MTS, the stock material is clamped in a fixturing device at one end (Fig. 5.9). The extending part of the material can be manufactured by horizontal and vertical operations. The final operation cuts the bottom surface of the component, leaving a small piece of material to keep a connection to the clamped part of the material. It is not allowed that the component would fall down while the tool spindle is still rotating. As posttreatment after the milling process, the component need to be freed from the bottom part (by sawing or breaking). By this MTS components can be produced which are sculptured on all sides, including the bottom surface.



(B) the product

(A) The set-up

Fig. 5.9: The sculpturing MTS

5.2.4 Standard fixtures

There are many fixturing devices available on the market which have specific advantages depending on the circumstances. However, DfMASS requires to standardize in as few fixturing solutions as possible, because it is hard to be familiar with all kind of fixturing systems during Manufacturing Design. For the manufacturer also welcomes a limitation in fixturing devices, because it is expensive to have all kind of fixtures available. Also by a large variety of adjustable fixtures it is difficult to instruct the operator how to apply the fixtures in the different situations defined by the manufacturing designer. Standard set-up configurations on the other hand, reduce failure risks and preparation time. Standard fixtures are kept in the fixtures library. Using fixtures from this library, the designer automatically obtains the required geometry in his CAD file. Applying non-standard fixtures require the designer to enter the fixture geometry in his CAD file.

The costs required for designing and acquisitioning a special fixture are relatively high (compared to the total manufacturing costs), especially if the lotsize is small. It is also an experimental fact that special fixtures initiate a lot of risks for the production phase (fixture not ready, components of fixture missing, fixture does not function, wrong use of the fixture, missing information etc.). Therefore, it is recommended to define extra standard fixtures, in cases the available set is insufficient (by on-the-job-standardization).

One should put special attention to the range of possible applications of a standard fixture, while selecting or designing it. It is also desired to choose fixture devices which can be applied in combination with other fixtures (identical hole diameters, identical pitches, suitable sizes, modular systems).

By having a sufficient number of standard fixtures, the manufacturing designer will be able to adapt his designs to these fixtures. It will be a challenge for the designer to design within the application limits of the standard fixtures, especially if it leads to a reduction of manufacturing costs. If a sufficiently large set of fixtures is obtained, the phenomenon of special, once used, fixtures will become an exception. In case the designer wants to deviate from the available standards, he should always be confronted with the question "Do you really need a special fixture?". If the answer is "Yes", the next question should be: "Is it worthwhile to define an extra standard fixture?".

In the DfMASS project, fixturing is concentrated on the use of small interchangeable top pallets, which can be mounted on a bottom pallet [40]. The bottom pallet will stay on the machine tool for several jobs (Fig. 5.10). The pallets are small because small pallets can be handled easily[1]. The material is mounted on the top pallet outside the machine tool. The placement of the top pallet on the bottom pallet on the machine tool takes less than a minute. Idle time of the machine tool, due to mounting of fixtures on the machine tool can be reduced to a single minute.

The pallets have a pitch of 8mm holes for fixing material on the pallet. If tapped holes are present in the start material, the start material can be bolted on the pallet. Extra devices are available to mount on the pallet, for different fixturing configurations.

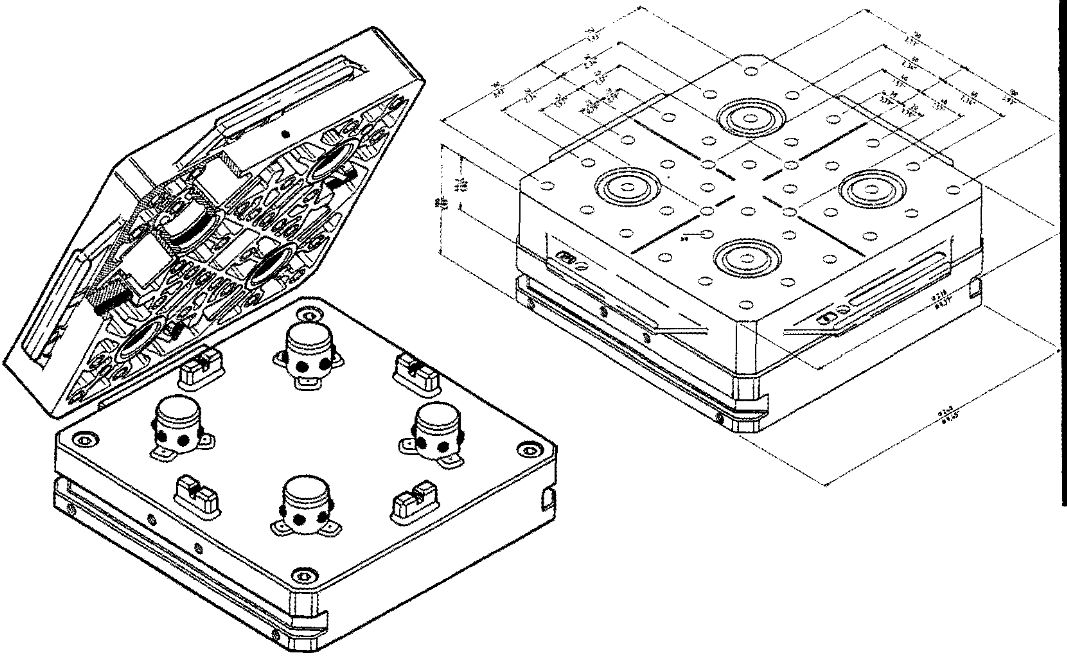


Fig. 5.10: The pallet system

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[1] Due to modular design (see Section 4.2), the majority of components is small and can be produced by small pallets. For the larger components another solution is required. An example of manufacturing larger components is illustrated by the module house example of fig 5.26.

The pallet system provides another possibility: low cost automatic pallet changing[1]. Pallets mounted with stock material are stored in a cabinet. A robot picks a pallet from the cabinet and positions the pallet on the machine tool (Fig. 5.11). After the production cycle is finished, the robot takes the pallet off and places it back in the cabinet. Then, the robot picks the next pallet and positions the pallet on the machine tool. This process goes on until all pallets of the cabinet have been used. This way of working increases the unmanned production time considerably. The investments are relatively small, compared to a machine tool including a pallet changing device. Also the number of pallets of this system is larger (about 20 positions) compared to a machine tool with pallet positions (between 2 and 10 positions). Restriction of the presented robot system is the limited size and weight of stock material[2].

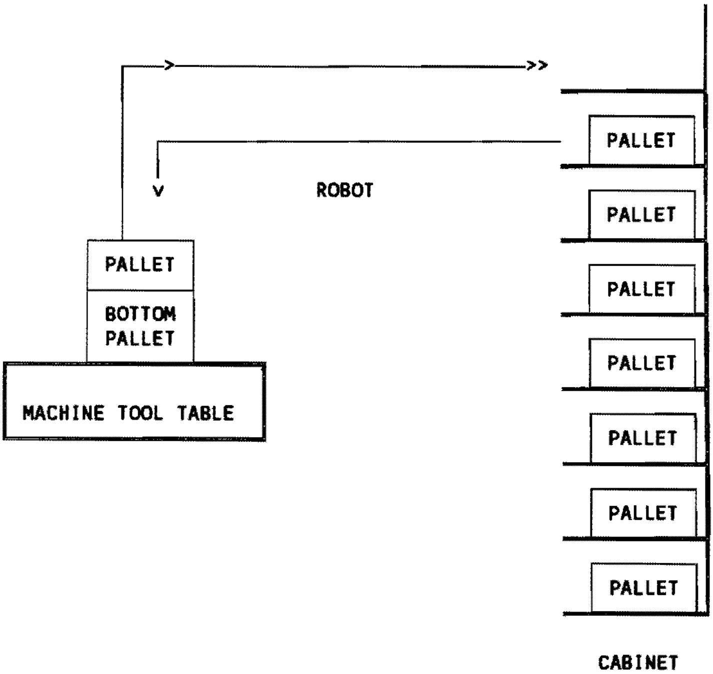

Fig. 5.11: The pallet changing device

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[1] This feature has not yet been installed at Philips Lighting, but may be considered as future extention. Suppose the investment for the device is $ 25.000,-, it will be worthwile if more than 100 unmanned hours per year can additionally be applied by this device (for an indication of possible unmanned production, see Section 6.4).

[2] Of course, this system is only applicable for cycles in which the amount of needed tools does not exceed the maximum number of tool positions of the tool changing device.

5.3 Applying Manufacturing Families

In a Manufacturing Family a lot of standard solutions (by means of design and manufacturing decisions) are collected in a standard product model database. Such a database can be used in new designs by copying the information into the new design and adapt it. Especially the allowance of adding features, by which the borders of a Manufacturing Family will not be passed, increases the variety of components belonging to the same family. Manufacturing Families avoid re-inventing already existing solutions. It has proven to be a very powerful way of re-use of design and manufacturing technology. Of course, Manufacturing Families must be tuned to the needs of the organization which uses them.

It would be nice to know, to what extent a family member may be adapted and changed, while still belonging to the same Manufacturing Family. However, it is utterly impossible to define the maximum possible variety of entities, within the same Manufacturing Family. The limits of data values are interrelated: values of some data influence the allowed ranges of other data. Currently, it is part of the designer's experience to know if borders of a Manufacturing Family are passed. The closer he comes to the border, the more he needs to check the process plan applicability. In the future, a family controller functionality (see Appendix E) may help the designer to stay within the limits of a Manufacturing Family.

Some components play an important role in the functions of the mechanical system, for those components the selection of a Manufacturing Family must already be done during the Functional Design (for instance the module house, Figs. 5.25 to 5.28 on pages 108 - 110). Other type of components serve a detailed function, which selection can be postponed to Manufacturing Design. In many cases, minor changes to the standard component are sufficient to create the desired specific component. For major functions, which are being applied in several projects, it is efficient to design an assembly, constructed from components belonging to Manufacturing Families. Because of the advantages of using Manufacturing Families, it is important to apply as much Manufacturing Families as possible, during each design decision. For special components, there may be no family present. Still some parts of a Manufacturing Family may be used for these special components. For these situations, a family may be partially used.

The creation of the Manufacturing Families has also been based on on-the-job-standardization. If, during a job, components need to be designed, from which it is worthwile to create a family, following special care must be applied:

1. Describe the process plan[1].
2. Evaluate the geometry of the component and change it, if necessary.
   Pay attention to arbitrary geometry shapes. Maybe another shape can be manufactured easier, or another shape will be easier in adjusting lateron.
3. Evaluate the process plan and change it if another solution is more efficient.
4. Define the variety for the different properties, by which the process plan still does not change (e.g. what is the maximum size, by which this process plan is still valid).
5. Document the Manufacturing Family.

Dependent on the type of mechanical systems to be designed, dependent on the applied manufacturing technology and dependent on the progress in manufacturing solutions, the set of Manufacturing Families will change during the time.

It should be noted that in many cases, material type is not a part of the family restrictions, because the technology will independently be derived from the technology libraries. Only for fixturing there may be a material restriction, if the forces due to cutting are too strong.

In the DfMASS project, it appeared to be efficient to construct structures from rather large pieces of aluminium, by contouring the outside and cutting the pockets[2]. This type of components replaces welded constructions, by which the routing reduces several manufacturing processes. For instance a welded housing may require six components for which 15 processes are required (six times cutting pieces, six times milling pieces, welding, final milling, finishing). The aluminium redesign requires 2 processes (milling bottom surface, milling top and side surfaces, Figs. 5.21 to 5.24 on pages 106 - 108).

For the wearing sections of the mechanical systems, tool steel is used, for which the sizes have been reduced to a minimum, because it is time consuming to mill tool steel, compared to aluminium. The tool steel components are connected to an aluminium housing.

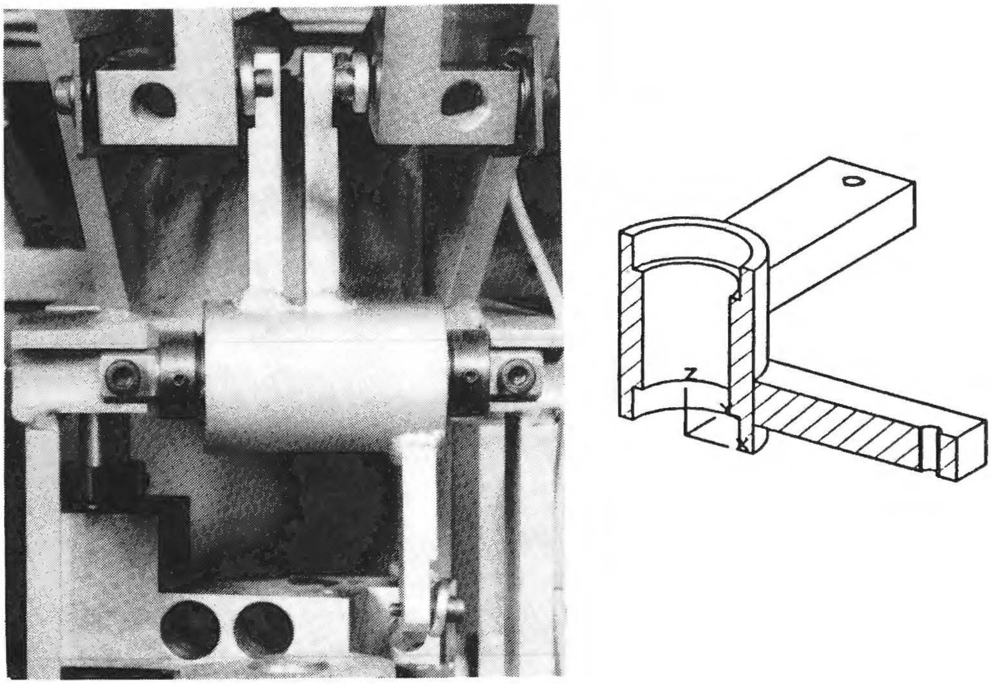
[1] Pretreatments, fixture set-up, minimum machine tool configuration, manufacturing task structure, interrelations between features, (no, or how), posttreatments.

[2] A special type of cast aluminium has been selected which has a high tensile strength combined with a minimum of internal stress.

Next, some examples will be described, to illustrate the philosophy of Manufacturing Families. Of course, each company will have its own type of components, to standardise on.

1. The lever family

Conventionally, levers were constructed by a piece of tube with welded wings (Fig. 5.12. The process planning of this type of levers consists of cutting a piece of tube, milling wings from steel plate, welding the wings on the tube, milling the top hole in the tube and a hole in the top wing in the first set-up, turning the lever upside down in the second set-up and milling the second hole in the tube and milling the hole in the second wing.



A three-wing lever in an assembly *a two-wing lever*

Fig. 5.12: the conventional lever

The DfMASS redesign of the lever produced the following manufacturing family. The stock material is a block of aluminium with two holes drilled in the bottom surface. The block is fixtured on a pallet by two bolts. Extension rings free the block from the pallet (Fig. 5.13).

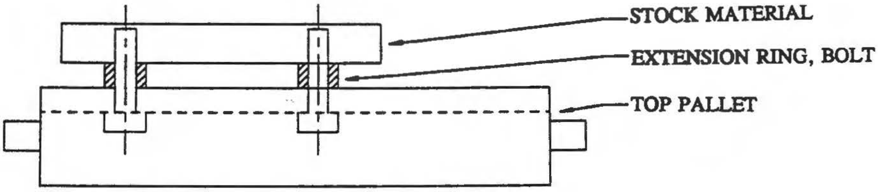


Fig. 5.13 A: A sketch of the fixturing configuration

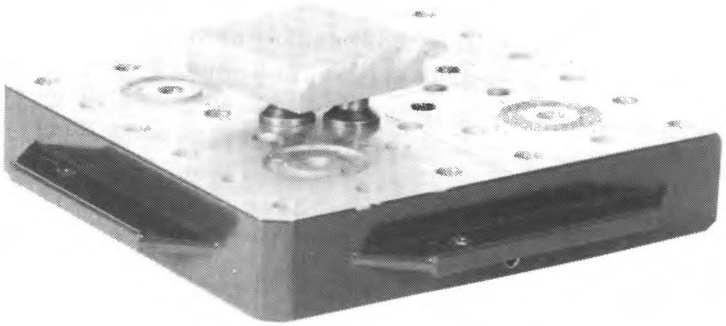


Fig. 5.13 B: A picture of the fixturing configuration

In a single set-up the lever is contoured and the holes are milled (Fig. 5.14). Because all surfaces, except the bottom surface are generated by milling, there is no need for fine positioning when placing the stock material on the machine tool.

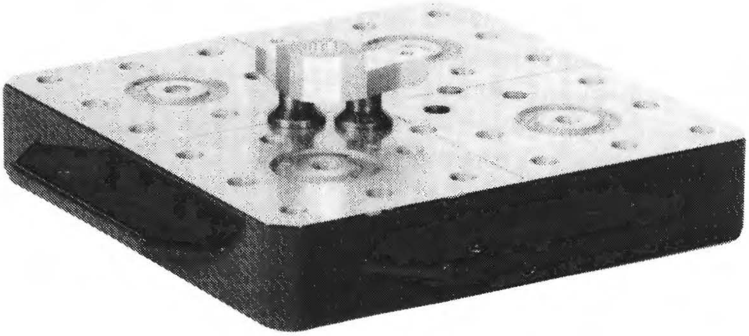


Fig. 5.14: The product after milling

In Fig. 5.15, levers are presented, which are manufactured by similar techniques.

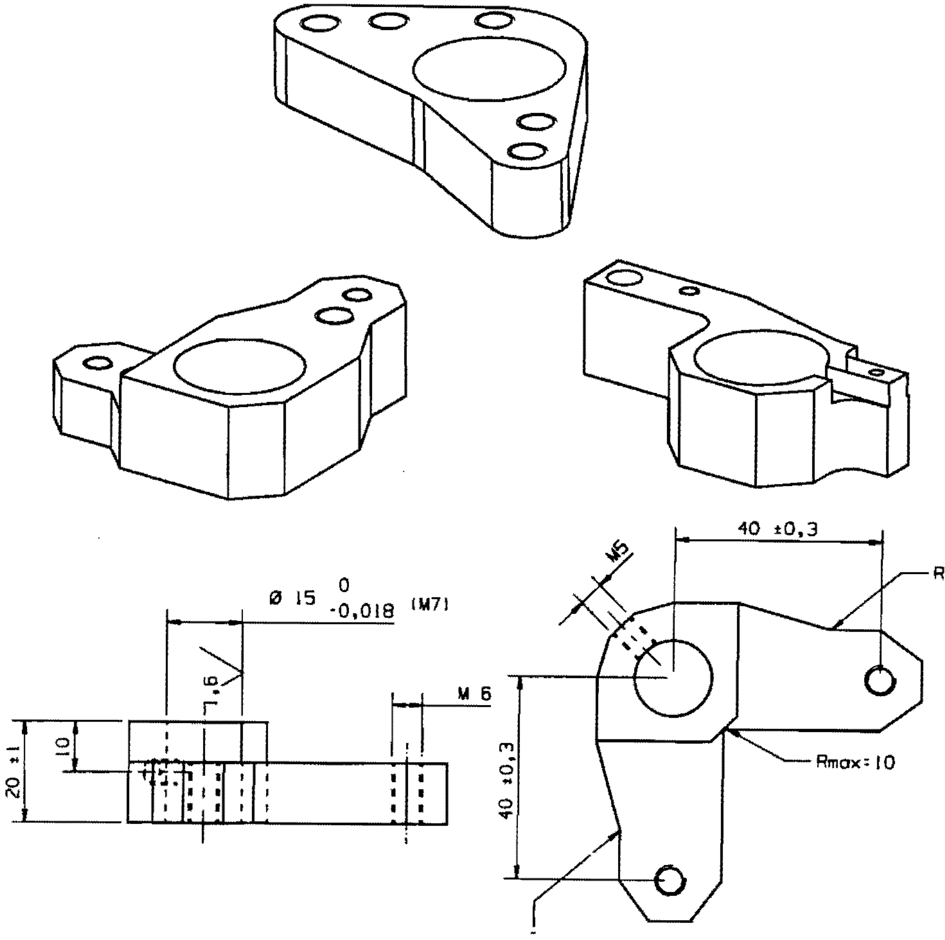


Fig. 5.15 A: Sketches of levers

Fig 5.15 B: Pictures of levers

Designing a specific lever, derived from a standard lever, may require an adaptation of the angle between the wings and an adaptation of the lengths of the wings. The time required for such a design is less than 15 minutes.

Conventionally, the lever has been produced by a total of six manufacturing processes. The alternative lever is milled in a single set-up, after two holes have been drilled as pre-treatment. The manufacturing time is approximately 20 minutes.

2. The standard CAM

For designing and manufacturing cams (Fig. 5.16), a parameterized program has been developed by with the contour of the cam is automatically generated from input values. The input values define the offset of the radius per angle by a mathematical function (e.g. a part of sinus). Blanks have been standardized for different types of cams. A blank is fixtured on a standard fixture device on a pallet. The manufacturing phase consists of milling the contour of the cam and engraving text. The manufacturing design time is less than 15 minutes. the manufacturing time is approximately 30 minutes.

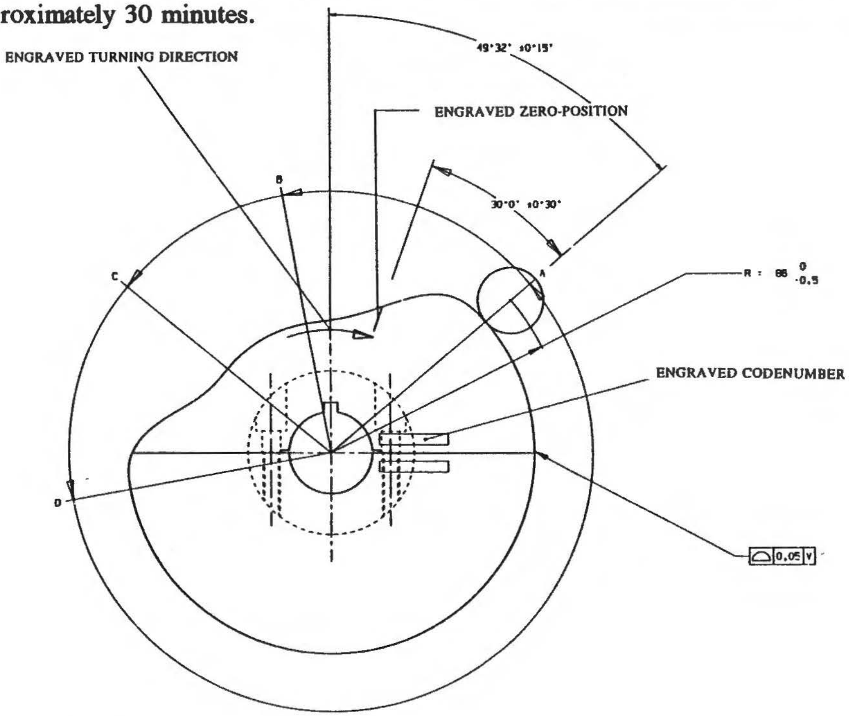


Fig. 5.16 A: A sketch of a cam

Fig. 5.16 B: A picture of cams

3. The standard house

In different designs, a house is required (Fig. 5.17).

Fig. 5.17 A: Assemblies based on a house

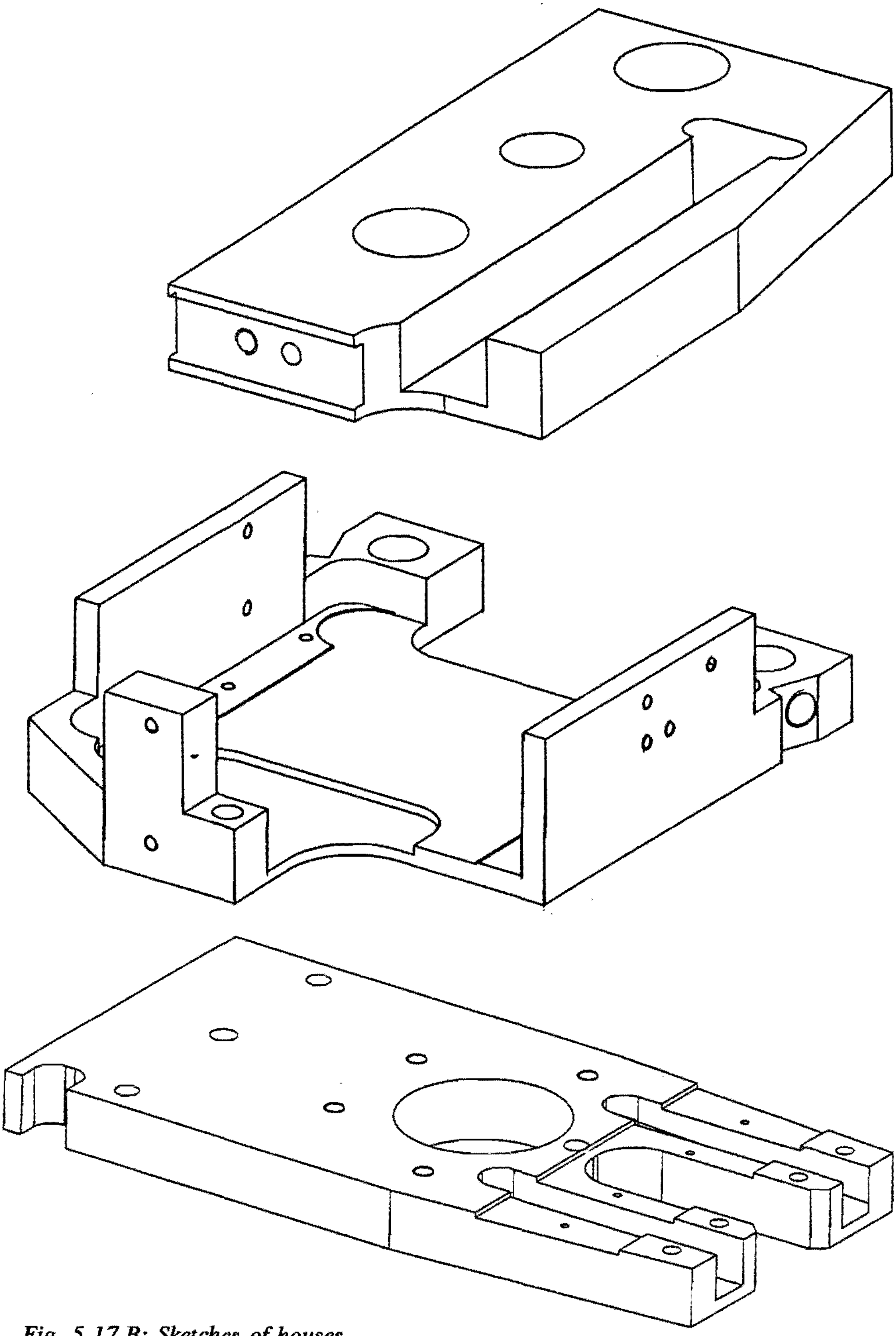


Fig. 5.17 B: Sketches of houses

For this kind of houses a Manufacturing Family has been developed. The family is based on vertical and horizontal manufacturing operations. No manufacturing is required in the bottom surface. The stock material consists of a block of aluminium (in some cases tool steel), containing two or more holes in the bottom surface. Because of the horizontal operations the fixturing must imply an offset from the machine tool table, to enable the horizontal ram of the machine tool to approach the component. For this purpose an offset fixturing devices has been developed which can be mounted on a pallet (Fig. 5.18).

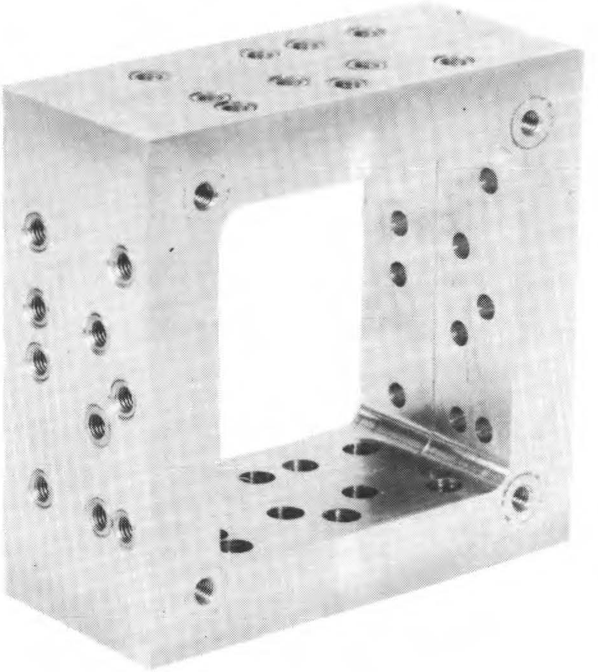


Fig. 5.18: The offset fixturing device

The stock material is fixtured on the offset block by two or more bolts from underneath. Extention rings have been used to free the stock material from the offset block. The house is manufactured by horizontal and vertical manufacturing operations. Because all surfaces, except the bottom surface, are produced by contouring and face milling, there is no need for fine positioning when placing the stock material on the machine tool. Fig. 5.19 presents a picture of a house on the fixturing configuration.

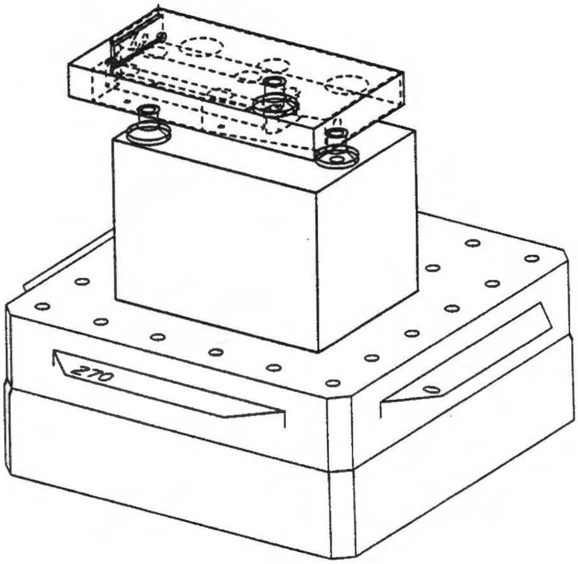


Fig. 5.19 A: A sketch of the house on the fixturing configuration

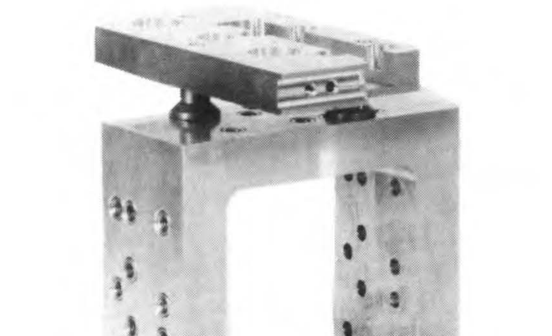


Fig. 5.19 B: The house on the fixturing configuration

In Fig. 5.20, a house is presented, which have been manufactured by the described method.

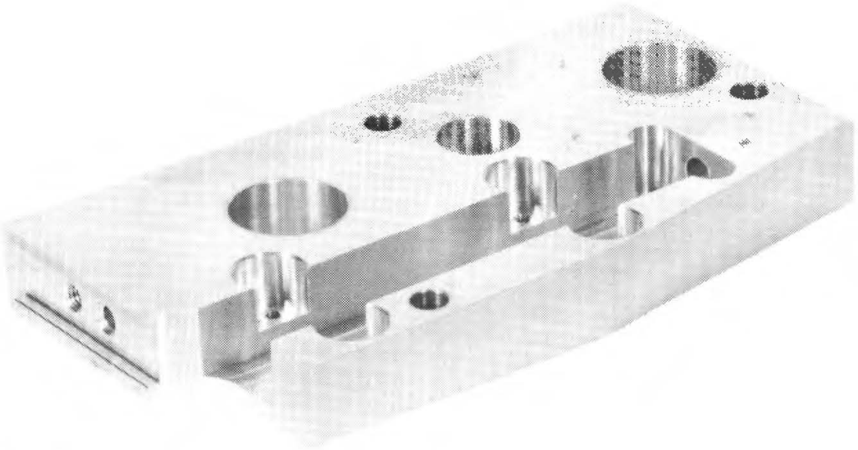


Fig. 5.20: House

4. The module house

In the modular design of production tools at Philips Lighting, different modules are placed on a standard basic machine containing an indexing turn table. Per module a module house is used on which the mechanical functions are built. Each module house is a variant design of a standard house. The stock material of the module house is a block of aluminium. In the first set-up, the block is clamped on the machine tool by machine clamps. There is no need for fine positioning of the block, because all surfaces will be milled. In the first set-up, the bottom surface is face milled, the contour of the bottom part of the house is milled and the holes in the bottom surface are produced (Fig. 5.21).

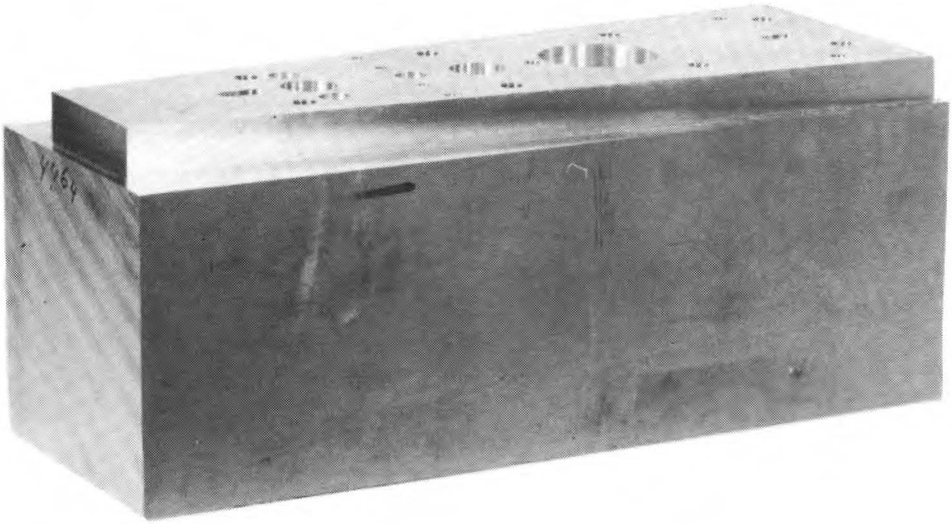


Fig. 5.21: The result of the first set-up

For the second set-up a standard fixturing devices has been developed (Fig. 5.22). The device is positioned at X=0 and Y=0 of the machine tool by a boss on the bottom surface. The center line of the device must be positioned in line with the X-direction of the machine tool. Now the devices must be fixed on the machine tool by bolting the side slots.

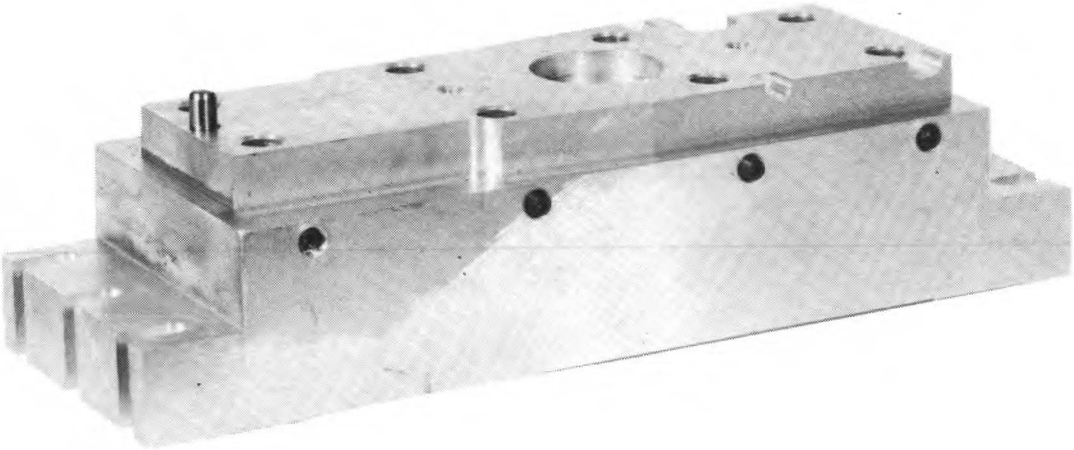


Fig 5.22: The fixturing device for the second set-up

The stock material is turned upside down and positioned on the fixturing device by a ring which positions the the main hole of the bottom surface of the stock material relative to the main hole of the fixturing device. The boss in the fixturing device snaps in a slot in the bottom surface of the stock material, by which the X-direction of the stock material is positioned. Fig. 5.23 shows the start position of the material for the second set-up. Now the manufacturing operations of the second set-up can take place, resulting in a module house (Fig. 5.24). Figs. 5.25 to 5.28 present illustrations of module houses.

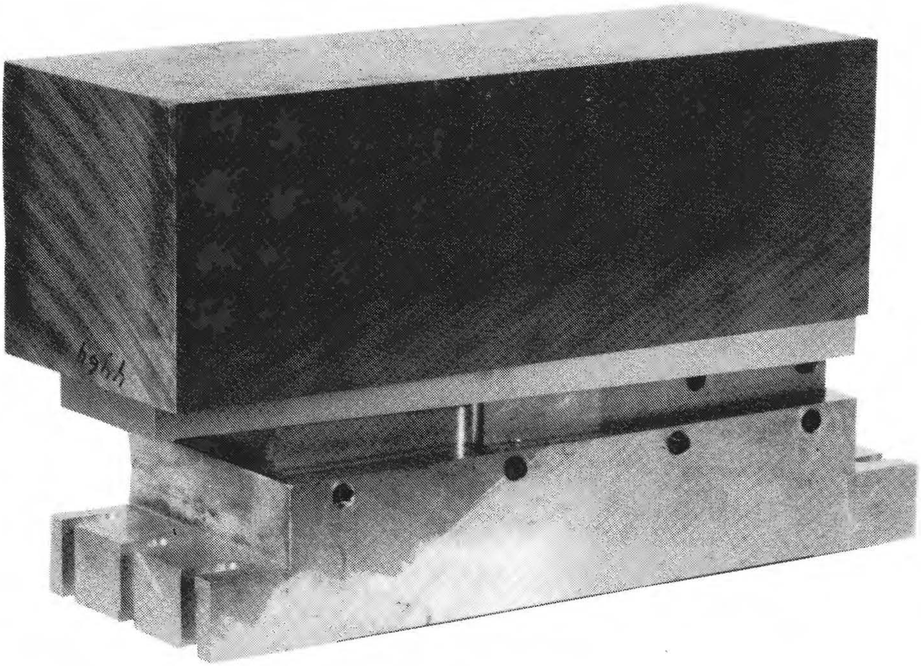


Fig. 5.23: The start situation for the second set-up

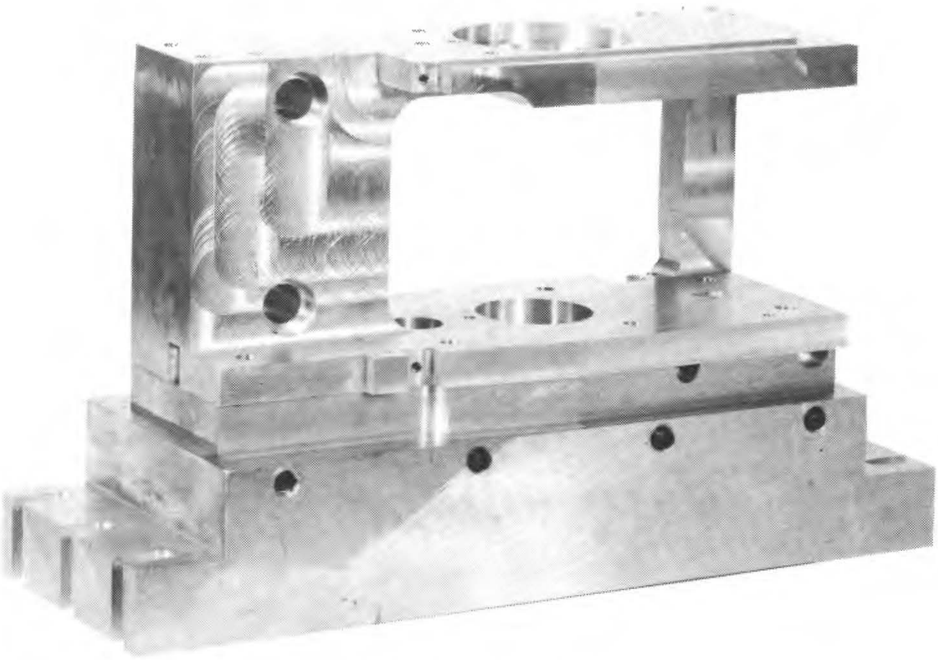


Fig. 5.24: The end situation for the second set-up

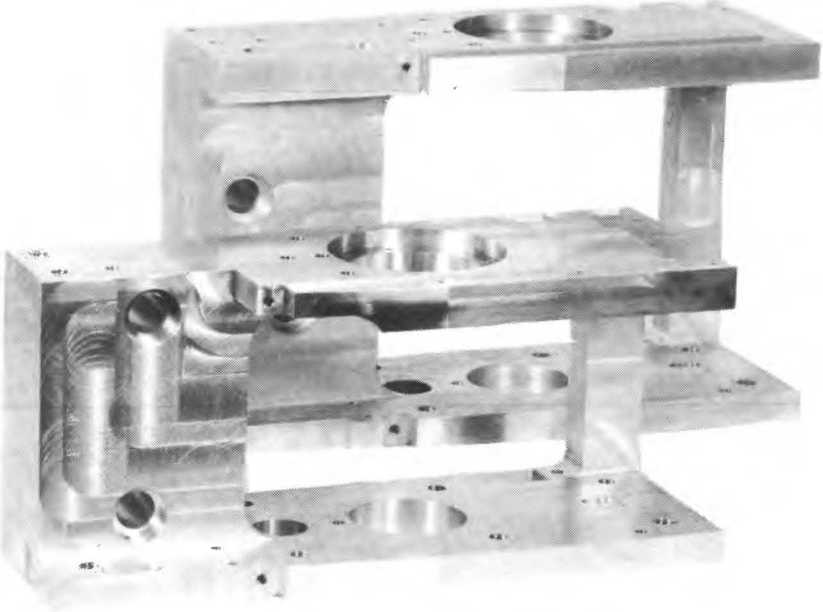


Fig. 5.25: Two examples of a module house

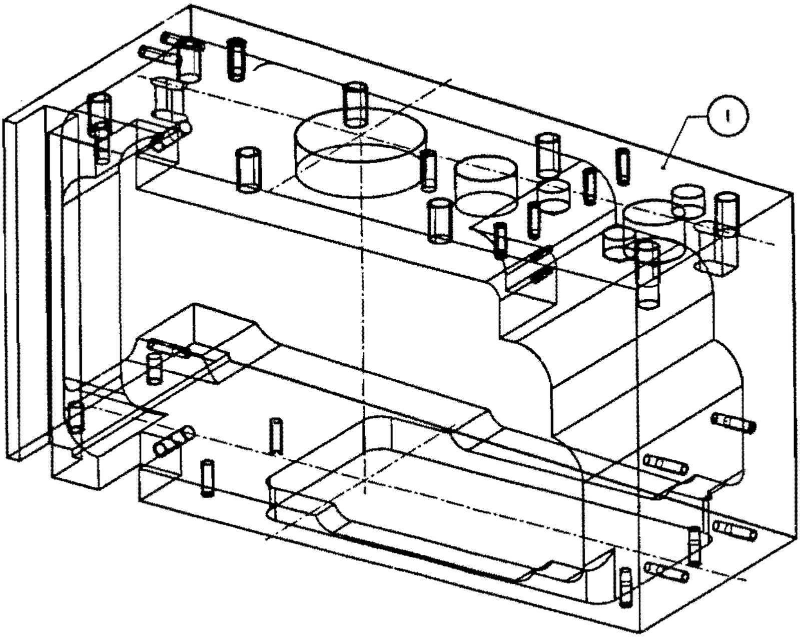


Fig. 5.26: A wire frame representation of a module housing

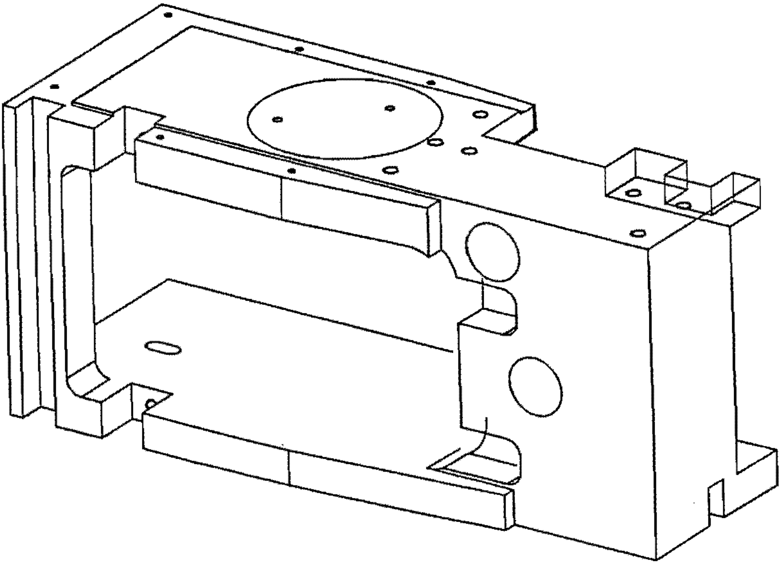


Fig. 5.27: A hidden line representation of a module house

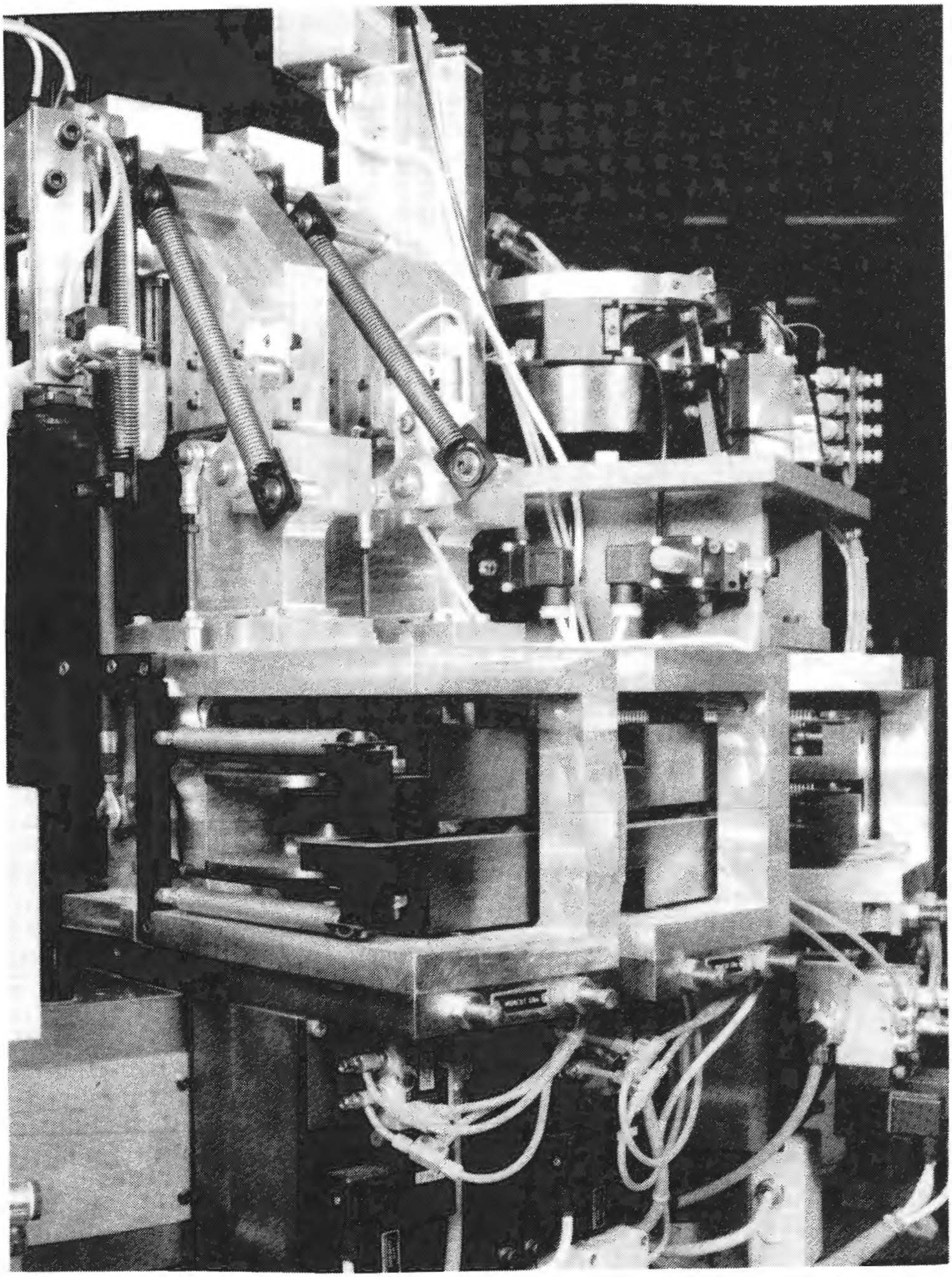


Fig. 5.28: Module houses on a production machine

By this method module houses can be produced with high quality, because the relative positioning between the first and second set-up is very precise.

5.4 Summary

A Manufacturing Family consists of a minimum machine tool configuration, a manufacturing task structure and a fixturing configuration. If consistent with the manufacturing task structure, it is allowed to add features without extending the limits of the Manufacturing Family. The NC dataset is generated based on a technology library. A description is made on components which can be manufactured within the limitations of this set of characteristics. At the start of Manufacturing Design, it will be decided, whether functional requirements can be translated in a component, which is a member of a Manufacturing Family. In that case, Manufacturing Design has been shrunked into copying the data of the Manufacturing Family and making adaptations in the copy file.

If a component is designed as a family member of a proven family, following advantages are achievable:

- accurate cost estimation,
- time savings in Manufacturing Design,
- known set-ups, available fixtures,
- no process planning mistakes,
- known quality of endproduct.

By discussing, evaluating and documenting the limits of a Manufacturing Family, the designer gets a feeling for manufacturability. It appears to stimulate the designer in thinking about manufacturability.

6. THE LOGISTICS OF MANUFACTURING

Introduction

In the present chapter, the difference will be shown between the logistics of Manufacturing conventionally and DfMASS, by first describing the conventional order activities, secondly indicating which of these activities are redundant for DfMASS and finally describing the manufacturing activities which remain in DfMASS (Fig. 6.1).

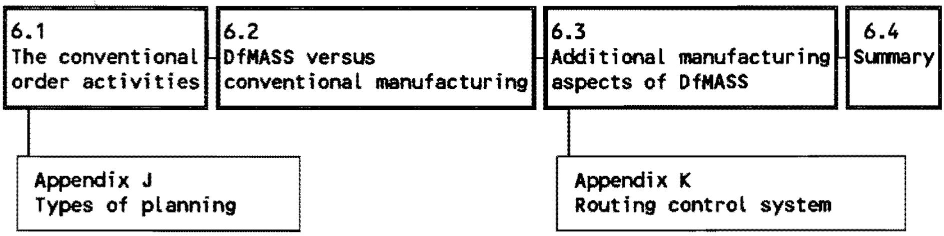


Fig. 6.1: Structure of this chapter

The design and manufacturing environment, considered in this thesis, is a typical engineer-to-order situation. Design activities are mainly driven by customer orders. The manufacturing orders follow from the design output. There is hardly any repeat in manufacturing orders. In this environment, logistic aspects are important for achieving the right results at the right time. By logistics is meant the organization, planning, control and execution of the manufacturing operations in order to satisfy the right quality, at the required leadtime within competitive costs.

In industry, time and costs involved in logistics are a significant part of the total leadtime and costs. In the process of creating mechanical systems the leadtime of Manufacturing is merely caused by the logistics of the process (waiting times are much longer than production times). This situation occurs particulary in prototyping and in other small lotsize production.

The efficiency of a production process can be improved by merely organizational measurements, without affecting the technical contents of the process. Examples of measurements are automated control systems, planning methods and organizational measures (like MRP, JIT, OPT and other production control systems [45].

A different approach in improving efficiency is by changing the technical contents of the processes involved to avoid logistic bottle-necks.

Bradley [46] mentions goals for competitive manufacturing:

- automatic generation of NC files from 3D models,
- simulation of production costs,
- sharing of electronic product data between Design and Manufacturing,
- families of product variants.

In his study on paperless manufacturing, Schijven [37-3] concludes that it is very complex to automate process planning, if Design is not involved in manufacturing decisions. Without this involvement, he does not see progress in paperless manufacturing.

In the Deere's CIM story, Rankin [47] describes the integration of the computer in the overall engineering and production process at the Deere[1] company. For this integration it was needed to simplify the manufacturing organization, and to provide a bridge between CAD and CAM by the use of features. In Deere's story it has been essential to influence the whole process from design to production. In the contrary to the DfMASS study, Deere does not combine modelling and process planning.

In DfMASS, logistic problems are avoided by reducing the logistic complexity by changing the primary design and manufacturing process. No further management attention is required to maintain these logistic advantages, because they are embedded in the working procedures.

6.1 The conventional order activities

This section describes the conventional way of producing large amounts of manufacturing components in a machine factory environment. Input of the process are the technical drawings and the bill of material, produced by the design office. The output are components required for Assembling (Fig. 6.2).

Fig. 6.2: The in- and output of Manufacturing

Different ways of planning (sequential; concurrent, see Appendix J) may be applied for the total process of design, manufacturing and assembling, dependent on the available capacity and on the leadtime requirements. The planning may also be influenced by the delivery dates of long leadtime purchase parts, which are on the

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[1] One of world's largest producers of agricultural equipment.

critical path. This chapter does not intend to deal with the planning and organization of order control in detail, but intends to demonstrate the reduction of complexity of the manufacturing process.

After Design has produced the drawing package of a system, the manufacturing order activities take place. It is divided into the following phases[1], which are illustrated in Fig. 6.3.

Aktivity 1: **Order acceptance**
Based on the available free capacity of the factory, known from the rough-cut planning, also considering third party capacity, the delivery date of the total package of manufacturing components is defined, after a rough estimate is made on the required total capacity and on the longest leadtime manufacturing components. The delivery date is presented to the client for approval, one week after request. At this stage it is not known, which manufacturing processes will be required, thus no claim can yet be put on capacity needed. Another activity, related to order acceptance, is the purchase of purchase items.

Aktivity 2: **Overall order control**
The overall order control manages the delivery of components. The activity contains:

- order split-up,
- workshop planning,
- delivery control.

Aktivity 2a: **Order split-up**
The total drawing package is checked against the bill of material, to see whether all the information is available. The components are divided into turning parts, small prismatic milling parts, large prismatic milling parts and others. Based on the available workshop capacity, it is decided whether the order can be accepted in the workshop. If the obtainable delivery dates do not match with the agreed delivery dates of the order acceptance, other capacities (third parties) need to be searched for, or priorities need to be reset. The overall order control monitors the division of orders over the different capacities.

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[1] The description is situated in a manufacturing order for a production machine for automated lamp assembly, containing a standard basic machine on which 42 modules are designed, each module executing a specific function. The basic machine can be ordered from a standard set of drawings. The modules in total contain circa 340 different milling parts in lotsizes from 1 to 42 and a few non standard turning parts.

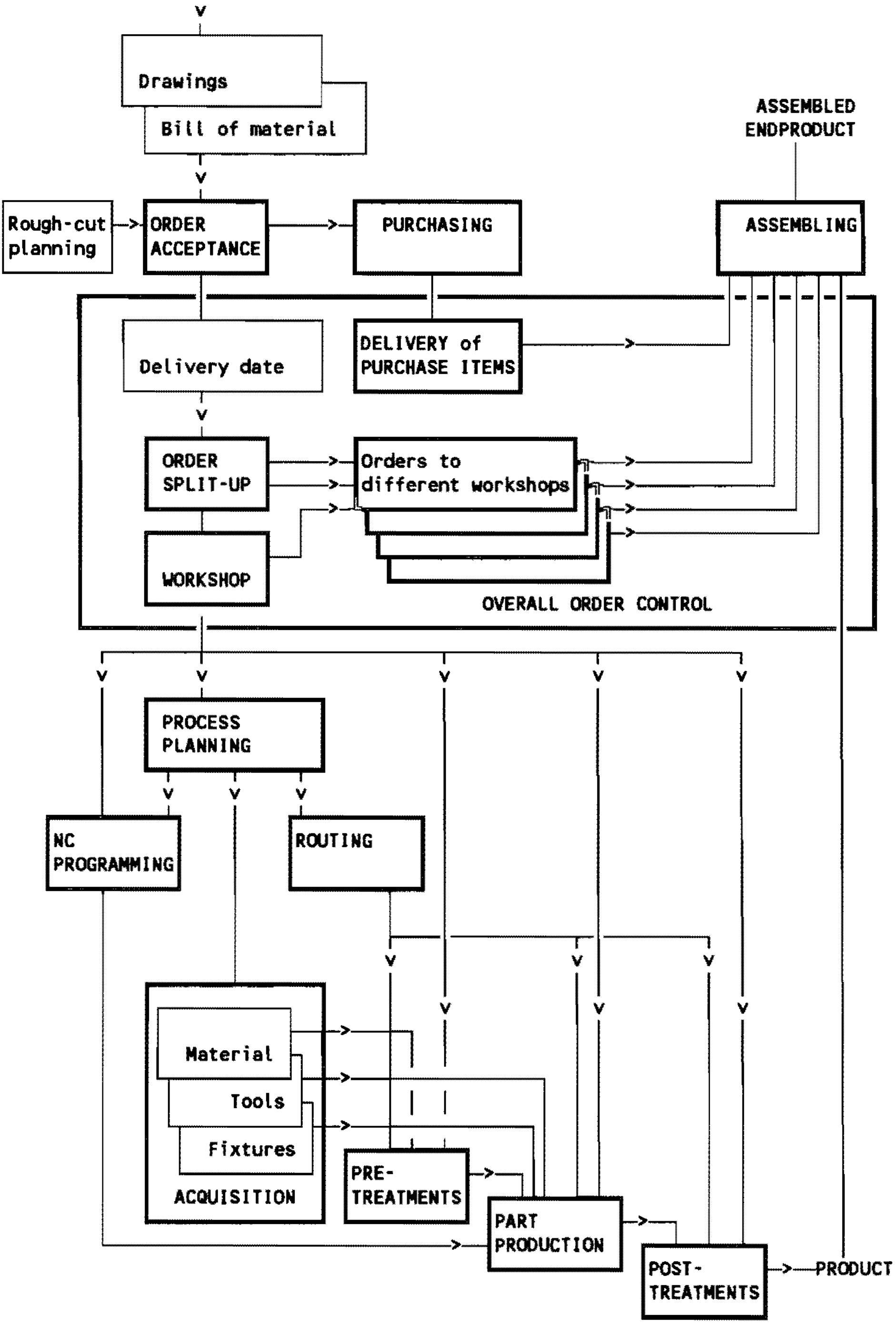

Fig. 6.3: Order activities of Manufacturing conventionally

Aktivity 2b: Workshop planning

Process planning, NC programming, material-ordering and -delivery, pretreatment-ordering and -delivery, preparing for production, production, posttreatment-ordering and -delivery and final control are activities controlled by the workshop planning. It is an important planning issue having the ability of priority setting of work, dependent on above mentioned interrelated activities. For instance, one can not delay production when an agreed delivery date for posttreatments will be exceeded or new agreements on posttreatment planning must be made.

The workshop planning will be adapted each time the contents of activities change, dependent on results of an activity. For instance, the process planning may lead to a different routing than was presumed in the first instance. Another example is the appearance of a process planning error during NC programming. In those cases it may even be necessary to replace an order to a third party, if the agreed delivery dates can not be fulfilled in the own workshop, because of the arosen delay.

Aktivity 2c: Delivery control

If the capacity of the the production of manufacturing components is divided between different workshops, the overall order control manages the delivery of orders. Besides, the overall order control checks the delivery of the purchase parts. Because the delivery dates of purchase parts and manufacturing components have a close relation to the assembling planning, it is usual to employ an overall planning schedule in which the main relations between purchase planning, manufacturing planning and assembling planning are tuned. In cases of problems in delivery, it can be checked whether a delay is acceptable.

Aktivity 3: Process planning

For all manufacturing parts the process planning will be carried out, defining stock material sizes, machine tool selection, fixturing, sequences of operations and pre- and posttreatments. In average, the routing per component will require 5 manufacturing processes. The most complex part will require up to 15 manufacturing processes. From the process planning a detailed calculation can be executed, resulting in the required capacities per machine tool. The workshop planning can be adapted by these more accurate figures. The process planning activity can easily require six weeks of throughput time.

After the process planning has been finished, three activities can be executed concurrently:

4. NC programming,
5. Acquisition,
6. Routing.

Aktivity 4: NC programming

If the process planning indicates NC programming, the drawings will be send to the NC programming department. NC programming will require approximately 3 weeks of leadtime. The acquisition will need to be reworked if during NC programming material sizes have been changed, or special tools or special fixturing devices are required.

Aktivity 5: Acquisition

After the process planning is finished, the ordering of material, extra tools and special fixturing devices can start. This will take 1 to 6 weeks depending on the availability of the items in the market. For some critical items acquisitioning may have already started in an earlier stage.

Although undesired, in some cases purchase parts, or even specificly manufactured parts are needed. Purchase parts require ordering and leadtime while specific parts need to be specificed, ordered and assembled. In case of manufacturing components are required, a similar process as for common manufacturing components will take place. In case of an assembly, also the assembling phase must be planned (Fig. 6.4).

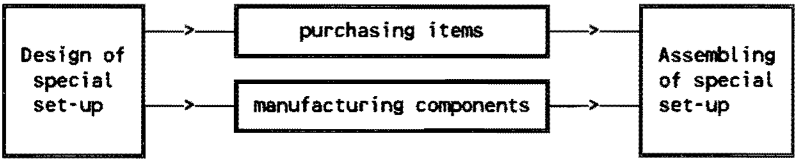

Fig. 6.4: A special set-up is a D&M process on its own

Aktivity 6: Routing

From the process planning information a routing is derived which need to be checked against the available capacity. In case of insufficient capacity, orders must be placed at third parties (see overall order control). The routing will control the flow of material from acquisition, pretreatments, preparation & production, posttreatments upto delivery.

Aktivity 7: Pre- and posttreatments

Dependent on the possibilities of the material supplier and the costs and leadtime involved, pretreatments may be part of the agreement with the supplier, or needs to be carried out in the workshop, or needs to be ordered through a second supplier. Posttreatments will be carried out after production. In case of complex pre- or posttreatments, these processes will follow the same workshop procedures as a workshop order (starting with activity 2, workshop planning).

Aktivity 8: Part production

After the NC program is ready and all the material is delivered (including special fixtures and tools, if applied) the production can start. Dependent on the routing, the material will follow several stations through the machine factory. Per station the operator collects the required fixtures and tools, mounts the material on the machine tool and starts production. Per production step, one week of throughput time is commonly required[1]. Thus for components with a routing of six stations, at least six weeks of throughput time is required.

Evaluation

Process planning is the backbone of the manufacturing control system, because it defines the actual activities to be carried out. By a variety of required manufacturing activities, the resulting logistic process is extensive (Dirne [8]), leading to complex organisations and long leadtimes.

In Fig. 6.5, the activities have been drawn in sequential order, from which the total timeframe of Manufacturing is shown. The mentioned throughput time is an indication[2] to illustrate the total required leadtime of Manufacturing.

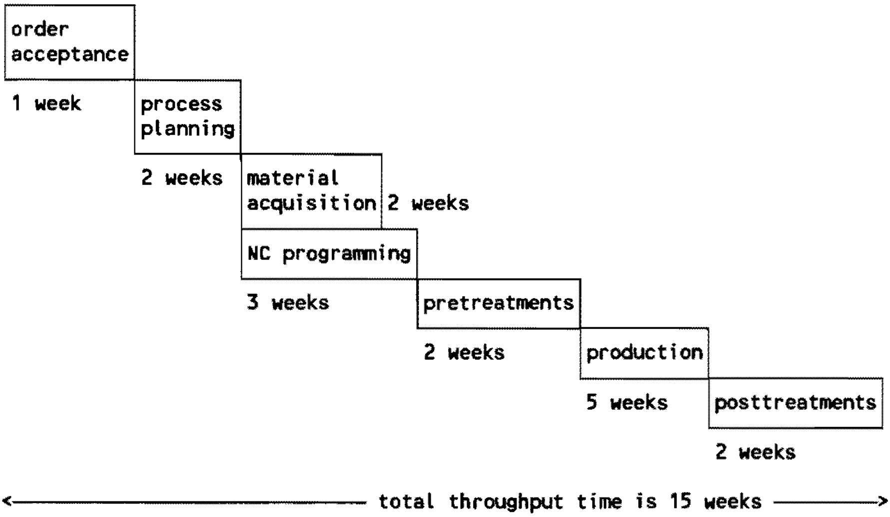

Fig. 6.5: The timeframe of Manufacturing conventionally

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[1] Bertrand c.s. [45] mentions a throughput time of 3 to 10 times the average processing time of a batch. A batch size of 4 to 8 hours results in a throughput time of one week per production step.

[2] The mentioned figures are indications, just for illustration purpose. Dependent on the organization and on the order load and available capacities, they may be different.

6.2 DfMASS versus Manufacturing conventionally

By implementing DfMASS, the complexity of the described manufacturing activities can be reduced substantially. DfMASS allocates all technological decisions to Design. Consequently Manufacturing is reduced to production without technological activities. This has a great influence on the logistics of the remaining manufacturing process. The main logistic differences in Manufacturing are:

1. Process planning and NC programming

Process planning is integrated in Manufacturing Design, thus does not need to be executed in the manufacturing phase. NC programming has been automated, for exceptional cases where still some NC programming is required, it is part of Manufacturing Design. As illustrated in Section 6.1, process planning is the backbone of the manufacturing control. By early knowledge of the process planning data, the routing of the manufacturing process can early be generated. By early knowing the production times, calculated from the cycle times in the NC dataset, and by the known routing, a detailed manufacturing planning can be made before the start of Manufacturing. Thus the need for a rough-cut planning has been eliminated.

2. Reduction of set-ups

By design for manufacturability, the number set-ups required for manufacturing of the component, will reduce if the designer is aware of the time and costs consequences of extra processes. In DfMASS designs, it is also intended to reduce the necessity of pre- and posttreatments. Reduction of set-ups and pre- and posttreatments has a great influence on the total leadtime of Manufacturing, because waiting times between processes are usually much longer than the processing times itself.

3. Reduction of fixturing configurations

By standard fixtures, selected for assurance of quality and efficiency of use, the preparation time for mounting the material reduces substantially. The avoidance of the need for special fixtures, or configuring a fixturing from adjustable components, reduces quite some preparing time and also reduces the risk of a rejected endproduct because of quality reasons.

4. Reduction of required machine tools

For a large part of the milling components,the selected machine tools (Maho 800 and Maho 600) have been sufficient. In the DfMASS project all parts could be manufactured by the selected machine tools. By reducing the number of required machine tool types, the number of machine tools of the same type will increase. Decrease of the variety of required machine tools, reduces the complexity of the planning and also increases the flexibility because there are more components to be produced on the same machine tool type, thus there will be more machine tools of the same type.

5. <u>Reduction of tools needed</u>
By the use of preferred feature values and automatic tool selection by the technology system (FAST-CADCAM), the number of tools needed has been decreased.

The qualitative indications of efficiency increase in this section, will be made quantitative in Section 7.1.

Through these five differences, Manufacturing has been changed. In DfMASS, Manufacturing contain the following activities:

- material acquisition,
* acquisition of purchase tools and special tools,
* acquisition of special fixture devices,
* pretreatments,
- preparation,
- production,
* posttreatments.

For many components designed for manufacturability, the marked (*) activities above are obsolete, by which only material acquisition, preparation and production remains (Fig. 6.6).

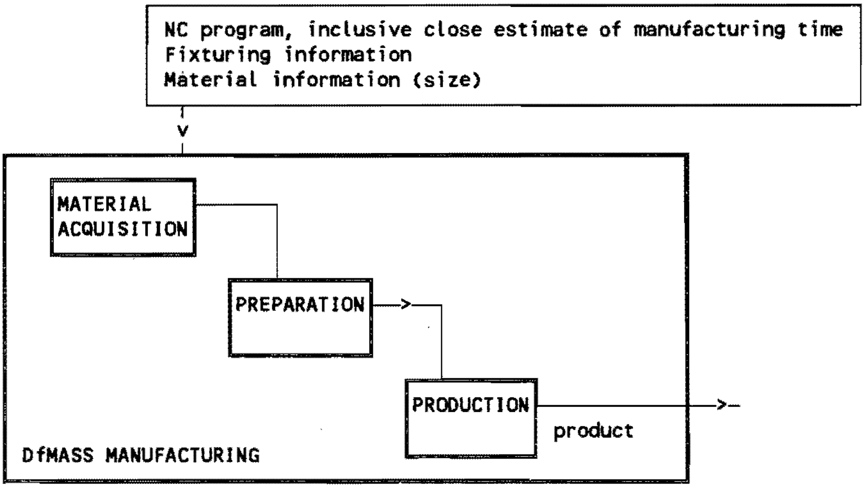

Fig. 6.6: Scheme of activities in the DfMASS manufacturing process

From comparison of Manufacturing conventionally (Fig. 6.3 on page 116) and the DfMASS manufacturing process (Fig. 6.6), it is concluded that the logistic complexity has been reduced. This reduction of complexity has two major advantages:

- reduction of leadtime,
- reduction of overhead.

Reduction of leadtime
A reduction from 15 weeks througput time conventionally (Fig. 6.5 on page 120) to 5 weeks in DfMASS is achievable (Fig. 6.7). Suppose this view is too optimistic and the leadtime of DfMASS manufacturing is twice as long, then still 30% of leadtime reduction is obtained. Also the number of dependent activities is less, which reduces the statistical fluctuations between the processes.

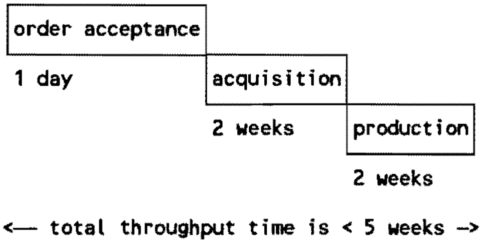

Fig. 6.7: The timeframe of the DfMASS manufacturing process

Reduction of overhead
In DfMASS, Design supplies all technical information required for Manufacturing. There is not much effort required anymore for order acceptance, order split-up, workshop planning, process planning and NC programming. The information supplied by the DfMASS design process is more detailed, which is of benefit for the workshop planning. By DfMASS following data are known before the start of Manufacturing. Conventionally, these data are known after the process planning has taken place:

- material type and size,
- pretreatments specification
- minimum machine tool configuration
- tool list, including tool data,
- set-up configuration,
- required fixtures,
- NC dataset, including cycli times,
- posttreatments specification.

The availability of this information has the following advantages:

- The manufacturing planning can be carried out in the order acceptance phase, because an estimation of the required machining times can be automatically calculated in detail from the NC dataset.
- Early acquisition of material and special tools is possible.

6.3 Additional manufacturing aspects of DfMASS

Additional opportunities of DfMASS are unmanned production, routing control and alternative machine tool selection.

If the NC dataset can be declared errorless, there will be no need for human control during the production process of it. When no human intervention is required, unmanned production is possible. A dataset can be declared errorless:

1. if the file has already been verified before in a previous production run and no errors have occurred. Thus repeat orders do not require operator control.
2. if the dataset is derived from a standard dataset and the adaptations are nearly certainly errorless (Manufacturing Family).
3. if the production of NC datasets for similar components have been proven errorless in earlier production.

Working with a different medium for communication (electronic data instead of paperbased systems) asks for an appropriate routing control system to keep track of the information through the different process steps. People are used to paperbased routing control. A stack of paper indicates the workload; a piece of paper dropped on someone's desk initiates an action. For DfMASS, this stack of paper has disappeared, thus another control system is required. For this purpose a computerized control system has been developed, which is descibed in Appendix K.

Due to DfMASS, the workshop flexibility in routing choices has been decreased a sizeable amount, because the NC dataset is created previously by Manufacturing Design. For a broad implementation of DfMASS in the future, flexibility is required in the types of (existing) machine tools, which can be used for DfMASS manufacturing. Therefore, it must be possible to change the machine tool selection in the manufacturing process, if the required manufacturing capacity can not be found in the selected machine tool types. For this logistic problem, two solutions are presented:

Solution 1: Minimum machine tool configuration
Manufacturing Design supplies a minimum machine tool configuration (see Section 4.3.2), which implies that other machine tools can be used if they have at least the required configuration. By postprocessor functionality the NC dataset can be adapted to the different machine tool.

Solution 2: Alternative process plan
An alternative process plan implies another set-up structure (Fig. 6.8). A new set-up plan must be made and operations need to be re-attached to set-ups. Thus the Manufacturing Design needs to be reconsidered. By having a task level structure related to the geometry, changing the process plan is a minor activity.

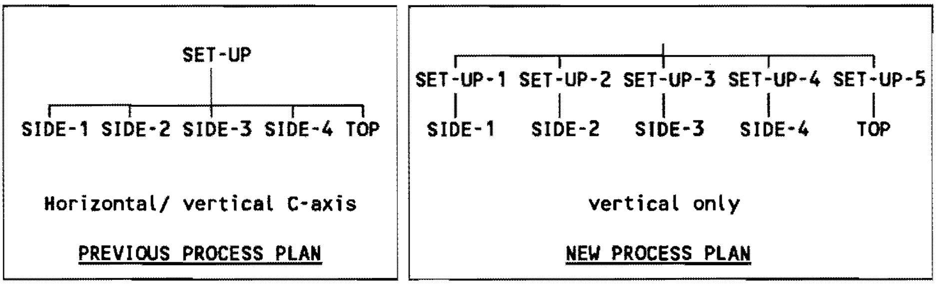

Fig. 6.8: Alternative process plan, when no horizontal/ vertical machine tool is available, but a vertical-only machine tool.

The possibility of changing the process plan in a late stage with less effort, can solve workshop bottle necks. In [45] Bertrand c.s. presents a graphics showing the reduction of leadtime due to ability to select an alternative machine tool (Fig. 6.9). This graphics is based on a computer simulation of throughput times by Wayson [54], which is supported by practical experiences. The FIFO line (First in first out) and the SPT line (shortest processing time) show leadtime (left Y-axis) per number of alternative machine tools (X-axis). The dotted line shows the percentage of applied alternative machine tools. For the FIFO line it can be concluded that if a single alternative is available, the waiting time reduces from 8.8 to 2.3 and the percentage of applied alternatives is 35%. For SPT the leadtime by a single alternative reduces from 3.3 to 1.5. Hence, alternatives increase the flexibility substantially.

Whether the functionality of altering the process planning, need to be a part of Manufacturing, or will remain part of Manufacturing Design is an aspect which need to be worked out in the organization structure of a future DfMASS implementation.

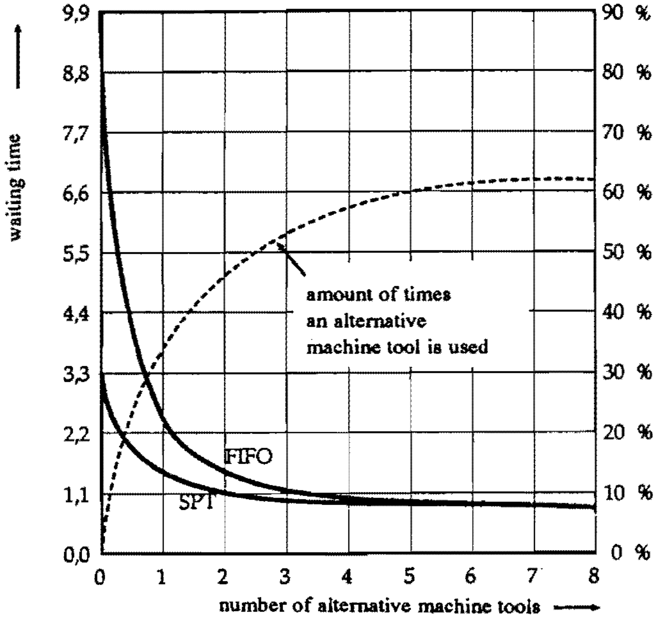

Fig 6.9: The reduction of leadtime by alternative machine tools

6.4 Summary

In conventional practice, the logistics of Manufacturing is a complex system (Fig. 6.3 on page 116). By DfMASS more information is available, by which Manufacturing has been reduced to a production process without technological decisions. This has been achieved by merging planning into geometric modelling. Also design for manufacturability, especially by Manufacturing Families, decreases the number of manufacturing processes and increases the use of standard tools. In optimal situations, Fig. 6.7 on page 122 show the process steps in Manufacturing. Compared to conventional practice, the DfMASS manufacturing process requires less leadtime and costs.

7. EVALUATION

In Section 7.1 an evaluation is given of the results of the pilot production with DfMASS at Philips Lighting, supported by detailed data in Appendix L. In Appendix M, potential problems of applying DfMASS are commented upon. During the study, it appeared that implementing an integral CADCAM system, requires many organizational changes. For small companies such major changes may be difficult to implement at once. For these situations, Section 7.2 describes partial implementations of DfMASS.

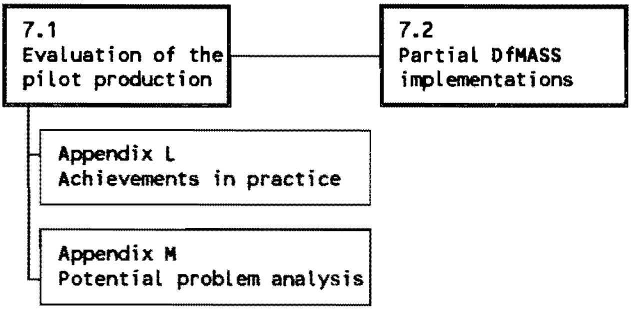

Fig. 7.1: The structure of this chapter

7.1 Evaluation of the pilot production

Early 1990, it was decided to develop a working method and supporting software tools to implement DfMASS principles in a pilot environment at Philips Lighting. A team, with the varying size of 3 to 6 designers, has performed the manufacturing design task. In executing this task, they have built know how on the aspects of manufacturability of designs. A pilot NC workshop was installed in production in January 1991 to manufacture components designed by DfMASS. This workshop consisted of 2 MAHO 600C milling machines and one MAHO 800C. The workshop has been manned with two operators who were experienced in NC milling and two craftsmen without NC experience. In October 1991 it was decided to work in two shifts, due to the increasing work load. A fifth craftsman was required, who needed to be trained in NC milling. In the period January to May 1991, this organization was being prepared for full production by training-on-the-job. In the mean time the design office has started to produce designs for DfMASS production. The evaluation period started May 1, 1991. From that date, all new jobs have been entered in the routing control system (see Appendix K), starting with Manufacturing Design.

Estimates of conventional costs have been added to be able to compare DfMASS with conventional production. The DfMASS orders were part of the professional mechanization projects and have also been under the pressure of tight project planning. Because of the large order quantities and the short leadtimes required, orders were placed at third parties (three companies). The suppliers were selected on the criterium of having the same type of NC machine tools. NC datasets were sent by floppy disk or network facilities. There has been no considerable learning time for them to produce these orders, although detailed drawings were not offered.
Fig. 7.2 shows the time frame of the pilot project.

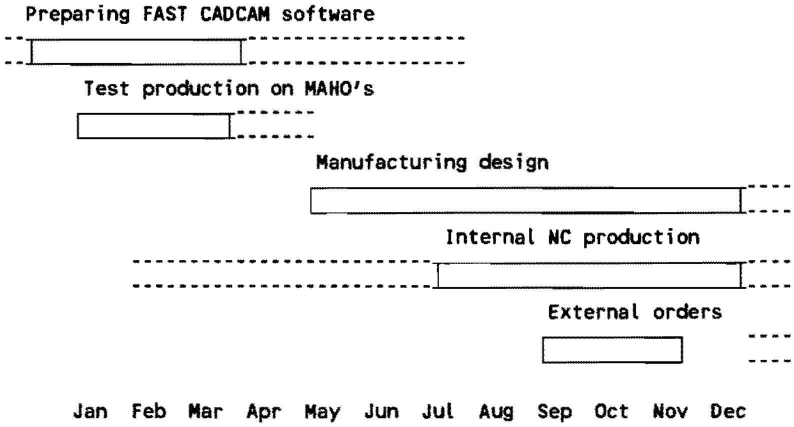

Fig. 7.2: The time frame of the pilot project

Because the jobs were part of real projects, some concessions were required to fit the results in the requirements of the client:

1. The clients still demanded conventional drawings, although drawings were not needed for DfMASS production. The costs of drawing production has been included in the DfMASS costs.
2. Manufacturing Design has mainly been using paper-based functional designs, because the organization preferred to achieve DfMASS results in Manufacturing Design before implementing these working methods in Functional Design.
3. For organizational reasons, a part of the detailed modelling has been carried out on drawing boards. Although, the principle of executing preliminary process planning before detailed modelling has been applied.

In the following cost comparison, detailed modelling has not been included, neither in DfMASS, nor in the estimate of conventional costs. The expenses mentioned for

Manufacturing Design are the additional efforts required for preliminary process planning and for final process planning.

Results

To avoid questioning of the results of this thesis, the calculations on the savings have been very conservative (in reality the cost savings of dfMASS will be higher than presented in the next calculations). All additional costs have been included in the results.

Manufacturing Design

The results are based on 140 different components in various lotsizes, which have been produced during the period of May through December 1991, in the DfMASS pilot production. In Appendix L, a table is given, representing the item codenumber, the real Manufacturing Design costs (without drafting costs), an estimate on drafting costs, an estimate of the number of set-ups by conventional Design and the real number of set-ups in Manufacturing Design. From Table 1 in Appendix L, the following summary has been made (Fig. 7.3):

Total amount of different component:	140
Real Manufacturing Design hours:	1200
Aftercare[1] (25% of Man.Design hours):	300
Additional hours due to the learning curve:	500
Drafting hours:	490
Estimate on the number of set-ups in conventional practice[2]:	463
Real amount of set-ups by DfMASS:	226

Fig. 7.3 The results of Manufacturing Design

Manufacturing

In the next calculations, a hourly rate of dfl 100,- has been used for NC production. The rate is based on five operators on three machines in two shifts. Although the

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[1] By aftercare is meant, error solving and optimizing the manufacturing task structure.

[2] In DfMASS, the designer considers manufacturability during geometric modelling. In conventional design, with less considerations on manufacturability, more set-ups are required. It is difficult to estimate how many set-ups would have been required, because one does not exactly know how the components would have been looked like in a conventional situation. The estimate on the amount of conventional set-ups in Table 1 in Appendix L is a conservative estimation. In many cases the amount of set-ups will be greater than the present estimate.

actual cost rate has been dfl 83,-[1], the rate of dfl 100,- has been used to avoid questioning about the benefits of DfMASS. In the estimation of conventional costs, a hourly rate of dfl 70,- has been used. For larger lotsizes, a reduction in the estimation of conventional costs up to 30% has been included, due efficiency increase in larger lotsizes. Overall, the cost savings of DfMASS will turn out more profitable above the presented calculated reductions.

A. Internal production at Philips Lighting

In Fig. 7.4 (summarized from the results in Table 2A of Appendix L), the NC production hours of the workshop at Philips Lighting are presented and the cost savings in Manufacturing, compared to conventional (absolute and proportional). The production hours have been recorded at ready-date.

	production hours	preparation & aftercare in hours	total capacity in hours	production costs	conventional costs	cost[2] savings	costs versus conventional
May	-	-	420	-	-	-	-
June	31.5	8	420	3950	7100	3150	56%
July	57.1	14	420	7110	9000	1890	79%
August	197.5	47	315	24450	22400	-2050	109%
September	358.0	86	441	44400	77000	32600	58%
October	272.2	65	483	33720	54850	21130	61%
November	727.1	174	798	90110	150740	60630	60%
December	199.0	48	630	24700	41866	17166	59%
Total	1842.4	442	3927	228440	362956	134516	63%

Unrecorded time from May to July: 1171.4 hrs[3]
Non DfMASS hours from August to December: 471.2 hrs

In November, a second shift has been installed, increasing the production to 14 hours per day.

Fig. 7.4: NC production hours and cost savings of internal production

B. External production

Due to the increasing amount of DfMASS manufacturing orders, it was required to involve third party capacity. In Table 3 of Appendix L, the results of the external

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[1] This cost rate is achieved by the reduction of idle time of the machine tool, due to the unmanned production, by which the operator can do additional activities during operation.

[2] In the cost savings, the preparation and aftercare has been subtracted. The hourly rate of NC production has been set on dfl 100,-; the hourly rate of conventional work has been set on dfl 65,-. The Dutch currency guilder, shortened "dfl", is today equal to circa $ 0.50.

[3] In May, June and July production has not been recorded in the routing control system, due to the fact that Manufacturing Design of this production had started before 1 May 1991.

orders are represented, which is summarized in Fig. 7.5.

Company	production costs (dfl)	conventional cost (dfl)	cost (dfl) savings	costs versus conventional
M	186600	258750	72150	72%
P	20475	38500	18025	53%
E	154100	227300	73200	68%
	------	------	------	----
	361175	524550	163375	69%

Fig. 7.5: NC production hours and cost savings

Conclusions of the evaluation

In next figures, savings have been related to the conventional manufacturing costs.

1. Manufacturing Design costs

Hours spended in Manufacturing Design were 1500, plus an additional 500 hours due to the learning curve. The total costs of these 2000 hours, were dfl 200.000,-.

2. Manufacturing savings

The total production costs have been dfl 589.615,- (internal production in Fig. 7.4 added by external orders in Fig. 7.5). The total manufacturing savings was dfl 297.891,-. The conventional production costs has been estimated on dfl 887.506,-.

3. Manufacturing savings minus Manufacturing Design costs

The savings of Manufacturing, subtracted by the costs of Manufacturing Design, realized a cost reduction of dfl 97.891,-. This is a savings of 11%.

4. Omission of drawings

If drawings are not required, an extra savings of more than dfl 39.550,- (see Table 1 of Appendix L) would have been shown. This will be an additional savings of 4%.

5. Training costs

The learning curve expenses of 500 hours in Manufacturing Design have been included in the costs of DfMASS. These expenses are unique for the training period. In the future it will not be part of the costs anymore. Therefore an additional savings of 6% is expected in the future.

6. Preparation and aftercare

Preparation (fixturing, testing) and aftercare (error solving etc.) were totaled up to 24% of the manufacturing hours of the internal production. This figure is expected to be reduced to the 10% range, if standard fixtures are applied and the experience of the manufacturing designer become more mature. This will be an extra reduction of 3%.

7. Manufacturing Families

Considerations on manufacturability requires the designer to be experienced. By conserving this experience in Manufacturing Families, an acceleration in efficiency will be achieved. This conclusion has been drawn in the pilot project in the cases, if Manufacturing Families have been applied (see the Manufacturing Family table of Appendix L). An exact calculation of the extra savings due to applying Manufacturing Families, is difficult, because some family-effect is already implied in the results presented. However some indication can be given.

The manufacturing design effort will decrease by more than 60% (derived from Table 3 in Appendix L). An additional savings in Manufacturing can also be expected, because of the optimization of the manufacturing task structure, due to extra manufacturing design effort which will be spent in developing Manufacturing Families. This savings is at least 25%. Suppose 50% of the components will be members of Manufacturing Families (which is a conservative estimate), then an additional savings of at least 15% will be gained due to Manufacturing Families.

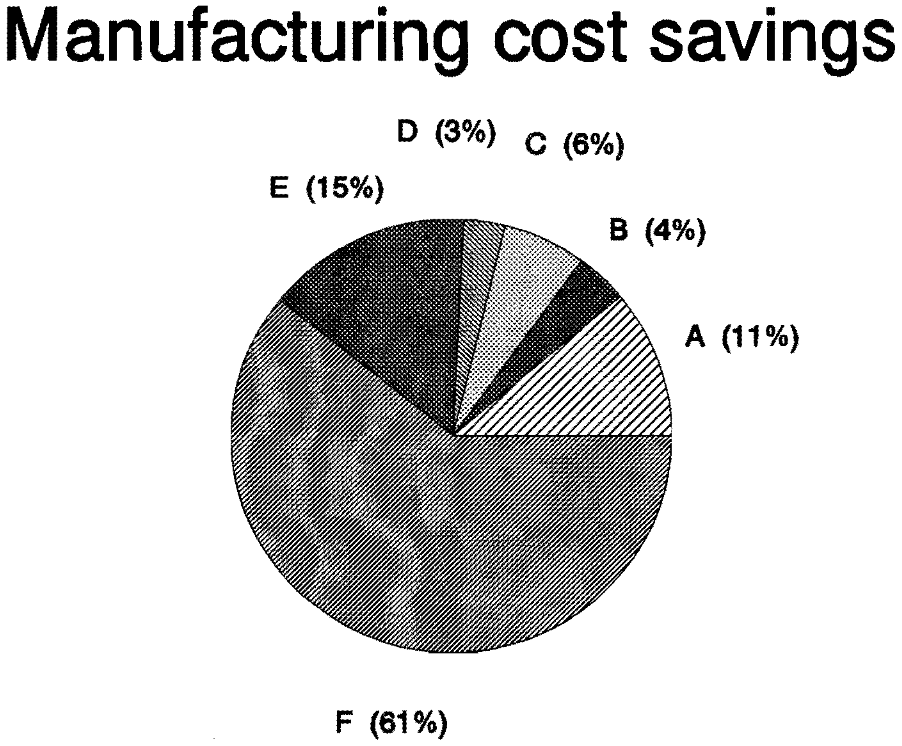
8. Manufacturing Design versus Detail Design conventionally

Manufacturing Design consists of geometric modelling and process planning. Detail Design conventionally consists of geometric modelling and drafting. From previous evaluations [52] it is known that the costs for geometric modelling in DfMASS are certainly not higher than in conventional methods. The process planning costs in the pilot production have been dfl 150.000,- (without the eductional costs). The drafting costs in Detail Design conventionally are more than dfl 39.550,- (Table 1 in Appendix L). If Manufacturing Families are applied for 50% of the components, the Manufacturing Design costs would have been less than dfl 105.000,- (see 7. above). Thus, the design costs will increase with less than dfl 65.450,-, which is dfl 455,- per component. On the other hand, the manufacturing expenses will decrease with dfl 297.891,- (see 2. above), which is dfl 2069,- per designed component.

9. Reduction of set-ups

In the pilot production, the number of required set-ups have been collected and presented in Table 1 of Appendix L. For the produced components a total of 226 set-ups have been required. For a comparison with conventional practice, an estimate has been made on the total number of set-ups, if the designs would have been designed conventionally. This estimation is conservative. The real number of set-ups in Design conventionally, will be higher. Comparing the number of set-ups in DfMASS with the estimation in conventional designs, shows a reduction from 463 to 226, in some cases to a single set-up per component. This is a reduction of 51%. For Manufacturing Families, Table 3 shows even a reduction of 66%. Reduction of set-ups increases the quality and opens possibilities for unmanned production.

10. <u>Summary</u>
In Fig. 7.6, the different savings are illustrated in a pie chart.



A = current savings due to the DfMASS implementation (11%)
B = extra achievable savings by the ommission of drawings (4%)
C = savings by trained manufacturing designers (6%)
D = savings by reduction of preparation time by use of standard fixtures (3%)
E = savings in Design by application of Manufacturing Families (15%)
F = the remaining manufacturing costs (61%)

Fig. 7.6: A pie chart of the different savings

In Fig. 7.7, the costs of the evaluated activities have been compared.

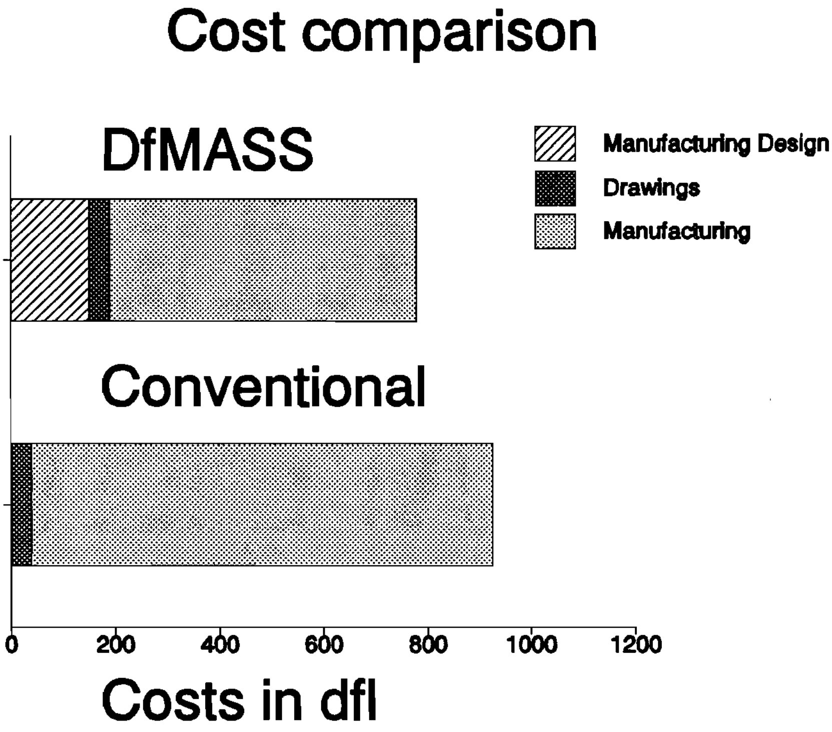


Fig 7.7: A comparison between the costs conventionally and by DfMASS.

It should be considered that these results have been realized after one year of applying DfMASS. Cost savings is expected to increase, due to the growing experience, the increase in Manufacturing Families, the ongoing enhancements on FAST-CADCAM software and the ongoing optimization of the technology libraries.

It must be noted that the material costs will slightly increase in DfMASS applications, because most of the components are produced from a solid piece of material, instead of welded constructions. However, the material costs are less than 4% of the manufacturing costs.

Above evaluation has been focussed on cost reduction. Besides cost reduction, a substantial leadtime reduction is achieved, due to a decrease of the logistic complexity of the manufacturing process (see Chapter 6).

The DfMASS method supplies two major advantages concerning quality:

- Components are modelled in a three dimensional assembly environment. Therefore it is possible to use dimensions of one component in the creation of a related component. For instance, the designer is able to copy the hole diameter and position of a bearing to the house in which the bearing will be mounted. The assurance of related dimensions will reduce problems during Assembling.
- DfMASS supplies a quality garantee in manufacturing components, because the endproduct will be manufactured conform the instructions of the manufacturing designer. For larger lotsizes, all copies of a manufacturing component will be similar within close tolerances.

Recommendations for the future of the pilot environment

The following recommendations are proposed for the future:

- Manufacturing Families should be extended to more areas of application.
- The use of standard fixtures should be extended.
- The implementation should be extended to Functional Design, by which the advantages of Assembly and Components functionality can be implemented. (see Section 4.2). Castelijn [37-7] gives an impulse on this subject in his Master Thesis.
- Drawings are not needed for Manufacturing by DfMASS. To eliminate the need for detailed drawings, a new documentation package for Assembling and Maintenance need to be agreed upon (see Sections 4.3.6 and 4.3.7) and the client must be convinced to drop his request for detailed drawings.
- Continuous attention on technology will result in more efficient manufacturing.
- Spare components in stock houses for maintenance purposes can be replaced by storing error free NC programs and raw stock material. This will reduce the costs of stocks substantially.
- The supplier of the CADCAM system should be stimulated to support FAST-CADCAM functionality.

7.2 Partial DfMASS implementations

Implementing a CADCAM system and installing a NC workshop is expensive, especially for small organisations. Therefore it is an useful exercise to describe which ideas of the DfMASS philosophy can be implemented without full availability of these automation systems. Step by step, such an organization can equip itself with additional tools of DfMASS.

The following steps are discussed:

- a DfMASS application without any CAD, CAM or NC system,
- a situation with only NC systems,
- based on a simple CAM system,
- based on a simple CADCAM system.

Without CAD, CAM or NC machine tools
Manufacturability considerations do not only count for NC production. If the number of set-ups can be reduced, it will have similar effect on manual milling. Therefore, applying manufacturing task structures in Design conventionally, will have a positive effect on manual milling. The task structures must always be focused on the manufacturing environment. The next rules may be evident, however they are not always applied.

1. The boundary feature in CADCAM allows the designer to shape the border of a pocket with all possible geometry entities. For manual milling, the shapes, designed on the drawing board, should be as simple as possible (lines and arcs).
2. Using preferred values for holes (e.g. M4, M8, M12) reduces the effort in Manufacturing and Assembling.
3. Using standard fixture configurations should be communicated to the designer, so they can consider these configurations in the design phase.
4. Design rules for manufacturability (Appendix H) can also be applied for manual operations.

With only NC machine tools
A technology data system can be developed, based on the functions of the machine control system. Cycle statements can be used to reduce the required amount of data entry. Manufacturing task structures will help the designer to stay within the limits of the manufacturing environment. Design features should be focused on the possibilities of the machine tool control system (e.g. rectangular pockets, holes).

With a simple NC programming system

By such a system, the programming effort can be taken away from the machine tool, by which the idle time of the machine tool can be reduced. PC-based CAM systems offer more functionality than the machine tool control system by means of applicable geometric functions (features), technology data system, storage of data (archiving on floppy disks) and interfacing to different machine tools. A local network can be installed to connect the machine tools to the PC for direct downloading of programs. A technology database as well as simple features can be developed in the CAM program. The design rules for manufacturing need to be focussed on the possibilities of the PC-CAM system.

With a simple CADCAM system

In 1985, the first professional 2D drafting systems on personal computers became available on the market. During the early years they were focussed on drafting functions. Currently, they are also entering the area of 3D modelling and certainly will supply form-feature-like functionality in future releases. The difference with a full 3D CADCAM system is the single user applicability. For extending PC systems to multi-user applications, will bring them in the same area of complexity as current 3D systems, like Computer Vision, Intergraph and Unigraphics.

By a 2D CAD system the different surfaces of a manufacturing component can be defined in 2D views. These views can be interfaced to a CAM system, which will control the manufacturing relations between the views by means of turntable- and spindle-rotations. The 2D geometry defined by the CAD system can be used as data for tool path generation in the CAM system. By development of tablet[1] applications standard functions can be built to provide form features, preferred values, set-ups etc.

It would be of interest for smaller companies, whether a full DfMASS system could be developed based on simple CADCAM systems.

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[1] A tablet is a flat device on which a pattern of blocks can be defined. Each block represents a specific function (standard function or an own written application program) By a pointing device (mouse) a function in the indicated block can be activated.

8. CONCLUSIONS

The main conclusion of the DfMASS study is:

DfMASS contributes in:
- quality increase
- leadtime reduction
- cost reduction

of Design of small lotsize mechanical components.

The main aspect of DfMASS is the merging of process planning into geometric modelling. This integration justifies the integral application of CADCAM and enlarges the applicability of NC machine tools for small lotsize mechanical systems. By considering process planning consequences during detailed modelling, the designer is able to optimize manufacturability of the components.
The technical interaction between process planning and modelling is so high, that merging them together, largely increases the quality of the total process (Chapters 2 and 4), because technologically connected decisions are merged in a single activity
If supported with sufficient software tools (FAST-CADCAM, Chapter 3), the designer is capable to define all manufacturing information, including NC datasets.

In Design conventionally, the designer makes a lot of arbitrary choices, because he is lacking the knowledge of the consequences on manufacturability of his designs. There is not a built-in feed back to assure optimal manufacturability. By information technology it is possible to supply the best solutions to the designer. These solutions are not constraints but recommendations. It has been demonstrated in the DfMASS project that the designer only deviates from the recommendations in case the required functionality can not be achieved by standard solutions.
In Fig. 8.1 (which is a copy of Fig. 0.1), a comparison is given between Design conventionally and DfMASS.

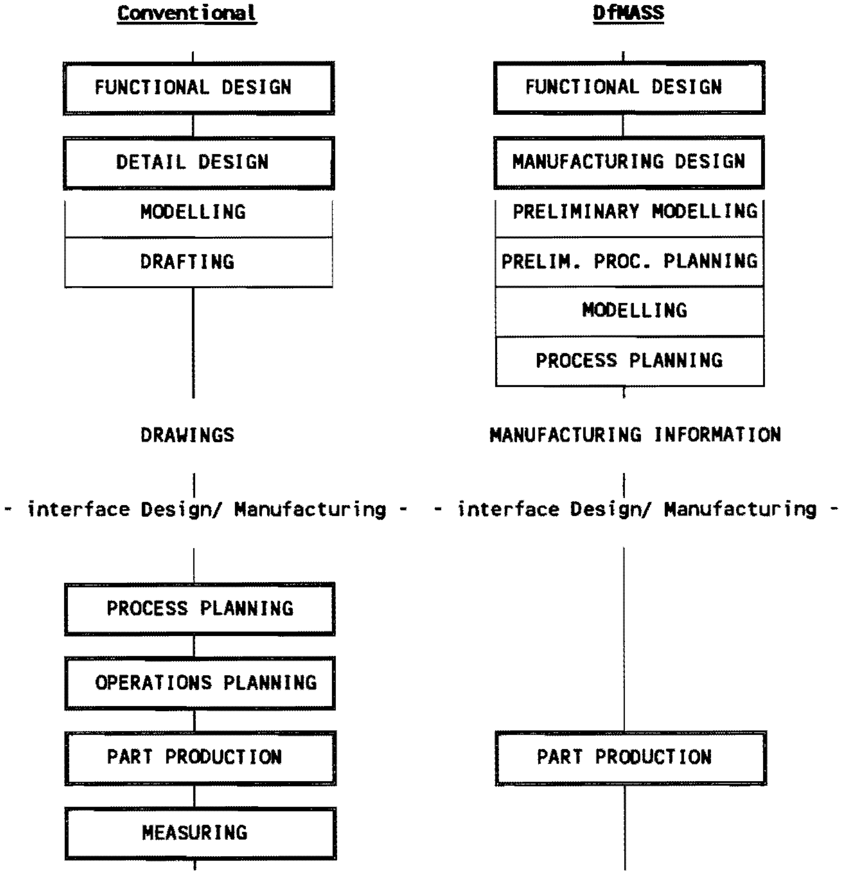


Fig. 8.1: The difference between conventional practice and DfMASS

The new working method implies the following advantages.

DfMASS increases quality
In DfMASS, components are modelled in a three dimensional assembly environment. Therefore it is possible to use dimensions of one component in the creation of a related component. The assurance of related dimensions will reduce problems during Assembling. DfMASS also supplies a quality garantee in manufacturing components, because the endproduct will be manufactured conform the instructions of the manufacturing designer. For larger lotsizes, all copies of a manufacturing component will be similar within close tolerances.

DfMASS reduces leadtime

An interface between two activities is a logistic buffer, thus waiting time. DfMASS reduces the number of interfaces from 5 to 3 (Fig. 8.1). Especially in large complex organizations, the waiting times are long. Besides, by the merging of process planning into geometric modelling, all manufacturing information is supplied by Design. The result is a substantial reduction of the logistic complexity of the manufacturing process. This reduction is illustrated by comparison of the manufacturing timeframes of Manufacturing conventionally and Manufacturing by DfMASS. Fig. 8.2 (copy of Fig. 6.5) shows the timeframe of the manufacturing process conventionally. Fig. 8.3 (copy of Fig. 6.7) represents the timeframe of the DfMASS manufacturing process. the mentioned figures are indications.

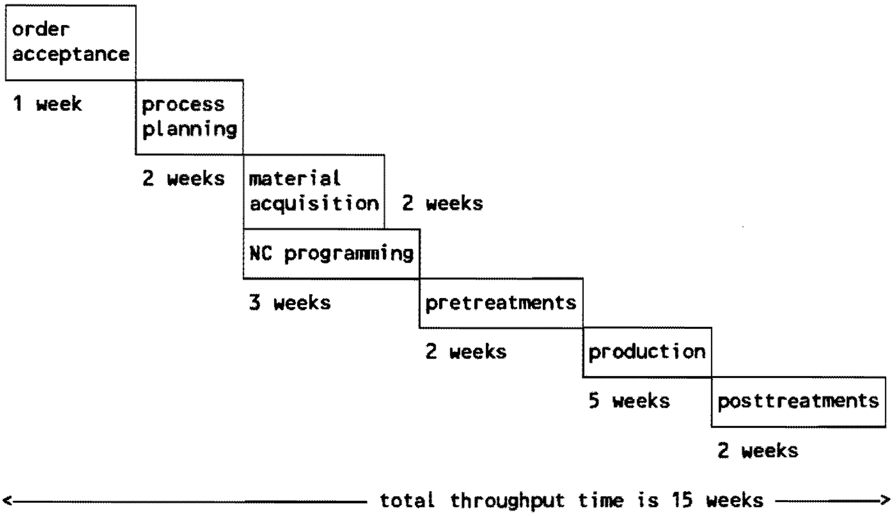


Fig. 8.2: The timeframe of the conventional manufacturing process

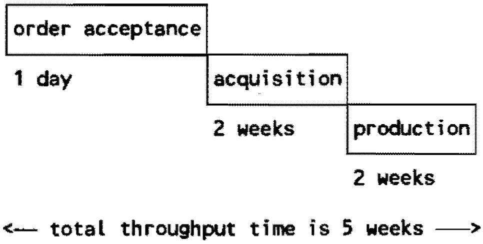
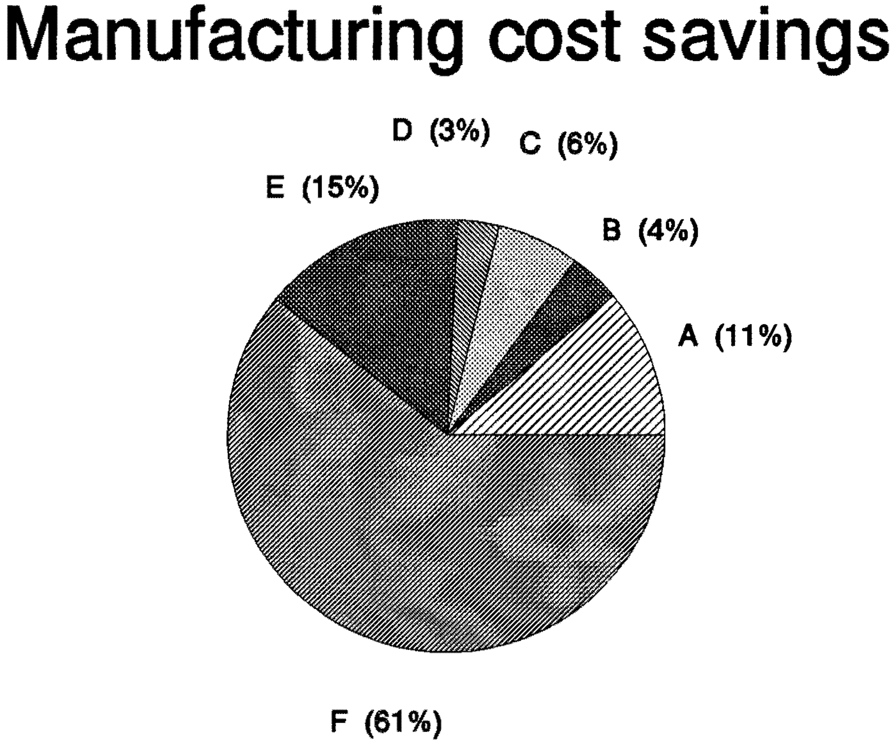


Fig. 8.3: The timeframe of the DfMASS manufacturing process

DfMASS reduces costs

The reduction of process steps and the merging of process planning into geometric modelling, saves effort. This has been proven in the pilot production at Philips Lighting during more than 6000 hours of manufacturing, which is illustrated in Fig. 8.4 (copy of Fig. 7.6).



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F = the remaining manufacturing costs (61%)

Fig. 8.4: A pie chart of the different savings

Savings A of 11% is already achieved, the savings C of 6%, D of 3% and E of 15% are achievable when continuing the DfMASS practice. Whether an organization will be able to convert their drawing-based information procedures is questionable. Therefore savings B of 4% is not in all cases expected to be reachable in the near future.

The general conclusion on costs is that already a savings of 11% of the manufacturing costs has be achieved and a total savings of 28% of the manufacturing costs is to be expected if continuing the DfMASS practice.

Besides the major advantages, quality increase, leadtime reduction and cost reduction, the following aspects are identified in the DfMASS method.

Data explicitness

The interface between Functional Design and Manufacturing Design is the product model database. This is a 3 dimensional model of the design on scale 1:1. All data in the product model database are explicit. In conventional practice, Functional Design often delivers sketches without accurate dimensions. The interface between Manufacturing Design and part production is a NC dataset, with clear, worldwide understandable statements. Interpretation of drawings by the workshop is not necessary anymore because all data have been made explicit. By unambiguous data, there is no need for interpretations in the workshop anymore, hence less discussions and less misunderstandings.

Feature based Design

The following hypothesis has been formulated and proved: "A limited set of manufacturing features will supply sufficient functionality to achieve the aims of DfMASS". By the holes of Fig. 8.5 (copy of Fig. 3.3) and the boundary feature, of which an example is presented in Fig. 8.6 (copy of Fig. 3.8), the majority of milling components can be produced by hardly using other geometry entities.

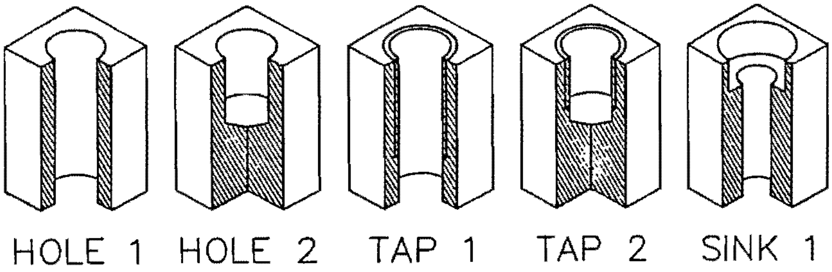

Fig. 8.5: Holes

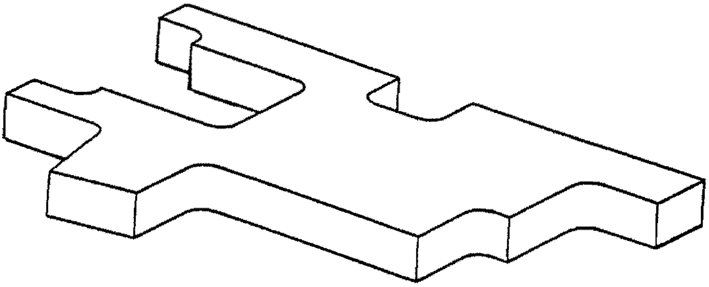

Fig. 8.6: An example of a boundary feature

NC applicability

The application of NC machine tools in small lotsize production, supplies possibilities to improve the organization of Manufacturing. DfMASS: "Design for manufacturability" is important. In 1988, the internal CAMEX study at Philips[1] concluded that without considering manufacturability during geometric modelling, an average of less than 4% of the designs are suitable for NC manufacturing [51]. The results of the DfMASS implementation at Philips Lighting demonstrate that the most milling components are suitable for DfMASS and thus suitable for NC manufacturing, because of the considerations on manufacturability during Design.

Manufacturing Families reduce design and manufacturing effort

By the merging of process planning into geometric modelling in a single activity, Manufacturing Design (Chapter 4), the complexity between the activities has been reduced. This approach has demonstrated a reduction of 11% of the manufacturing costs. However the complexity within Manufacturing Design has increased. By Manufacturing Families (Chapter 5), the effort in Manufacturing Design again reduces with at least 15%.

By DfMASS a single sourcing information system can be achieved

Computerized information gives the possibility to supply all required data to each user, without the need to make copies. All information is stored in a single product

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[1] Philips Lighting, Philips Centre for Manufacturing Technology and Philips Machine Factories

model database. All activities use the same product model database for reading and writing information: outdated information does not exist anymore.

A standardized manufacturing environment produces the majority of components

Because the designer considers the possibilities of the given manufacturing environment, he will only deviate from this environment, if the functional requirements of the component ask for a deviation. In practice it appears, that in most cases, the designer finds a solution within the restrictions of the given environment.

DfMASS stimulates modular design

By defining the interface geometry between modules before starting Detail Design, and by using a single product model database, different persons can design the different modules.

Implementation of standards in DfMASS is easier than conventionally

By DfMASS the drawing board can completely be replaced by CADCAM workstations. Hence, standards manuals can be replaced by standards databases. An adjustment of a standard in a database is immediately available for all designers, because retrieval of a standard is done by an online search in the database. In conventional practice, it is a big effort to communicate changes in standards to the designers.

Recommendations for future studies

Functional Design

This study has been focussed on geometric modelling and process planning. In the area of Functional Design and the relation to detail design working methods and software tools could be developed to improve the use of 3D CAD in Functional Design (see Appendix F).

Machining centres

A current trend in machine tools show an integration of different operations on single machine tools, for instance the integration of milling and lathe. This trend may open additional possibilities for Manufacturing Families. How these tools may be adapted in DfMASS-type of applications, should be investigated.

Automation of measuring

In DfMASS, it is stated that measuring the result of milling is merely redundant, because the amount of errors are limited. However still error may appear. It could be investigated how the NC program can be used to execute automatic measuring by the machine tool control.

The Eindhoven University of Technology (Section Workshop and Production Automation) is continuing in extending the applicability of CADCAM, especially in the area of automatic measuring and automatic generation of process planning solutions during the design phase.

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CURRICULUM VITAE

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1975: Gymnasium-beta, Lutger College, Doetinchem

1980: Master's degree Mechanical Engineering, Twente University of Technology

1990-92: Doctoral study at the University of Technology Eindhoven in cooperation with Philips Lighting on Design for Mass Production of small lotsize mechanical systems

Jobs:

1980-86	Project Engineer CAD and technical databases, Comprimo Engineers & Contractors, Amsterdam
1986-87	Implementation manager of CA drafting systems (AUTOCAD) at Comprimo Oman (Middle East) and different daughter companies of Comprimo in the Netherlands and Belgium
1987-91	Project Manager CADCAM[1], Philips Lighting, Eindhoven
1991-now	Manager Realization department of Equipment & System Engineering, Philips Lighting, Eindhoven

Miscelleaneous:

Member of the committee of the Section Mechanical Engineering of the KIVI association of engineers, The Netherlands

Mentor of students in their final study in the industry

Hobbyist in maintaining a classic car (1964) on the road

---

[1] He has run projects in CADCAM for small lotsize mechanisation, providing a better cost effectiveness. Besides, he was responsible for the operations of the computer system (a.o. 45 workstations, Unigraphics, Oracle, Ansys)

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The DfMASS study started as an internal project at Philips Lighting. In 1990 it has been transferred into a Ph.D.study at the University of Technoloy Eindhoven.

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---

[1] In 1991, McDonnell Douglas Information Systems has been sold to EDS

Appendix A

Explanation of used terms

Assembling
See Design.

Assembly
See Structure of a mechanical system.

CA
When activities are supported by computerized systems the term CA (Computer Aided) is used.

CAD
CAD is an acronym of Computer Aided Design.

CAM
CAM is the umbrella of all computerized activities to create NC datasets from a design.

CAD/CAM
CAD/CAM, with a slash in between, is used if they are organisationally split up into two separate activities.

CADCAM
CADCAM without a slash is used when there is an organisational integration of CAD and CAM.

Component
See Structure of a mechanical system.

Conventional practice/ conventionally
By conventional practice or by conventionally is indicated the way in which a process is normally executed. In the context of this thesis, *conventional* expresses the working practice of Design and Manufacturing by the use of paper-based technical drawings.

DfMASS
DfMASS is an acronym for Design for Mass production.

Design
In the present thesis, the following definitions have been used:

> Design All the activities required to describe the configuration of a mechanical system, by which description the components can be acquisitioned (purchased or manufactured), and the system can be assembled, put in operation and maintained during life time.
>
> Functional Design For the design of a mechanical system, Functional Design defines all functions of the system. It is not an aim of Functional Design to define all geometry of the components of the mechanical system.
>
> Manufacturing Design All activities, required to derive manufacturing information from the functional design, including geometric modelling and process planning. This activity has been developed for the DfMASS working method.
>
> Manufacturing All the activities required to produce parts from the manufacturing information, supplied by Manufacturing Design.
>
> Part production The stage in Manufacturing in which the actual execution of manufacturing is done. For instance the cutting process is the production phase of the total manufacturing process of milling.
>
> Assembling The assembling of purchase parts and manufacturing components into machines.
>
> Detail Design The stage in Design conventionally, in which the components are designed in detail, based on the information from Functional Design.

Detail Design
See Design.

Feed
The feed is the velocity of translation of the tool during part production.

Fixturing configuration
See set-up.

Form feature

A form feature is a set of geometry, consisting of a topology of elementary shapes (cylinders, cones, surfaces etc.). This topology is focussed on manufacturability. Examples of form features are holes, pockets, faces, grooves, slots etc.

Functional

By the term functional is meant "related to the functions of the mechanical system". Thus functional entities in a CAD file are entities which are part of the configuration of the function. Opposite of functional entities are modelling details, which do not play a part in the execution of the function. For a lever, for instance, the position of the centers of the bearing holes are functional entities. The outside surface of the lever is a modelling entity.

Functional Design

See Design.

Logistics

The term logistics is derived from the army. In the army, logistics is all the aspects of dealing with procurement, maintenance, and transportation of military material, facilities and personnel. The term has become used in industry for the handling of the details of operations.

Machine tool

On a machine tool, manufacturing components are produced by a manufacturing process (e.g. milling, lathe).

Material

Material is the substance, from which a component is being manufactured.

Manufacturing

See Design.

Manufacturing component

See Structure of a mechanical system.

Manufacturing Design

Manufacturing Design is a new activity in the DfMASS design process. It consists of all actions needed to transform the Functional Design into NC datasets and additional information for Manufacturing, Assembling and for maintenance activities.

Manufacturing Family

A Manufacturing Family describes a set of manufacturing limitations and supplies a standard process plan. Designing a component, belonging to a Manufacturing Family, is restricted to these limitations.

The limitations comprehends:

- manufacturing technology,
- minimum machine tool configuration,
- manufacturing task structure,
- fixturing configuration,
- a set of standard form features.

Manufacturing operation

A manufacturing operation is an operation to produce a specific shape, which is performed by a single tool.

Manufacturing process

All the manufacturing operations which can be executed in a single set-up, are called a manufacturing process.

Manufacturing task structure

The manufacturing task structure defines the configuration of the manufacturing tasks. A manufacturing task contains sequences of operations.

Mass production

Generally, mass production is producing in quantity, usually by machinery. In DfMASS, the term mass production is used if the following two conditions are valid:

- large quantities can be produced (manufactured) without human intervention in the primary manufacturing process (e.g. the milling process),
- the remaining processes do not contain technological decisions, but only contain planning, ordering and preparation activities.

Mechanical system

A mechanical system is a mechanism or machine, replacing manual operations, especially in production environments. Instead of consumer products, the design of mechanical systems concentrates on the functionality, not on the aesthetics of shapes. An example of a mechanical system is a pick and place unit for assembling purposes.

NC

NC is an acronym for Numerically Controlled. If the steering commands of a machine tool are read from a computer file, it is called a NC machine tool.

NC dataset

The NC dataset is a set of commands by which a numerically controlled machine tool produces a component. When the NC statements are generated (manually or by a CAM system) they are in a semi-independent readable format, which means not specific for a type of machine tool control system. In that format, the NC dataset is called a CLS file (Cutter Location Source file). It is called a source file because it can be read (c.q. edited) by the NC programmer. Next, the file will be translated by a pre-processor into a neutral computer format, in which process also some optimizations can be built in. An example of an optimization is deleting a change-tool command, in case the next tool is the same as the previous one. This file is called the CLF file (Cutter Location File). The CLF file is not easily readable. The postprocessor finally translates the CLF file into a NC file, in which process the file will be tuned for a specific machine tool control system.

Operations planning

By operations planning is meant the decisions taken on tool choice, speeds and feeds and the definition of tool pathes. In NC production, operation planning is all the activties to create a NC program from the process plan.

Part

See Structure of a mechanical system.

Part production

See Design.

Process planning

All actions to be executed during Manufacturing are defined and sequenced during the preceeding activity process planning.

Product/ product model/ product model database

Product is a term used for things to be produced. The product of Manufacturing is a manufacturing component; the product of Assembling is an assembled part. The product model is all information of the product created by Design. Drawings and other documents can form the product model; computer files substituting the drawings and other documents can also be the product model. These computer files are called the product model database.

Purchase part
See Structure of a mechanical system.

Set-up
A set-up is the fixed position of material relative to the machine tool, in which position manufacturing operations can take place. The set-up is fixed by a fixturing configuration. The fixturing configuration consists of devices which fixes the material on the machine tool.

Speed
The speed is the velocity of rotation of the tool during part production.

Structure of a mechanical system
A part is an element belonging to an assembly. A part can be a component or a sub-assembly.
A component is a single part which is not assembled.
A purchase part can be an assembly or a components. In case it is an assembly it is still treated as a single element of the mechanical system.
A manufacturing component is a component which is created by a manufacturing process (milling, lathe etc.).
An assembly consists of assemblies, manufacturing components, and purchase parts. The top level of the mechanical system is an assembly.

Technological decisions
This term is used in this study for "HOW a component has to be manufactured", by means of the technical details like machine tool, set-up, operations, tools, speed, feed.

Technology
The know how from which the required data of a machine tool operation can derived (speeds, feeds, motions etc.) is called the technology.

Tool
A tool is a component, mounted on the machine tool, which is the basic instrument of part production, eg. a drill, a mill, a bore.

Appendix B

Detailed description of Design and Manufacturing

In the present appendix, the conventional method of Design and Manufacturing is described. As defined in Section 2.1, this process consists of two phases, the Definition phase and the Manufacturing phase.

The Definition phase

The definition phase contains the User Requirement Specifications and the different design stages (Fig. B.1).

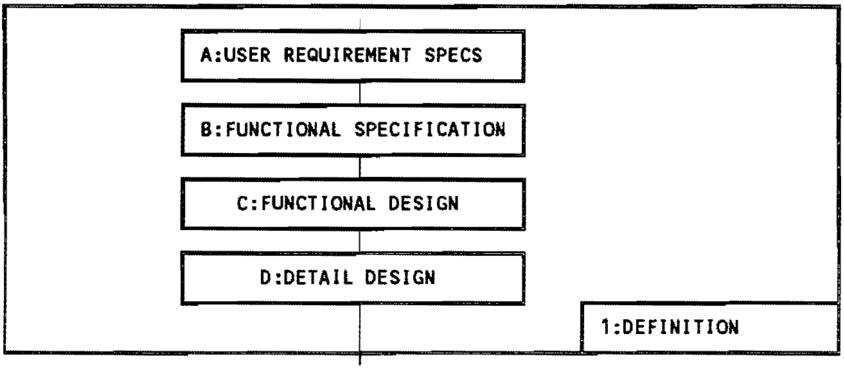


Fig. B.1: The definition phase

A. User Requirements Specifications

The User Requirements Specification (URS) is a qualitative and quantitative description of the characteristics of the required system. The URS is defined in cooperation between the designer and the client. After the URS is defined, a global indication on the budget needed and on project timeframe can be given.

B. Functional Specification

Based on the URS, the functional specification (FS) can be generated. The FS is a qualitative and quantitative definition of the required functions of the system. Dependent on the complexity of the total system, the FS can be divided into FS's per system, per apparatus or even per module.

The FS is structured by following steps:

B1. Problem formulation

The problem formulation describes the problems, which need to be solved by identifying the problems as a part of a wider problem; determining the real underlying needs; gathering background information; searching for side-effects (desirable and undesirable); identifying constraints; specifying objectives, performance and operating conditions [17].

B2. Develop technical concepts

For the recognized problems, principle solutions must be found. It is recommended to generate more alternatives per problem. For the total system, concepts can be defined, containing different combinations of alternatives per problem[1]. Dependent on the complexity, know how and experiences with the proposed solutions, the designer has to go in detail as far as necessary. In extremity, a prototype has to be build for testing the potential solution. In such cases a nested working procedure can be applicable, because designing a prototype does have the characteristics of a whole design process.

B3. Choose concept

A feasibility study per alternative [17] has to be executed. Constraints, costs, side effects and performance can be evaluated. The alternatives must be checked against the URS and the problem formulation.

At the end of the FS, a more accurate estimate of costs and planning can be made, from which the client can determine whether to continue, to adapt or to stop the project.

C. Functional Design

In Functional Design, the total architecture of the mechanical system in three dimensions is created, with a minimum of details, just enough to describe the functions of the system. It is divided into:

C1. description of the main functions
C2. division the system into modules
C3. system lay out, showing the relations between the modules
C4. description of the interface characteristics between modules
C5. description of functions per module

---

[1] An applicable technique is the morfological survey [26]. A morfological survey describes different principal solutions for specific machine functions such as translate, orientate, rotate, cut, pick, place.

D. Detail Design

Definition of geometric solutions for the design on system-, module- and submodule-levels.

- D1. Description of the geometric interface between (sub)modules
- D2. Division of functional modules in physical parts
- D3. Define purchase parts
- D4. Define the functional geometry of machining parts[1]
- D5. Completion of the total geometry of the machining parts
- D6. Documenting the geometry on a technical drawing.

The Manufacturing phase

When the definition phase is finished, the manufacturing phase will be started. The different activities of this phase are shown in Fig. B.2.

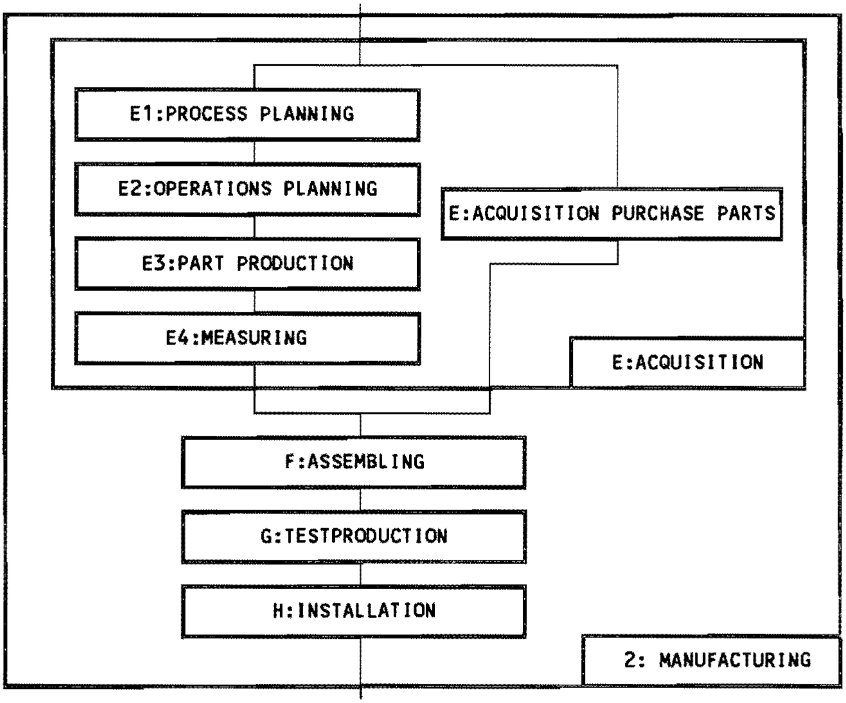


Fig. B.2: Manufacturing conventionally

---

[1] In most cases D4, D5 and D6 are integrated in one activity called Detail Design.

E. Acquisition of purchase parts and machining parts

Acquisition will supply the required components. For some components, it is a purchase activity, while other components need to be manufactured. For purchase parts, acquisition consists of ordering, control and delivery. Manufacturing of components consists of following phases:

E1. Process planning

Definition of manufacturing method(s), machine tool type, set-up configuration, fixtures, tools needed, stock material.

E2. Operations planning

Defines sequence of manufacturing operations per manufacturing shape, tool per operation, toolpath, speed and feed. If using a NC machine tool, this activity is called NC programming. On conventional machines this activity is integrated in the part production activity.

E3. Production of components

Production of components consists of:

E3.1 prepare stock material
E3.2 select tools and toolholders
E3.3 measure tools
E3.4 select fixturing devices
E3.5 fixture stock material
E3.6 put tool in spindle
E3.7 start operations for this tool
E3.8 take tool off

- go back to E3.6 until all operations for this set-up have been executed
- go back to E3.5 until all set-ups are produced

E4. Control of result by measuring against the drawing

F. Assembling

Guided by the assembling documentation, the components are built together in modules. The modules are assembled together, forming the total system.

G/H. Testproduction/ Installation on site

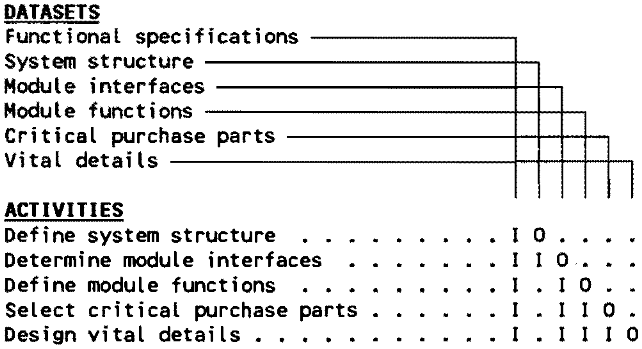
The system is started up for pilot production. Possible errors are detected and a solution generated. Performance of the system is compared with the required performance. Finally after approval, the system is installed on site.

Appendix C

SMX matrices of DfMASS

In the present appendix, the SMX matrices of the activities of the DfMASS working approach are presented, these are:

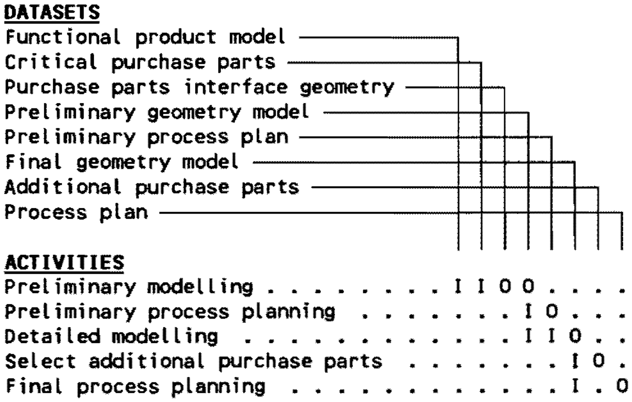
- Functional Design (Fig. C.1)
- Manufacturing Design (Fig. C.2)
- preliminary process planning (Fig. C.3)
- final process planning (Fig. C.4)
- automated operations planning (Fig. C.5).



```
DATASETS
Functional specifications
System structure
Module interfaces
Module functions
Critical purchase parts
Vital details

ACTIVITIES
Define system structure . . . . . . . . . . I O . . . .
Determine module interfaces . . . . . . . . I I O . . .
Define module functions . . . . . . . . . . I . I O . .
Select critical purchase parts . . . . . . . I . I I O .
Design vital details . . . . . . . . . . . . I . I I I O
```

Fig. C.1: Systematrix of Functional Design



```
DATASETS
Functional product model
Critical purchase parts
Purchase parts interface geometry
Preliminary geometry model
Preliminary process plan
Final geometry model
Additional purchase parts
Process plan

ACTIVITIES
Preliminary modelling . . . . . . . . . I I O O . . . .
Preliminary process planning . . . . . . . . I O . . .
Detailed modelling . . . . . . . . . . . . . . I I O . .
Select additional purchase parts . . . . . . . . I O .
Final process planning . . . . . . . . . . . . . I . O
```

Fig. C.2: Systematrix of Manufacturing Design

DATASETS

ACTIVITIES	Preliminary geometry model	Process plan level Preliminary stock material size	Machine tool	Manufacturing planes	Task structure	Set-up configuration
Estimate stock material	I	O	.	.	.	.
Define minimum machine tool configuration	I	I	O	.	.	.
Define manufacturing planes	I	I	.	O	.	.
Define manufacturing task structure	I	I	I	I	O	.
Define fixturing	I	I	I	I	I	O

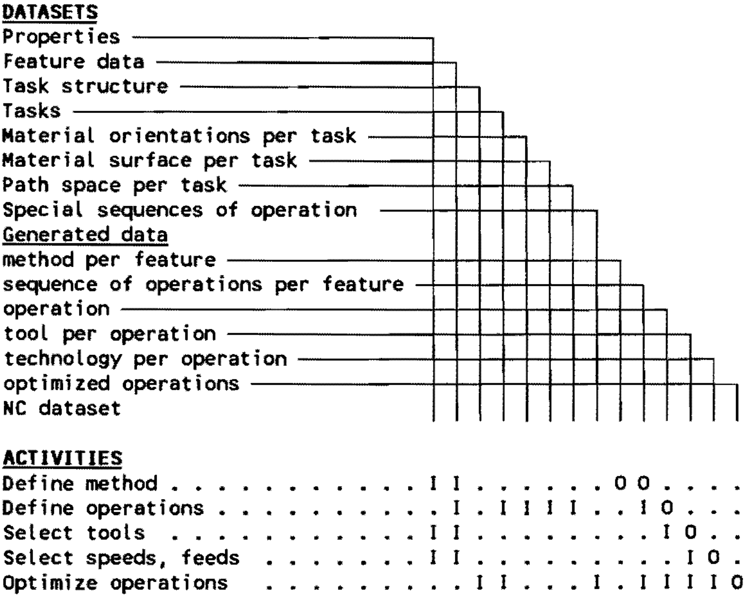
Fig. C.3: Systemmatrix of preliminary process planning

DATASETS

ACTIVITIES	Final geometry model	Stock material	Pre treatments	Task structure	Machine tool	Fixturing configuration	Manufacturing planes	Boundary features	Hole features	Special sequences of operations	Post treatments
Adjust stock material	I	O	.	.	.	.	.	.	.	.	.
Define pretreatments	I	I	O	.	.	.	.	.	.	.	.
Adjust task structure/ machine tool/ fixturing	I	I	I	O	O	O	.	.	.	.	.
Define manufacturing planes	I	I	.	I	I	I	O	.	.	.	.
Define boundary features	I	I	.	.	.	.	I	O	.	.	.
Select features	I	I	.	.	.	.	I	.	O	.	.
Define special sequences of operations	I	.	.	.	.	.	.	.	.	O	.
Define posttreatments	I	.	.	.	.	.	.	.	.	.	O

Fig. C.4: Systemmatrix of final process planning

Operations planning (NC programming) disappeared from the activities, because it is completely automated. The structure of the automated process planning is presented in Fig. C5.



```
DATASETS
Properties
Feature data
Task structure
Tasks
Material orientations per task
Material surface per task
Path space per task
Special sequences of operation
Generated data
method per feature
sequence of operations per feature
operation
tool per operation
technology per operation
optimized operations
NC dataset

ACTIVITIES
Define method . . . . . . . . . . . . I I . . . . . . O O . . . .
Define operations . . . . . . . . . . . I . I I I I . . I O . . .
Select tools  . . . . . . . . . . . I I . . . . . . . . I O . .
Select speeds, feeds  . . . . . . . I I . . . . . . . . . I O .
Optimize operations   . . . . . . . . . . I I . . . I . I I I I O
```

Fig. C.5: Systemmatrix of automated operations planning

Appendix D

The technology libraries

In the present appendix, the technology libraries for the FAST-CADCAM functionality are described and the relations between the libraries. From these libraries the FAST-CADCAM software automatically derives the technology required for manufacturing of features.

The process of deriving the right technology starts with the feature attributes in the product model database. Each feature has a feature code and a set of attributes.

The Methods library

The feature code is the link to the methods library (Fig. D.1). Dependent on the ranges of radius, depth, width and length, a method is selected. For example for a large cavity with a small minimum radius, premilling will take place with a large tool diameter. For final milling, a tool will be selected with a radius just smaller than the minimum radius. Different methods are required for different ranges of the tolerance and roughness data of the form feature. Output of a search in the methods library is a method code.

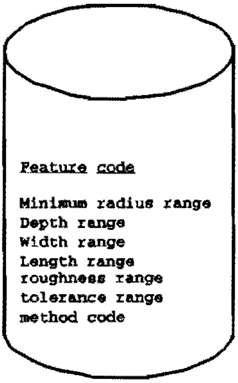


Fig. D.1: The methods library

All above attributes exist once per method record in the methods library. Records with the same feature code may appear multiple times in the methods library to cover different ranges.

The Operations library

For creation of a shape, operations[1] are needed in a fixed sequence. This sequence is called an order of operations. The required operations to produce a manufacturing shape are derived from the operations library, via the method code. The method code defines the way a feature will be manufactured by relating a set of operations in a fixed order, which order and operations are stored in the operations library. An example of a method is given in Fig. D.2.

---

[1] An operation is one single treatment carried out by one tool (eg. centering a hole).

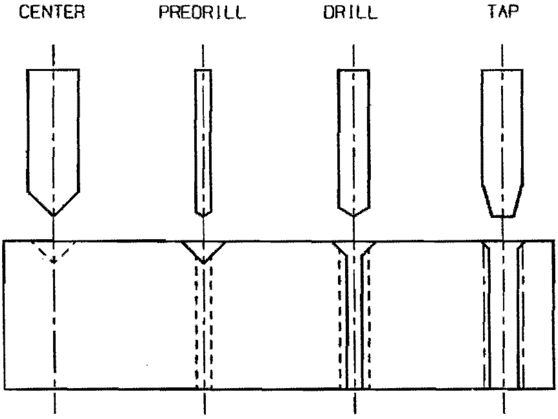


Fig. D.2: For producing a tapped hole, the manufacturing method consists of 4 operations

Per method, a number of operations in a specific order of sequence are derived from the operations library (Fig. D.3). Per operation, a motion code, a tool type, treatment type and a diameter algorithm is found.

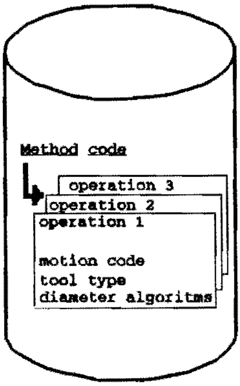


Fig. D.3: The operations library

Examples of a motion are:
- rectalinear (drilling, boring)
- follow pocket rough with side- and bottom-stock (is a clearing operation starting from the center of the pocket, in a spiral motion going to the outside border of the pocket)
- profile rough with side- and bottom-stock (is a contouring operation, following the form feature boundary)
- follow pocket finish (the same as follow pocket rough, but without side and bottom-stock)
- profile finish (the same as profile rough, but without side and bottom-stock).

The tool type is related to a required quality of the surface, for instance for rough pocketing a end mill with step teeth profile is suitable.

The diameter algorithm depends on the treatment. It gives the maximum range of applicable diameters for the treatment. For rough pocketing, for instance, a large diameter can be chosen, for profile finishing the tool diameter has to be smaller than the minimum boundary diameter.

Examples of diameter algorithms are: Tooldia < 2 x min pocketradius,
Tooldia < width of the pocket.

The Motions library

A motion is a pattern movement of the tool, during the execution of the operation. By the motion code in the operations library, a motion is found in the motion library (Fig. D.4). For drilling, the motion can include break-chips retractions. For milling the motion can be contouring, clearing or zigzag. Different motions create different quality classes of shapes.

The treatment type is rough or finish.

Side- and bottom-stock are attributes of the motion. Side stock is used to specify the amount of remaining material tangential to the tool on the part edge, after a milling pass. Bottom-stock is used to specify the amount of remaining material axial to the tool at the bottom.

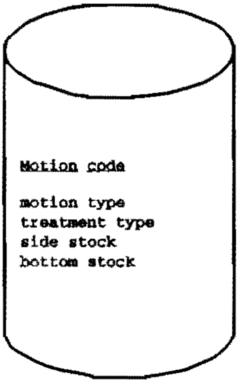


Fig. D.4: The motions library

The Material library

The material library consists of a code, a name and the material class.

Code, name and class have a one to one relation. A name is only needed for documentary reasons. Class is related to the tool library. By class it is possible to have more material types having the same technology in the tool library.

It has been chosen to store all speeds and feeds in the tool library instead of storing them in the material library, however these parameters are dependent on the material properties. If storing parameters in the material library, to derive speeds and feeds from, clear algorithms cannot be defined to calculate them for all kind of relations. If they are stored in the tool library, fine tuning of the parameter values per tool-type and -size is possible. Disadvantage of this structure is the larger amount of data to store in the tool library.

The Tools library

The tools library contains all needed tool data. Tool class indicates the application area of the tool (e.g. hardened steel). Tool type is for instance a shell end mill. Diameter, length and flute length are geometry data needed for matching against the geometry data of the shapes to be manufactured. Per treatment type (like rough or finish), a subrecord exists with the following data:

- maximum depth step,
- feed,
- speed.

Maximum depth step is the maximum depth which can be done in one operation, dependent on the treatment type. Feed and speed are also dependent on the treatment type.

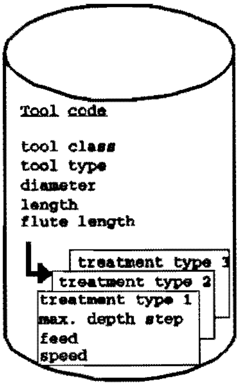


Fig. D.5: The tools library

Relations between the technology libraries

Methods library

The methods library is related to the product model database via the feature code. Dependent on geometry ranges of the form feature and the tolerances and roughnesses of the form feature (in case values are blank, they are found in the general attributes[1]) a method code is derived.

Operations library

With the methods code a specific order of operations is derived from the operation library. Per operation a motion code, a tool type and a diameter algorithm is also derived.

Motions library

From the motion code a motion type, treatment type and side- and bottom-stock is

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[1] General attributes have general values which apply for the whole component. In case values of a feature are blank, the general attribute value is default.

found in the motions library.

Material library
From the material code of the feature (in case this value is blank, it is found in the part attributes) a material class is selected in the material library.

Tools library
With the diameter algorithm, the material class, the tool type and the treatment type a record in the tools library is selected. Then all operations information can be derived to create automatically a NC dataset.

This relation is schematically illustrated in Fig. D.6.

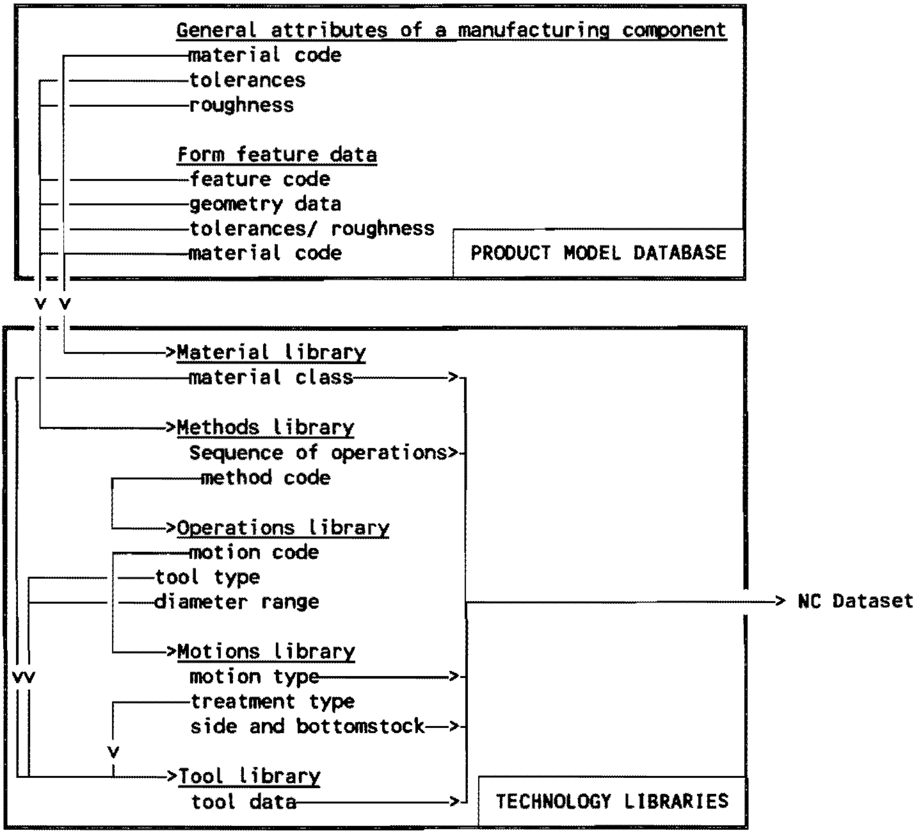

Fig. D.6: Scheme of the relations between the product model and the described technology libraries

Appendix E

Future enhancement requirements

The efforts to create FAST-CADCAM software at Philips Lighting has been limited to the minimal required functionality[1]. Building your own application shell on a CADCAM system, which is still under development, will require adjustments of the application shell each time a new release of the CADCAM system is implemented.

Although the functionality of FAST-CADCAM has been restricted, quite some wishes have been documented for extention of the software functionality. Hopefully the commercial CADCAM vendors will supply these functions in future releases of their CADCAM software. First enhancement requirement is the merge of the FAST-CADCAM application shell in the standard functionality of the CADCAM system. Additional enhancement requests are described in the next sections.

Classification of feature values

Current feature implementation uses a menu-driven input of data, supplying default values for each parameter. The user can accept the default values, or change one or more values. A problem of this way of defining parameter values is the fact that the designer thinks in classes instead of parameters. For instance the designer knows that he needs a hole to insert a M6 bolt. From a table he can derive the standard diameter for such a hole (6.3 mm), but he does not know this value from his memory. Therefore it is more efficient to present the different classes (M4, M6, M8 etc.) instead of values (4.2 mm, 6.3 mm, 8.4 mm etc.)[2]. Examples of classes are:

Size classes for holes:	M4, M8, M12, M16;
Quality classes for holes:	rough, normal, fitting;
Quality classes for pockets:	rough, normal, smooth.

After entering a class by the designer, the computer can derive values for the related parameters.

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[1] The present FAST-CADCAM functionality is still far from a complete automation of automatable technological decisions. For an implementation in practice however, it was required to cover all situations. For those situations, where no automated solution was present, it has been chosen to cover them by working procedures. The intent of the working procedures has been to separate automatable sections from the non-automatable sections. By proven applicability of the working procedure, actions have been carried out to automate the automatable sections.

[2] This is a simple example to illustrate the functioning of classes instead of values.

Manufacturing task structure

For automatic NC programming of form features, a sequence need to be defined by the computer to generate the NC dataset. This sequence can be derived from a manufacturing task structure. The manufacturing task structure represents the relation between manufacturing tasks.

On the lowest level, a task is a set of operations in a fixed order, to produce a manufacturing element (e.g. a form feature). On a higher level, a task is a set of tasks. The way of manufacturing is captured in the task structure and therewith, the task structure is a main element of the process plan. The ability to define a task structure in the product model database, is a serious demand to the supplier of the CADCAM system, because this functionality is difficult to achieve in an application shell.

The task structure consists of 4 relations:

- the hierarchical structure,
- the manufacturing plane relation,
- the material relation,
- the succeeder relation.

1. Hierarchical structure

The hierarchical task structure represents a logical division of the manufacturing elements of the component (Fig. E.1). The manufacturing designer uses this structure for documenting and editing his process plan structure. The configuration of set-ups, also virtual set-ups, is part of the hierarchical structure. A virtual set-up structure is used for creating alternative process plans afterwards (see Chapter 5). The hierarchical structure is a logical structure for the designer; the final structure of operations to be done by the machine tool may look completely different due to optimization of operations, but is based on the task structure.

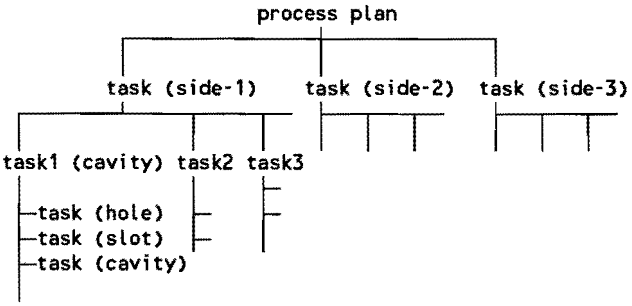

Fig. E.1: An example of a hierarchical task structure

An example of a task level structure is a manufacturing component with a set of holes in the bottom of a topside cavity and holes in the front and back side (Fig. E.2). The manufacturing sequence may be (dependent on the machine tool and the required accuracy):

- face mill the topside surface
- contour mill the sides
- mill the cavity
- mill all holes.

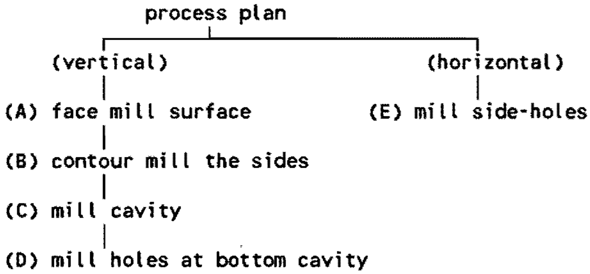

Fig. E.2: A scheme of the above example

2. The manufacturing plane relation

Tasks operating on the same manufacturing plane, have a manufacturing plane relation. In the scheme of Fig. E.2, the operations (A), (B) and (C) have the same manufacturing plane.

3. The material relation

Normally, per manufacturing component, tasks operate on the same material. There are exceptions. Tasks may have a different material code, for instance if the operations take place on a hardened section of the part. Tasks which operate on the same material have a material relation.

4. The succeeder relation

A task may not be performed before another task has taken place. This is called the succeeder relation. In the scheme of Fig. E.2, the operations (B) and (C) are succeeders of (A). (E) is succeeder of (B). (D) is succeeder of (C).

An advantage of geometry related task structures occurs during changes in the geometry model. A lot of task level relations will automatically be adjusted, if geometry changes. This is a challenge for wider re-use of designs. If the manufacturing task structure is present in the product model database, a lot of extra functions can be developed to increase the efficiency of the CAM functions and to reduce errors in the NC file (see "Efficiency enhancements" in the present appendix). Supplying task level functionality is reserved to the source owner of the CADCAM software. In the current implementation of DfMASS, task levelling is just a structuring method in the mind of the designer.

Collision control

During part production, there may be a risk of collisons between the following items:

- machine tool,
- tool and toolholder,
- fixtures,
- manufacturing component.

For example, a collision occurs if the machine tool can not retract tool and toolholder far enough to rotate the part on the turntable, a collision will appear. Collision control is not yet a functionality of the CADCAM system. Currently it is checked by the manufacturing designer by the help of the graphical tool path simulation. To be able to control collision, the CADCAM system should be extended by a machine tool library, containing the free space in which the tool, the fixtures and component can operate. Also geometry information should be available on the space occupied by the combination of tool and tool holder. As long as there is no automatic collision control, collisions can be checked visually by simulation of operations. Besides this application, simulation of operations can be applied for testing purposes, to be able to see the contents of the NC dataset. An illustration of the production steps of the milling process of a particular NC dataset, can also be used for instruction purposes for the workshop. Current simulation function of the applied CADCAM system has a poor functionality, which could be improved by following functions:

- user-control of the display speed of the tool path (fast, slow, freeze, rewind) during simulation,
- change the view (rotating, panning, zooming) on the simulation process, during execution,
- refresh the screen to wipe out already inspected tool pathes,
- display set-up number, task number, needed tools etc.
- solids visualisation of part production (see the material being cut away).

Family Controller

The Family Controller helps the user to stay between the restrictions of a Manufacturing Family (see Chapter 5: Manufacturing Families). It controls interactively during modelling whether family borders are being exceeded. If a family is exceeded, the family controller should propose a next family and further on control whether next geometry stays between the border of the new family. Today, family control is a function of the manufacturing designer and is not supported today by software tools.

Efficiency enhancements

If the form features functionality, related to technology databases and the manufacturing task structure functions were built in the CADCAM software, following enhancements could be added to improve the efficiency of the whole system.

- Minimization of the number of tools needed

  Currently, a fixed diameter value per operation is derived from the technology system. By producing a diameter range per operation, instead of a fixed diameter, the postprocessor is able to derive a minimum set of diameters from all diameter ranges. This system will lead to the smallest number of tools needed.

Based on a manufacturing task structure in the product model database, the next two functions check whether all form features and free geometry has been taken into account in the NC file. Form features and free geometry which has no manufacturing task relation will not be manufactured.

- Check form features on task relation

  By this functionality the user can check whether all form features of the product model have a task relation. Also the coordinate system of the form feature will be checked against the coordinate system of the task.

- Check geometry entities on task relation

  By this functionality the user can check whether free geometry in the product model does have a task relation. To be able to have entities in the product model which do not belong to the component geometry, this functionality should only check a certain set of layers (on which the component geometry is represented). For example the geometry of the fixtures can be put on a layer which will not be affected by this functionality.

- Check form features on available technology

  After all attributes for the form feature are entered during modelling, the computer should interactively check whether this feature can be produced by the available technology. This function would give a faster response to the designer about the manufacturability of his design. It is even possible to generate an estimated cost of the form feature simultaneously, to aid the designer in cost efficient design.

- Automatic allocation of features to a task by rules

  Today features are manually selected per task. Automatic allocation of features to tasks makes this human interaction redundant. For this function rules need to be defined by which the allocation decision can be made.

- Automatic sequencing of tasks by rules

  Although this idea is not yet completed, there are possibilities to automate sequencing of tasks. For instance features which are completely enclosed by another feature, should be operated in a succeeding task.

- Library storage

  The technology libraries consist of tabulated data, stored in index sequential files. Index sequential files are used for fast access by the CADCAM system. For simple implementations with few records in the libraries, they can be controlled by simple file access routines. For extensive implementations, index sequential files soon will be hard to read and difficult to maintain. The need for database functionality like SQL[1] or even an expert system as interface to the index sequential files, becomes evident for editing large databases. An example of an advanced editing function is automatic checking whether the appearences in the operation library are covered by records in the related files.

  Because fast access of the technology is needed, it is expected that the source still will be stored in index sequential files (Fig. E.3).

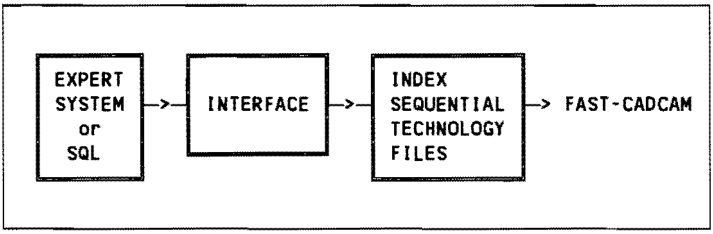

Fig. E.3: The relation between an advanced editing system and the technology files.

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[1] SQL is the standard user interface of a lot of relational database systems (e.g. of Oracle). By SQL records can be retrieved and data can be changed for instance by user friendly input and edit forms.

- Interference between operations

  Undesirable interference between operations will cause defective parts. Interference can be divided into in sequential interference and interference between shapes. An example of sequential interference is a hole in the edge of a pocket. If first drilling the hole and second milling the cavity, the product will be alright. If first milling the pocket and second drilling the hole, the drill may deviate from the programmed toolpath by sideforce. Priority setting of operations should be covered in rules, to avoid mistakes by the designer. An example of interference between shapes is two pockets with a thin ridge in between. The way to produce it is by milling the pockets first with a thick ridge in between and step by step reaching thin ridge from both pockets. Rules should be developed to detect interference and to produce operations which avoid interference.

- Generate pallet changing in the post processor functionality

  In case an automatic pallet changing device will be applied, the postprocessor must be able to generate a pallet change, after a job is finished and a load command for the next NC file.

- Adjust maximum feed to maximum speed in the postprocessor functionality

  The feed and speed of an operation is given in the NC file, generated by FEATURES-NC, STANDARD-PLANAR-MILLING and by standard CAM functions. In case a machine tool is used, which maximum speed is less than the generate speed in the NC file, the postprocessor will reduce the speed to the maximum speed of the machine tool. The feed has to be adjusted as well, relatively to the reduction of the speed.

Appendix F
CAD applications for Functional Design

By using CAD as a design tool, additional possibilities become applicable for Functional Design.

Knowledge based engineering

In the early nineties knowledge based engineering and design by constraints have started becoming available in CAD systems (ICAD, Pro-engineer). By knowledge based engineering a model of the mechanical system can be build in the computer in which geometrical and functional constraints, group technology, database and knowledge relations can be stored. By varying parameter values, specific specimen of this model can be defined. This method is suited in case different variants need to be derived from one design model (group technology).

For specific single designs this method is not applicable. It would take a lot of time to set up a knowledge model of the system, from which only a single specimen would be derived. In this case it is more efficiënt to enter the desired values directly instead of working with parameters.

Design by constraints

Design by constraints is a promising tool for single designs. As soon as a relation between geometrical entities is defined by the designer, it can be entered in the computer model and will remain during the entire design process[1]. The commercial CADCAM systems are beginning to introduce this kind of design philosophy. Unigraphics has introducted UG-concepts for conceptual modelling. The constraints can even be entered without knowing geometry data itself. In conventional CAD systems it may be possible to enter a relation between geometrical entities, but this relation is only used during creation of the entities. The relational information is not stored in the model. In changing an entity, the previous related entity is not taken into account anymore.

Design by constraints functionality has not been applied in practice at Philips yet, because it has just become available, but it is expected to play an increasing role in Functional Design in the near future. It may even replace todays techniques of building product geometry in the product model database.

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[1] An example is the dimension relation of a lever (eg. $L2 = 0.5 * L1$), if L1 is changed, L2 will be adapted immediately by the computer.

Retrieval and re-use

Another characteristic of CAD is the ease of editing and copying. The CAD designer likes to create new modules, by copy and edit functions, instead of the designer behind the drawing board, who dislikes to change drawings by scratching and redrafting. The CAD designer copies parts from existing designs into his present design and adapts it. For selecting functions from existing designs, the computer offers userfriendly retrieval systems (for instance on keywords). By these techniques and by having existing designs stored in product model databases, existing designs can be selected for re-use and adapted by the userfriendly editing techniques of CADCAM systems. Re-use of proven solutions, will increase the quality of Design and decrease costs and leadtime.

Finite elements method

For parts which are critical in strength, deformation or temperature gradient, the CAD model can be used to create a FEM model [41]. Unigraphics is able to generate a mesh model, directly from the geometry file, on which directly a simple FEM calculation can take place (Fig. F.1). For more extensive FEM calculations, the mesh model can be used as input for a professional FEM package (ANSYS, MARC, Patran). Especially if the critical part is geometrically related to other components, adaptations of the part can be done in the assembly design environment of the CAD system and again used as input for FEM calculations. FEM systems have not been made for extensive modelling (whole assembly models for instance, can not be handled easily), therefore the connection between CAD and FEM is very welcome.

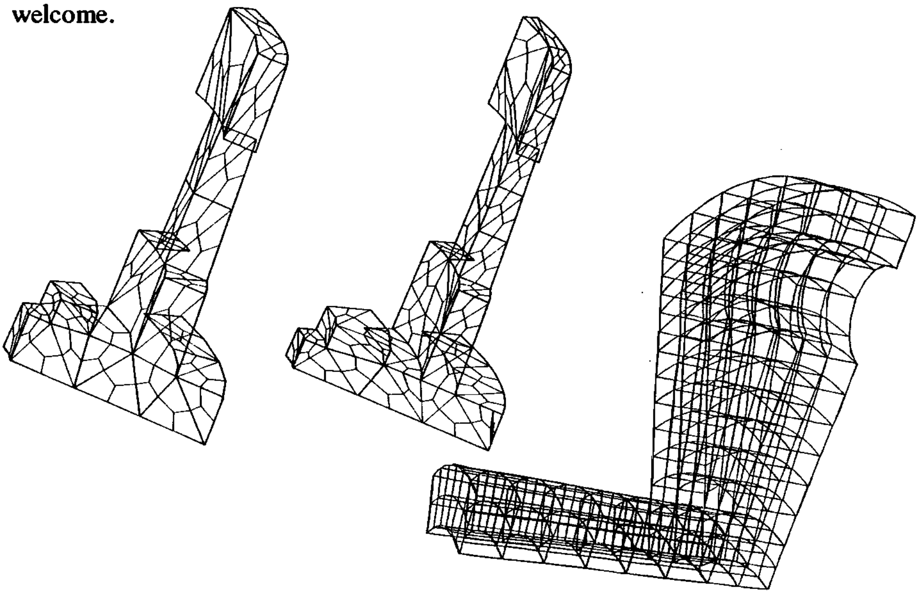


Fig. F.1: Mesh models (ref: [41])

Simulation of movements

Philips Lighting has written application software, which is based on Unigraphics functionality. This software gives the possibility to define three different groups of entities, which can be translated and rotated in interrelated movements (by a place-time diagram). Each time the relative position of entities can be checked during a simulation session. By evaluating the distances between entities, collison can be controlled, dynamic clamping functions can be checked, etc. (Fig. F.2).

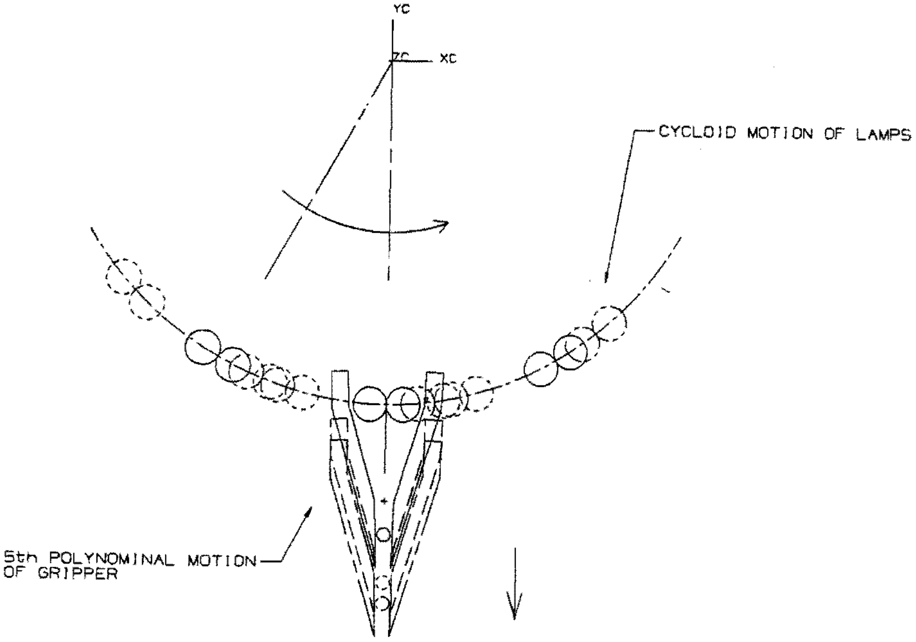


Fig. F.2: An example of a simulation

Mechanisms

Unigraphics supplies functionality to simulate lever mechanisms, by which the optimal dimensions of lever systems can be designed (Fig. F.3).

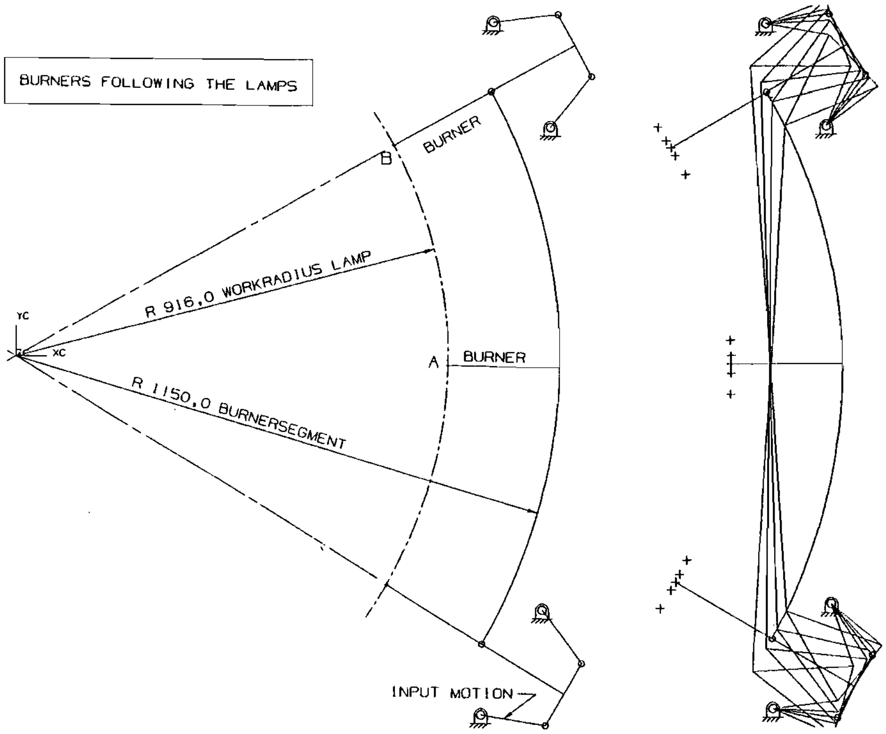


Fig. F.3: A mechanism analysis

Appendix G
Advanced CADCAM in Manufacturing Design

By using CAD as a design tool, additional possibilities become applicable for Manufacturing Design.

Parameterized parts

In drawing based design, the use of parameterized parts is limited. Mostly those parts vary only in lengths and diameters. In computer models of parts (eg. geometry producing programs) also angles, interrelated geometry (e.g. fillets) etc. can be parameterized. The parameters can also be calculated by the computer, eg. by placing such a part and adapting it to the environment. Design by constraints functionality can also enlarge the possibilities of parameterised parts.

Simulation of disassembling

In Functional Design disassembly requirements have been specified. Because a whole model of the system is available in 3D CAD information, disassembling can be simulated. By selecting a part of the system and rotating and translating it, the designer can see whether the part can be removed from the surrounding parts. By a well considered assembly structure, the designer can remove whole assemblies on the screen and discover, whether it is the right sequence of disassembling. By documenting the different situations during this simulation session, e.g. by a hard copy on paper, this can be used in maintenance later on.

Automatic generation of information

Information, such as bill of material (BOM), tool lists, etc. can be generated from the product model database by lists on paper, directly on the screen or connected to database driven BOM applications. Dependent on the needs of the organization, report generators can be built to supply the desired information.

Engraving of code numbers

By automated milling, it is quite easy to add code numbers to components. By a specific function, a character string, plane, position, size is translated into milling instructions. By reading the code numbers directly from the machine, the engineer in the assembly workshop is able to relate this information to the technical documentation on paper or in the computer. Mistakes by outdated drawings is not possible anymore because the engineer will recognize the mismatch with the code numbers on the machine. Also for maintenance purposes, engraved code numbers are welcomed.

Integration of CAD and CAM

An important opportunity of integrating geometry modelling and process planning using an integrated CADCAM systems is found in the relations which can be made between geometry and process planning entities. If changing the geometry, the process planning data are adapted automatically. An example is the relation between a boundary and underlaying geometry data. The boundary is a closed chain defined by geometry entities. The boundary is the starting-point for calculating the tool pathes (e.g. for pocketing a cavity). If the underlying geometry is changed, the boundary is adapted automatically. Also if hole features are changed (moved, adapted, deleted), this change will automatically be taken care of by the process planning.

Alternative process planning

The process plan structure is dependent on the machine tool configuration. If the specified machine tool is not available in the workshop, due to peak loads, failure or other reasons, an alternative process plan can be derived from the manufacturing task structure. The NC dataset will be automatically regenerated in the new structure. The possibility of creating alternative process plans can be very important from a logistic point of view.

Geometry changes related to fixtures

Because the fixtures are a part of the product model database, changes to the geometry of the component can automatically adapt positions etc. of the fixtures. In other cases where the fixtures will not be adapted automatically, a misfit of the existing fixtures can be seen clearly in the geometric views on the screen.

Generating process planning entities in parameterized part programs

Besides generating the geometry of a part by parameterized programs, additional process planning entities can be defined automatically. Because boundaries can be related to the geometry model, it is possible to generate boundary information and a fixturing configuration, by the same program, which generates the 3D geometry model. By this technique an extensive degree of automation can be realized. Especially organizations, which have introduced group technology for manufacturing components, will benefit from this function.

Appendix H

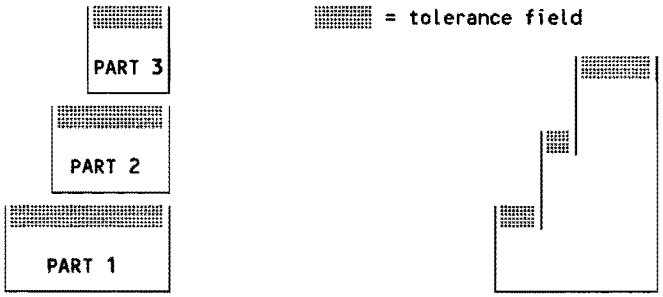
Design rules for manufacturability

In this appendix, rules for manufacturability are presented for detailed modelling. Some designs are easily manufacturable, others are more difficult to produce. Sometimes complexity is caused by disregarding manufacturability. Unfortunately design rules for manufacturabilty are dependent on the manufacturing environment. By manufacturing environment is meant machine tools, fixtures, tools, toolholders, technology. Especially for highly automated part production, a consequence of these dependencies is the required knowledge of the manufacturing environment to the manufacturing designer. A standardized, well documented manufacturing environment reduces the complexity for the manufacturing designer.

The rules are described for general application and need to be adjusted to the concerned manufacturing environment.

RULE 1: Avoid assembling

Besides the resources needed for assembling, high costs are caused by the logistic process to collect all components for the assembly (drawings, bill of material, purchase components, manufacturing components). Besides, by assembling, expectable deviations of the different assembly parts need to be summarized to calculate the possible deviations of the assembly. This "building up" of tolerances is avoided by combining components to a single component (Fig. H.1).



(A) total tolerance = 3x tolerance per part (B) no building up of tolerances

Fig. H.1: Building up of tolerances

RULE 2: Minimize the use of manufacturing components

Especially in small lotsize, fast development projects, purchase parts often reduces leadtime and costs and are less riskful. Therefore it is recommended to apply purchase parts instead of manufacturing components, where they can fulfill the same function.

It should be noted that there is a contradiction between rule 1 and 2, due to the fact that in Manufacturing Design different functions can be integrated in one manufacturing component. To realize a function by purchase parts is often by assembling adjustable parts.
A break point can be found between applying purchase parts and manufacturing components (Fig. H.2).

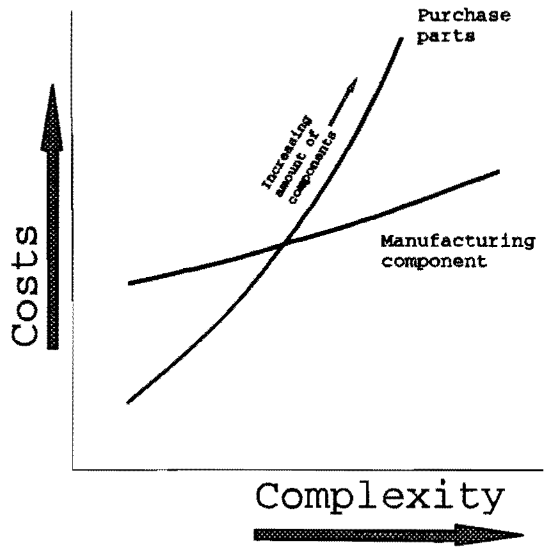


Fig. H.2: Scheme of application of manufacturing components versus purchase parts

RULE 3: Use available manufacturing technology

Avoid special treatments which can not be executed by the standard machine tools, fixtures and tools. Special treatments need to be done by an unusual routing (e.g. by unusual suppliers) and increase the logistic complexity.

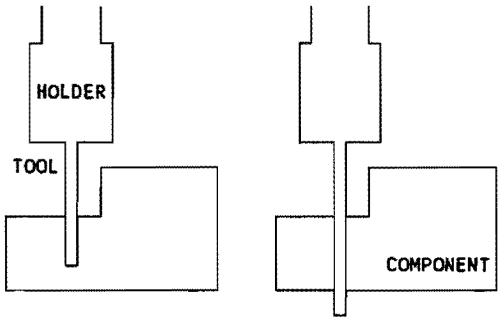
RULE 4: <u>Design within reach of the machine tool</u>

It is not easy to produce mathematical algoritms for the allowed dimensions of a component, regarding the reach of a machine tool. The dimension limits of a component depends on:

1. The dimensions of the machine tool.
2. The length of the tool, including toolholder

   The toollength depends on:
   - the availability of tools in certain lengths,
   - the required minimum tool length, dependent on maximum hole depths and on possible collision of the toolholder to the manufacturing component or to fixtures (Fig. H.3).

CUTTING A THROUGH HOLE



(A) tool too short (B) tool allright

Fig. H.3: The relation between toollength and component

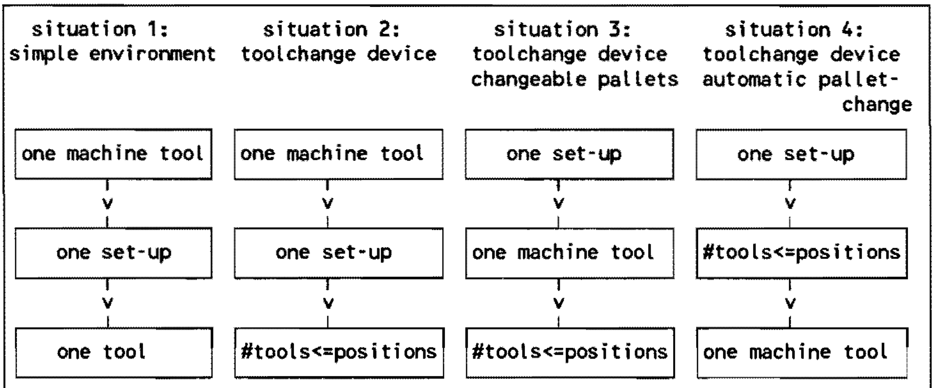
3. The dimensions of the material
4. The dimensions of fixtures
5. The position of the material on the machine tool

The above five circumstances have mutual relations and, as said, are difficult to combine for all possible situations. There is one simple solution: the designer has to avoid to reaching the machine tool limits. Unfortunately the manufacturing designer can not always avoid to reaching the limits.

RULE 5: Delimit the manufacturing process steps

Between two process steps human intervention is often required. Between process steps a change of a machine tool, another set-up, a tool change, or an intermediate adjustment of the tool may be required. Therefore it is recommended to restrict the number of:
- machine tool changes,
- set-up changes,
- tool changes,
- extensive tolerance and roughness requirements.

A change of machine tool may cause a waiting time, which can easily extend a period of a week delay in large organisations. Changing the set-up causes idle time for the machine tool. By changing the set-up, extra tolerances are generated because of inaccuracies. Labour is required to perform the set-up change. If a machine tool lacks a tool changing device, a tool change will require human interference which causes waiting time and operator attention. The consequences of changing machine tool, set-up and tools depends on the manufacturing environment (Fig. H.4).



Situation 1 gives the sequence of priorities if the machine tools have no tool changing device and no pallet system is used. First priority: try to design, such that all operations can be executed on one machine tool; second priority: avoid more than one set-up.
In situation 2, the production can be executed without operator intervention, if the number of tools needed is less or equal to the tool positions in the tool chain.
Situation 3 includes the use of pallets, which can be interchanged between machine tools without introducing extra tolerances.
Situation 4 uses pallets which can be automatically changed between machine tools by a robotized system. In this situation, in case more tools are needed than the available positions in the tool chain, it can be efficiënt to use two similar machine tools by which the total number of tool positions will be doubled.

Fig. H.4: Manufacturability depends on the environment

RULE 6: Use standard material
For standard material the technology is known. For non-standard material the technology needs to be defined.

RULE 7: Use standard stock sizes
This rule can be supported by a stock material database from which the standard sizes can be retrieved. In case a special size is needed, which is not available in the the stock material library, one should try to use standard sizes and introduce contour and face milling to achieve the desired result.

RULE 8: Avoid pretreatments/ posttreatments
Pre- and posttreatments increase the logistic complexity of Manufacturing. If pre-/ posttreatments are inavoidable, choose processes which have limited logistic risks. Make a list of pre-/ posttreatments and indicate the complexity of the processes. Also regard leadtime consequences, costs and risk. Especially avoid posttreatments which need a succeeding manufacturing process (e.g. hardening, which may require an extra grinding operation afterwards).

RULE 9: Use preferred dimensions
To restrict the size of the technology database and the tools needed, it is preferred to use a limited set of dimensions (for hole diameter, pocket radius etc.). This can be realized by using a menu driven geometry modeller, producing standard shapes with preferred parameter values (form feature based design environment).

RULE 10: Use standard tools
This rule is related to rule 9. By using automatic tool selection based on a database of standard technology, standard tools will be selected automatically. However for exceptional shapes, other tools may be required. In that case one has to consider the tool selection. There are three levels of tools:

a. standard tools, which are available in the workshop,
b. purchaseable tools, which can be purchased from a catalog,
c. special tools, to be manufactured.

a. is preferred above b., b. is preferred above c.

RULE 11: Delimit total number of tools
It is efficient to restrict the number of tools, even if the tools are standard. Each tool, which is needed, must be collected and measured before starting part production. In case of a tool changing device on the machine tool, it is preferred to delimit the total number of tools needed to the maximum number of tool positions in the

tool chain. The number of tools will be restricted by applying the same sizes in a component. For instance if M6 is required for a specific function, while other hole diameters are not restricted, consider using M6 for the non-restricted holes too.

RULE 12: Avoid extensive tolerances

By extensive tolerance and roughness requirements is meant all manufacturing results which can not be achieved by the standard automated technology. The range of standard achievable results is dependent on the manufacturing environment.

RULE 13: Delimit VHB: V preferred, HB second, VHB third

VHB means vertical and horizontal operations required with the use of the B-axis (= turn table). The less restrictive requirement is vertical-only (V): besides on a vertical machine, it can also be produced on a horizontal-only machine, no turn table is required. Second best is HB (horizontal operations with use of the B-axis (= turn table). Those components can be produced on a machine, which spindle can be changed manually from vertical to horizontal and on a horizontal-only machine. Third best is VHB: those components require a machine with automatic change from horizontal to vertical and with a turn table.

RULE 14: Use standardized set-up configurations

By bringing Manufacturing Design to the design office, the set-up configuration is not coming from the mind of the craftsman behind the machine anymore, but from the designer. To avoid problems with set-up configurations, it is preferred to use standard solutions which are known by the manufacturer and which have proven to be right. By using standard manufacturing task structures and using a database of standard fixtures the manufacturing designer avoids defining uncertain set-ups and unavailable fixture devices.

RULE 15: Avoid fine positioning of the material

If the process plan requires a fine positioning of the material on the machine tool, extra operator time is required to position the material. The quality of the endproduct will depend on the quality of the operator. If the component is produced by contouring the entire circumference, the material does not have to be fine positioned. The quality of the product is within the tolerances of the machine tool.

RULE 16: Use shape-locked fixturing devices

Producing a product with internal tensions may lead to bending afterwards. This can be solved by shape-locked fixtures. In case of risks that internal forces are built up during milling in the product, due to clamping forces of the fixturing, special fixturing devices need to be designed by which the product is clamped by a similar shape (shape-locked). By a shape-locked fixture, the stresses are less than by standard standard fixtures which clamp only locally (Fig. H.5).

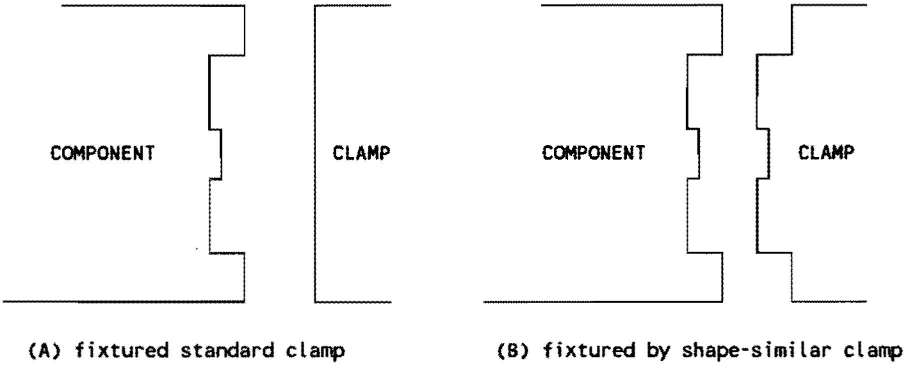


Fig. H.5: Shape locked fixture

RULE 17: <u>Clamp close to high toleranced operations</u>
Milling forces cause bending of the material. If high tolerances are required, the fixturing configuration should consider deviations, due to bending. A simple rule is to clamp the material close to the accurate operations, so bending will be limited to a minimum.

RULE 18: <u>Avoid loosing material during part production</u>
If a piece of material is separated from fixturing, during part production, this piece may be launched in space by forces of the tool. This situation must be avoided. A way to avoid such situations is to clamp the part of the material which will be separated. Another solution is to cut away the entire section by pocketing (Fig. H.6).

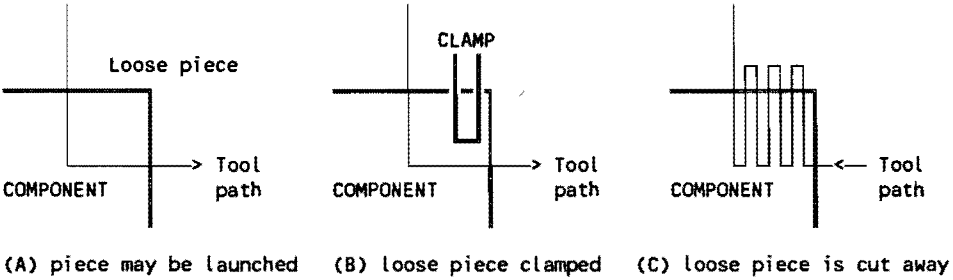


Fig. H.6: Loose piece of material

RULE 19: Avoid accumulation of chips

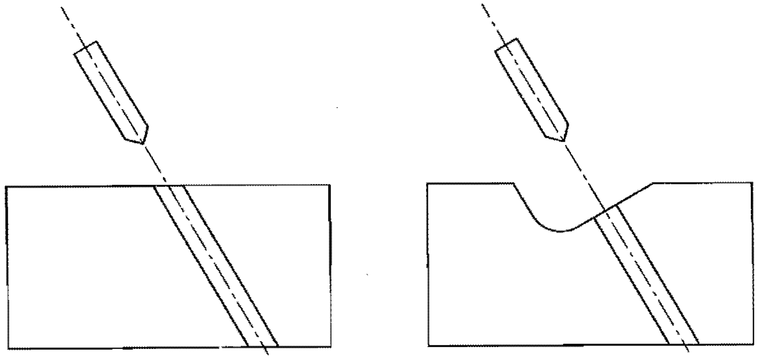
During production, chips will fall down and accumulate. If heaps of chips interfere with the milling process, the quality of the endproduct decreases. Therefore consider chip heaps during Manufacturing Design. For instance, by milling in side surfaces the chips are able to fall below and away from the product; by milling in the top surface, the chips may remain on the surface and cause problems.

RULE 20: Avoid non orthogonal/ non polar operations

Shapes with an obliquing angle to the horizontal and vertical axis of the machine tool can only be produced by a tipping table or tipping tool axis, or by another set-up. In case of a turn table, operations can be performed with a tool axis in line with the table origin.

RULE 21: Avoid non-perpendicular operations

Drilling and milling non-perpendicular to material surface causes a sliding off of the tool from the material. If the material surface is at a horizontal side of a product, which surface will be created by contouring with a vertical mill, the contour may be adjusted in a way where the surface will become perpendicular to the horizontal axis (Fig. H.7).



(A) Non perpendicular, wrong situation (B) Perpendicular, correct situation

Fig. H.7: Non perpendicular operations

RULE 22: Avoid "hard to reache" operation spots

If a small hole need to be manufactured in a narrow deep pocket, special extended tools (drills and taps) need to be used to avoid a collision between the tool holder and the product. In case such a situation is unavoidable, documenting with extra attention to avoid problems during part production becomes very important (Fig. H.8).

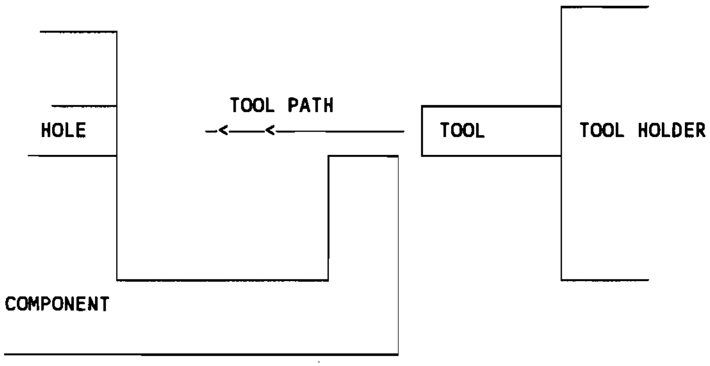


Fig. H.8: Hardly reachable spot: hole can not be produced by given tool

RULE 23: Define absolute tolerances (absolute to the machine tool origin)
The positioning accuracy of a machine tool decreases relative to the distance from the machine tool origin. Therefore absolute tolerancing of the manufacturing component relative to the center is preferred, thus avoiding relative tolerancing. For instance relative tolerancing between two holes, which are positioned at a great distance from the machine tool origin, may cause problems.

RULE 24: Minimize interference between form features
If the manufacturing of two form features interfere (eg. a thin rim between two pockets), they can not be manufactured by standard technology, but need special methods and technology. The required result can sometimes only be achieved by special fixturing devices, which are adapted after each operation.

RULE 25: Avoid narrow differences
If a manufacturing components can fit in the assembly in a wrong position (or almost fits), assembly errors may occur. For assembly purposes different components should not look similar. A asymmetric shapes in a component, which look symmetric, should be avoided. This seems to be in contradiction with the intent to use families of parts, but by simple changes similarity can be decreased without changing the manufacturing task structure of the component.

Examples of asymmetric shapes are:

- placing a hole slightly away from the center line,
- two holes with slightly different diameters,
- a slightly declining surface.

RULE 26: Tool radius must be smaller than contour radius

It is evident, that the tool radius must not be larger than the contour radius, if the surface is hollow. If the tool radius is equal to the contour radius, in theory the curve can be milled. However the roughness of the surface increases, because the tool cuts over the whole touching area. The technology system, described in chapter 3, sometimes avoids these situations, but in cases where the system only suggests a value, which can be changed by the manufacturing designer, this rule need to be considered (Fig. H.9).

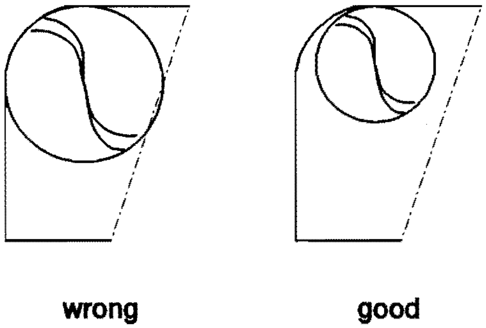


Fig. H.9: Tool radius must be smaller than the contour radius

RULE 27: Use maximum radii by hollow curves

By hollow curves, the mill diameter must be smaller than the contour radius to avoid undercutting during milling. In case the minimum radius is small compared to the size of the shape, numerous tool pathes are required to cut the shape by a tool with a smaller diameter than the minimum radius. In those cases, the major part of the hole is often milled by a tool with a larger diameter and only the last material is cut away by the smaller tool. It is better to avoid small radii (Fig. H.10). Also the surface quality (tolerance, roughness) increases by bigger diameter/depth ratio's.

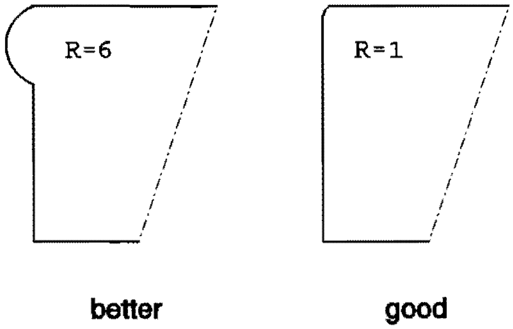


Fig. H.10: By smart modelling, often the minimum tool diameter can be increased a lot

RULE 28: An open pocket is preferred above a closed pocket

To realize a closed pocket, more operations are required (drill hole, clear the pocket), than by an open pocket (clear the pocket) (Fig. H.11).

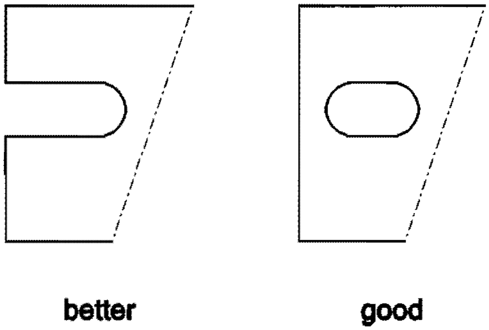


Fig. H.11: An open pocket is preferred above a closed

RULE 29: Avoid engage and retract on functional surfaces

Engaging the tool and retracting it cause a disturbance (roughness) on the surface. If only a part of the contour has a functional purpose, it must be designed that the engage and retract area of the tool is on a non-functional section of the contour.

RULE 30: Avoid small diameter/ length ratio's

If the tool diameter is small compared to the depth of the shape, the tool will bend during milling, causing a deviation of the shape. In case of a small diameter/ length ratio, the surface need to be milled by extra operations (see technology table in Section 4.2.1).

RULE 31: Avoid double curved shapes

Double curved shapes need to be produced by a global mill or by a special mill. Dependent on the tolerance and roughness requirements of the surface, the required operation time can be relatively long, because the material reduction per operation is limited for a global mill. Special mills require extra attention and thus increase the complexity of Manufacturing.

Appendix I

The archiving system

When changing from information on paper to electronic data, it appeared to be necessary to control the design output in an appropriate computerized way. To stay with a conventional archive system, two problems arise:

- one can not live with just datafiles stored in user directories (files stored in userdirectories are not easily retrievable by other users. Therefore a userindependent storage system is required.
- the paper-based archive system does not store the source information, but a copy of the design.

Therefore an archive system needs to be realized, codenumber based, with formal release procedures, to make sure the storage of design information is strict and user independent. Files are to be created in the userdirectory of the designer. Once ready, the designer sends them to the user independent archive environment for further processing. For changes to archived files, the designer is provided with a copy of the archived information in his userdirectory. After he completes the changes, he offers the new version to the archive system (Fig. I.1).

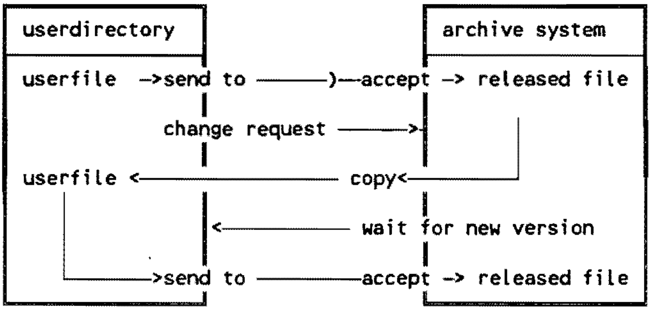


Fig. I.1: A scheme of the release control system

The archive system has been build in such a way that the user is forced to follow the release procedures. The system provides an automatic control on the data offered to the archive system.

Examples of the embedded release procedures are:

- the design file is checked on the main characteristics the contents should hold,
- when a file has been retrieved for changing, the system knows. In case another user requires a retrieval, he will be informed of the outstanding change.
- an official document cannot be produced without offering the information to the archive system; herewith it is ensured that information is stored in the archive system before next processes start using the information.

To create a plotfile from the archived graphical file is a computer time consuming effort. Therefore microfilm cards are produced by the computer and, when paper copies are required, a copy of the microfilm card will be produced.

Appendix J

Types of planning

Dependent on the circumstances, the planning of Design, Manufacturing and Assembling may be of a specific type. There are two ways of planning control:

- Sequential planning,
- Concurrent planning.

Sequential planning

By sequential planning is meant that the total design process is finished before Manufacturing will start. Assembling will not start until all components are ready.
Sequential planning can be based on push control or controlled by pulling.
By push control, the preceeding activity pushes the execution of succeeding activities. In other words, the succeeding activities wait until they can start. If a preceeding activity is finished completely, it signals the succeeding activity and supplies the information. The information is often supplied as a total package. This method avoids interference of one activity in the internal proceedings of another activity. It is a procedural way of planning, causing relatively long leadtimes.
By pull control, the succeeding activity asks for output from a preceeding activity when the planning of the succeeding activity asks for it. The succeeding activity pulls the order through the organization. If the preceeding activity is still being developed when the succeeding activity asks for input, often partial information will be supplied to feed the succeeding activity. This method of supplying partial information implies the risk of later changes.

Concurrent planning

When an activity is finished for a part of the total system (e.g. all information for one module is ready), the next activity can begin for this part, while later information on other parts of the system will follow. The disadvantage of this method is the complexity of the detailed planning. On the other hand, by concurrent planning the total leadtime of a creation process can be minimized.

Which type of planning control should be considered, depends on the situation.

1. Few items with very long leadtimes in acquisitioning

Dependent on the planning of components with a long leadtime (the critical items), a planning can be made for the other components (purchase parts and manufacturing components). Design need to define the critical items as soon as possible (push from Design). Planning control should focus on these items (Fig. J.1).

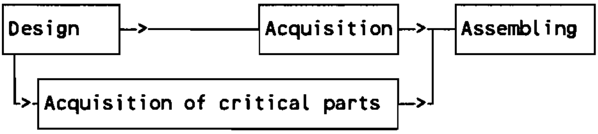


Fig. J.1: Acquisition of critical parts control assembly planning

2. Many projects with many components with small leadtimes

If there are many components to produce, all not lying on the critical path, a planning should be initiated by the needs of Assembling. This department will pull the components out of the manufacturing process (Fig. J.2).

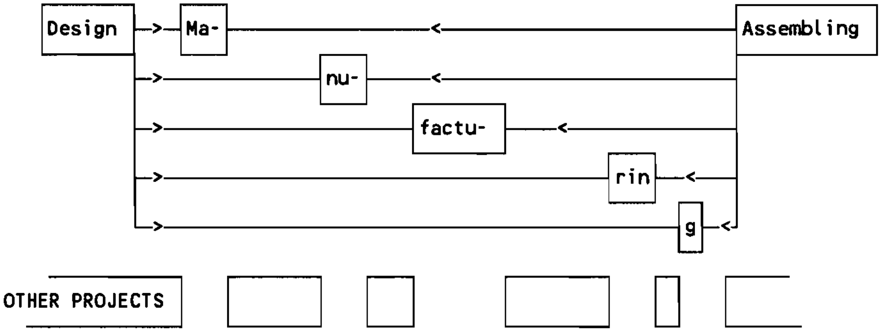


Fig. J.2: Manufacturing controlled by the assembly planning

3. Very short leadtime projects

If the design capacity is less than required, the different modules of a mechanical system can not be designed concurrently; some modules have to be designed sequentially. If the manufacturing and/or assembling capacity is also limited, one can decide to execute the project concurrently. It means that a module, after the design has been finished, directly goes into acquisitioning and later on into assembling, without waiting for the whole system to be finished. (Fig. A6.1.3).

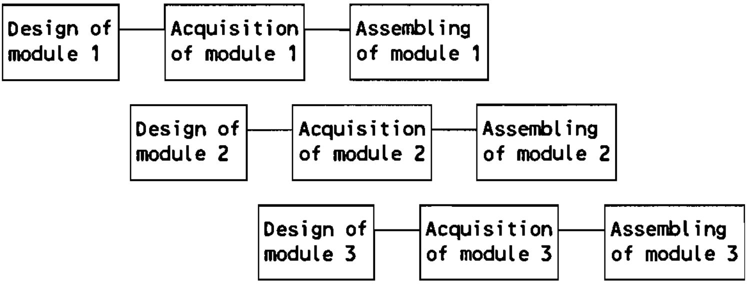


Fig. J.3: Concurrency in Design, Manufacturing and Assembling

Appendix K

Routing systems

Working with a different medium for communication (electronic data instead of paper-based systems) asks for an appropriate routing control system to keep track of the information through the different process steps. To handle CA information asks for a CA control system, so the user can control the whole job behind his screen. For this purpose a routing control system has been specified. Routing control has been developed in the same spirit as DfMASS itself, namely as an online single sourcing multiple access system.

Advantage of an online, multi access system is the availability of control data to the whole organisation. In conventional workshops, the routing sheet accompanies the material through the factory. It is only readable for executor of the current activity.
In a computerized system, all intermediate information is available for all disciplines concerned, including for management information.

Necessary electronic actions can trigger the routing control system. Eg. when the manufacturing designer sends his output to the the manufacturer, by a computer command, the routing control system can be signalled about this action automatically. By these techniques, one can be sure that the status data in the routing control system cope with the reality.

The availability of the status of components and modules in a project is of great support for decreasing the leadtime of a project. On his terminal, the project manager can derive the required resources and inform the capacity manager of this requirements. Priority between projects can be adjusted to this information and flexible resources can be made available for expected future peak loads.

Current status of the routing system

At Philips Lighting a routing system has been developed and implemented, following the above principles. The scope of the system covers the routing from Manufacturing Design up to component delivery. Assembling has not been implemented, and also no interrelation between components exists.
Additional to the above mentioned attributes, extra data has been added for planning and cost control of manufacturing components. A feature of the system is comparison of the achieved results of NC manufacturing, versus a cost estimate of conventional prices.

Specification of the routing control system

Logistic control systems on computers are often very extended but also very complex (eg. COPIX like systems). Their implementation require many resources and also changes to the organisation and therefore they often fail on the long term. The routing control system, which has been developed for supporting DfMASS, has been restricted to a simple but effective system.

The routing control system controls components through Design and Manufacturing. After an activity has been completed, the system knows the next activity to be executed. Per component, four main attributes control the routing, see Fig. K.1.

1. parttype is the type of part:
   A: assembly
   M: manufacturing component
   P: purchase part

2. stadium is the latest finished phase of the part

Next table show the possible stadia per parttype.

Parttype	Stadium
for A:	F: Functional Design C: all needed components are available (delivered by workshop or by purchasing) R: assembled (R = ready)
for M:	F: Functional Design M: Manufacturing Design R: manufactured (R = ready)
for P:	O: ordered R: delivered (R = ready)

3. errorstatus indicates whether, during execution of an activity an error in a preceeding activity appears (<blank>: no error, E: error)

   (Eg. during Manufacturing a design error occurs, or during Assembling a component does not fit, or a purchase part is not obtainable.)

4. quantity indicates the amount of these parts needed in the assembly.

Fig. K.1: The four main attributes of the routing control system

The following rules have been defined to derive a new status situation of a component after an activity has been taken place.

Events are indicated by (a,b,c,d). a is the parttype, b is the stadium, c is the errorstatus, d is the quantity. A <blank> for an item means "no value". A "." for a value means different values possible. A leading "*", like *(, ,) means other components, than the present one.

Situation	Activity	Endsituation
(, , ,)	Functional Design	(A, , ,) or (S, , ,) or (P, , ,) During Functional Design the codenumber and parttype (A, S or P) is defined, thus the value of the first attribute (parttype) is changed.
(A, , ,)	Functional Design/ Manufacturing Design	(A,F, ,) and *(., , ,) In some cases during Functional Design, in other cases during Manufacturing Design, the codenumbers and parttypes of the components of an assembly are defined. When all components of an assembly are defined, the Functional Design of the assembly is completed.
(A,F,E,)	Functional Design	(A,F, ,) and *(.,., ,) or *(.,.,E,) When an error has occurred in the assembly design, the components of the assembly need to be checked. They may still be alright, or may be wrong.
(A,C, ,)	assemble	(A,R, ,) or (A,C,E,) When all components of an assembly are ready, the assembly can be assembled.
(A,C,E,)	check error	(A,F,E,) and *(.,R,E,) When an error occurs during Assembling, the concerned components will get an errorstatus.
(P, , ,)	order	(P,O, ,)
(P,O, ,)	deliver	(P,R, ,)
(P,O,E,)	deliver	(P,R,E,)
(P, ,E,)	delete	remove record from database A purchase part, not yet ordered, which appears to be wrong, must be deleted.
(P,O,E,)	cancel	remove record or leave (P,O,E,) An ordered purchase part, which appears to be wrong, must be tried to cancel. If cancellation is not possible the status stays (P,O,E,).
(P,R,E,)	remove	part is unuseable, remove it from database.
(M, , ,)	Functional Design	(M,F, ,)
(M,F, ,)	Manufacturing Design	(M,M, ,) or (M,F,E,) During Manufacturing Design an error may occur in the Functional Design. For material with long delivery time, it is advisable to define the start material and order it when it has status (M,F, ,), before the detailled Manufacturing Design takes place.
(M,F,E,)	Functional Design	(M,F, ,) and possibly *(.,.,E,) By changing the Functional Design of the

		component, other components may be affected.
(M,M, ,)	Manufacturing	(M,R, ,) or (M,M,E,) An error may occur in the Manufacturing Design during manufacturing. To reduce time, it is advisable for the manufacturing organisation to check the NC dataset before ordering material and before detailled workshop planning.
(M,M,E,)	Manufacturing Design	(M,M, ,) or (M,F,E,) In case the error is not be solvable in Manufacturing Design, the Functional Design need to be altered.

These rules are summarized in following scheme (Fig. K.2), the error situations have not been represented. By this system the different resources can be supplied with information on the current workload. In Fig. K.3 an example is given of a print out supplying information to the workshop.

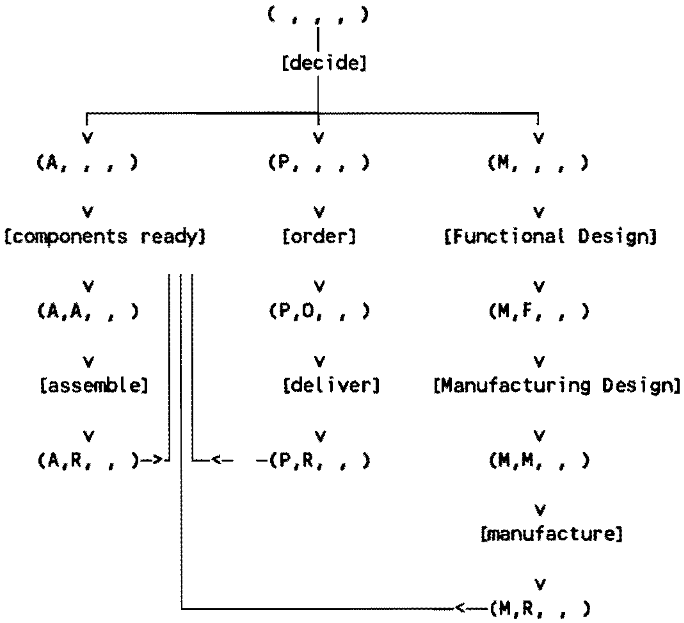
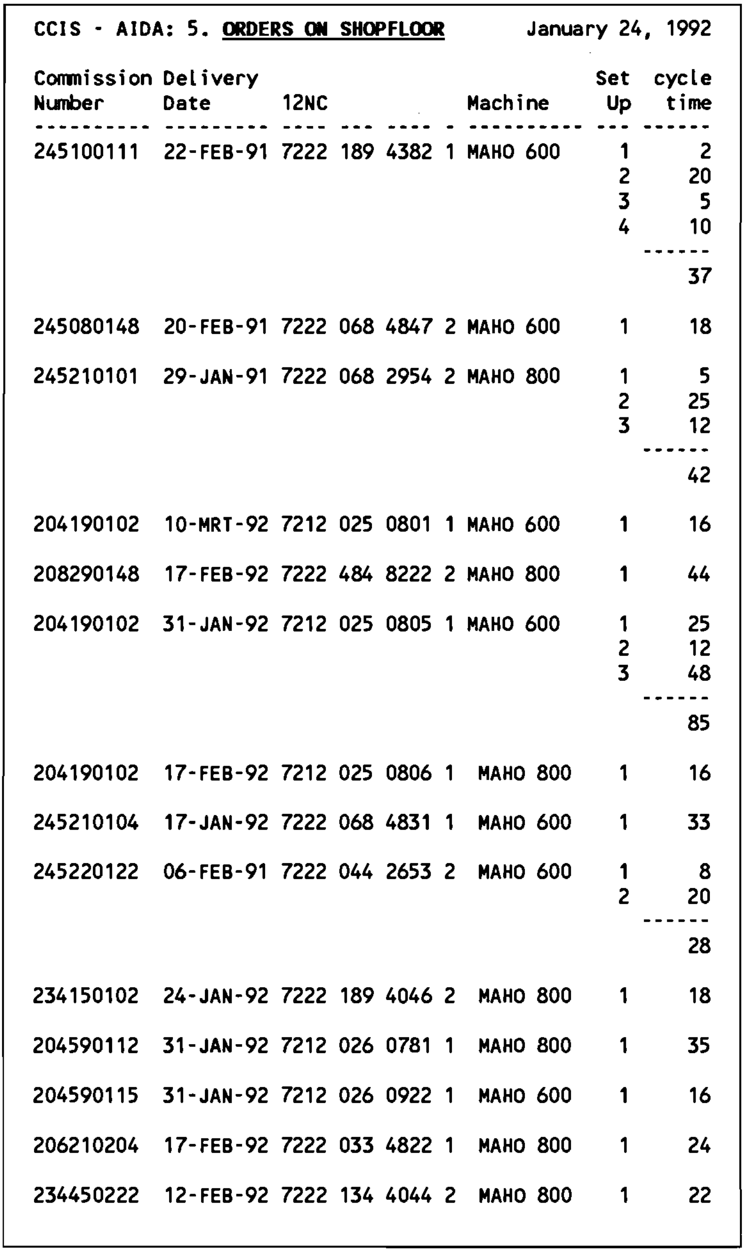


Fig. K.2: Scheme of the interrelations between the situations



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CCIS - AIDA: 5. ORDERS ON SHOPFLOOR        January 24, 1992

Commission Delivery                             Set  cycle
Number     Date      12NC             Machine    Up   time
---------- --------- ---- --- ---- - ---------- --- ------
245100111  22-FEB-91 7222 189 4382 1 MAHO 600     1      2
                                                  2     20
                                                  3      5
                                                  4     10
                                                      ------
                                                        37

245080148  20-FEB-91 7222 068 4847 2 MAHO 600     1     18

245210101  29-JAN-91 7222 068 2954 2 MAHO 800     1      5
                                                  2     25
                                                  3     12
                                                      ------
                                                        42

204190102  10-MRT-92 7212 025 0801 1 MAHO 600     1     16

208290148  17-FEB-92 7222 484 8222 2 MAHO 800     1     44

204190102  31-JAN-92 7212 025 0805 1 MAHO 600     1     25
                                                  2     12
                                                  3     48
                                                      ------
                                                        85

204190102  17-FEB-92 7212 025 0806 1  MAHO 800    1     16

245210104  17-JAN-92 7222 068 4831 1  MAHO 600    1     33

245220122  06-FEB-91 7222 044 2653 2  MAHO 600    1      8
                                                  2     20
                                                      ------
                                                        28

234150102  24-JAN-92 7222 189 4046 2  MAHO 800    1     18

204590112  31-JAN-92 7212 026 0781 1  MAHO 800    1     35

204590115  31-JAN-92 7212 026 0922 1  MAHO 600    1     16

206210204  17-FEB-92 7222 033 4822 1  MAHO 800    1     24

234450222  12-FEB-92 7222 134 4044 2  MAHO 800    1     22
```

Fig. K.3: A print out of workload information for the workshop

Appendix L

Achievements in the pilot production

In this appendix, three tables are given, showing the results of the pilot production with DfMASS in the period running from May to December 1991.

In Table 1, the Manufacturing Design effort is represented.
In Table 2, the manufacturing results are divided into internal production and
production at third parties.
In Table 3, an evaluation is given on using Manufacturing Families.

TABLE 1 : **Recording the Manufacturing Design of the pilot production**
In Table 1, for all components in the DfMASS pilot project, the realized Manufacturing Design hours are represented in column 2. In column 3 an conservative estimate is given on the hours required for making the drawing. In column 4 an estimate is given on the required number of set-ups in Design conventionally, supposing manufacturability would not have been taken in account in same extend as in DfMASS. In column 5, the realized number of set-ups is given for the DfMASS approach.

Codenumber	MD real	DWG	SETUP conv	SETUP DfMASS
7212 014 8865	2	3	1	1
7212 014 8866	1	3	1	1
7212 014 8923	1	3	1	1
7212 014 8924	1	3	1	1
7212 014 9944	1	3	1	1
7212 025 0033	1	3	1	1
7212 025 0034	1	3	1	1
7212 025 0035	1	3	1	1
7222 068 2384	3	3	2	2
7222 068 2401	3	3	3	2
7222 068 2405	4	4	3	3
7222 068 2406	8	5	3	3
7222 068 2656	8	4	4	1

Codenumber	MD real	DWG	SETUP conv	SETUP DfMASS
7212 014 8865	2	3	1	1
7222 068 2657	8	4	4	1
7222 068 2658	13	4	6	3
7222 068 2664	7	4	2	1
7222 068 2665	3	3	1	1
7222 068 2666	6	2	2	1
7222 068 2669	2	3	1	1
7222 068 2672	12	3	8	2
7222 068 2673	8	3	8	2
7222 068 2686	8	5	4	2
7222 068 2688	10	5	5	5
7222 068 2689	13	4	1	1
7222 068 2699	1	2	1	1
7222 068 3277	8	4	5	2
7222 068 3281	12	5	6	3
7222 068 3325	13	5	5	3
7222 068 3326	11	5	5	3
7222 068 3327	15	5	5	2
7222 068 3370	3	3	5	1
7222 068 3416	3	3	5	1
7222 068 3428	16	6	6	4
7222 068 3470	3	3	5	1
7222 068 3733	3	3	1	1
7222 068 4076	1	3	1	1
7222 068 4077	1	3	1	1
7222 068 4153	6	3	1	1
7222 068 4158	23	6	6	2
7222 068 4164	5	3	1	1
7222 068 4171	23	6	6	2

Codenumber	MD real	DWG	SETUP conv	SETUP DfMASS
7212 014 8865	2	3	1	1
7222 068 4174	23	6	6	2
7222 068 4195	6	6	6	2
7222 068 4255	6	3	1	1
7222 068 4265	11	6	6	2
7222 068 4266	11	6	6	2
7222 068 4860	1	3	1	1
7222 068 4925	7	4	5	3
7222 068 4926	9	4	6	3
7222 068 4927	3	3	4	1
7222 068 4928	3	3	4	1
7222 068 4929	5	3	4	1
7222 068 5449	17	4	2	1
7222 068 5475	1	3	1	1
7222 068 5476	1	3	1	1
7222 068 5525	3	3	3	1
7222 068 5526	12	4	4	2
7222 068 5527	2	3	3	1
7222 068 5531	4	4	3	1
7222 068 5535	2	3	3	2
7222 068 6250	1	3	1	1
7222 068 6251	1	3	1	1
7222 068 6348	4	4	6	1
7222 082 3372	13	4	3	1
7222 114 1691	18	4	5	2
7222 182 6297	22	4	4	1
7222 182 6404	8	3	3	2
7222 182 6875	11	4	5	2
7222 182 6876	8	5	5	4

Codenumber	MD real	DWG	SETUP conv	SETUP DfMASS
7212 014 8865	2	3	1	1
7222 182 6877	12	5	5	4
7222 182 6878	6	4	2	1
7222 182 6879	10	5	5	4
7222 182 6880	13	5	5	4
7222 182 6881	5	4	2	1
7222 188 3466	8	4	4	3
7222 189 3731	29	8	10	1
7222 189 4043	3	3	1	1
7222 189 4061	7	3	1	1
7222 189 4064	10	4	3	1
7222 189 4095	1	2	1	1
7222 189 4155	11	5	6	4
7222 189 4381	16	4	3	1
7222 189 4382	8	3	2	1
7222 189 4425	1	3	5	1
7222 189 4428	18	5	5	2
7222 189 4441	19	5	5	2
7222 189 4444	6	5	5	2
7222 189 4447	4	5	5	2
7222 189 4448	2	3	2	1
7222 189 4449	6	5	5	2
7222 189 4453	6	5	5	2
7222 189 4455	6	5	5	2
7222 189 4458	6	5	5	2
7222 189 4460	6	3	1	1
7222 189 4463	7	3	1	1
7222 189 4464	7	3	1	1
7222 189 4470	10	4	1	1

Codenumber	MD real	DWG	SETUP conv	SETUP DfMASS
7212 014 8865	2	3	1	1
7222 484 5164	20	5	7	2
7222 484 5280	3	2	3	3
7222 484 5431	6	4	4	2
7222 484 5444	50	6	2	2
7222 484 8025	20	3	3	2
7222 484 8031	1	2	1	1
7222 484 8032	3	2	2	2
7222 484 8033	3	2	2	2
7222 484 8040	47	6	5	1
7222 484 8050	3	2	3	1
7222 484 8064	2	3	1	1
7222 484 8222	2	3	1	1
7222 484 8751	13	5	5	1
7222 484 8752	21	5	5	1
7222 484 8754	2	3	3	2
7222 484 8755	2	3	3	2
7222 484 8757	10	4	5	3
7222 484 8769	11	4	6	4
7222 484 8770	18	4	5	2
7222 484 8771	4	4	4	2
7222 484 8793	8	4	5	1
7222 484 8799	1	3	1	1
7222 484 8873	3	3	2	1
7222 484 8879	14	6	5	1
7222 484 8891	1	3	2	1
7222 484 8892	1	2	1	1
7222 484 8894	1	2	2	1
7222 484 8895	2	3	2	1

Codenumber	MD real	DWG	SETUP conv	SETUP DfMASS
7212 014 8865	2	3	1	1
7222 484 8905	2	2	1	1
7222 484 8909	3	3	2	1
7222 484 8910	3	3	3	1
7222 484 8971	4	3	4	2
7222 860 7066	20	10	3	2
7222 860 7070	20	10	3	2
7222 860 7694	25	8	12	1
7222 860 7695	6	4	3	2
7622 556 1692	9	5	2	2
8222 190 9975	8	6	4	1
8222 190 9978	72	15	1	1
8222 190 9979	72	15	1	1
8222 716 3122	10	6	1	1
	1191	565	463	226

Conclusions

The total Manufacturing Design hours was 1191. For aftercare and postprocessing 25% must be added to the realized Manufacturing Design hours. Including aftercare and postprocessing, the total hours was then 1488 hours.

500 additional hours was expended due to training of new people (learning curve).

The total estimate on drafting hours for all the components in the list was at least 565. At a hourly rate of dfl 70,-, the drafting costs are more than dfl 39.550,-.

The number of set-ups for Design conventionally would have been 463. In DfMASS this has been reduced to 226, which is a decrease of 51%.

These results have been summarized in Fig. 7.3 in Section 7.1.

TABLE 2 : **Recording the manufacturing production of the pilot project**

2A: INTERNAL PRODUCTION

Period: May 1991 no data recorded

Period: June 1991 Commiss. Number	12NC	Qty	Conventional Costs	CADCAM Costs	Profit due to CADCAM
206580202	822219099751	1	1600	1200	400
	822219099781	1	500	1130	-630
	822219099791	1	5000	820	4180
			-----	-----	-----
			7100	3150	3950
8 preparation hours					-800
					=====
					3150

Period: July 1991 Commiss. Number	12NC	Qty	Conventional Costs	CADCAM Costs	Profit due to CADCAM
109055600	722218834661	2	1600	2000	-400
170040200	722286076941	2	4000	3000	1000
245090111	722206834161	2	800	100	700
245090112	722206834701	4	1600	200	1400
245090115	722206833271	1	300	80	220
245090116	722206833271	1	300	80	220
245120104	722206824051	1	400	250	150
			-----	-----	-----
			9000	5710	3290
14 preparation hours					-1400
					=====
					1890

Period: August 1991 Commiss. Number	12NC	Qty	Conventional Costs	CADCAM Costs	Profit due to CADCAM
157403901	722218268751	1	400	1050	-650
	722218268761	1	400	800	-400
	722218268771	1	400	800	-400
	722218268781	1	400	250	150
	722218268791	1	400	800	-400
	722218268801	1	400	700	-300
	722218268811	1	400	200	200
208060107	722248487701	3	1200	2400	-1200
	722248487711	3	900	800	100
245090109	722206849271	1	400	150	250
	722206849291	1	400	400	0
245090111	722206832771	2	2400	2700	-300
245090112	722206832771	4	4800	5400	-600

```
245093509 722206849281  1     300     200     100

245100104 722206855271 12    1200    1100     100
          722206855351 40    8000    2000    6000
                           ------  ------   -----
                            22400   19750    2650
          47 preparation hours              -4700
                                           ======
                                            -2050

Period: September 1991    Conven-          Profit
Commiss.                   tional  CADCAM  due to
Number    12NC        Qty   Costs   Costs  CADCAM
--------- ------------ -- ------- ------- -------
105038600 722286070663  3    2400     900    1500
          722286070703 30   24000    9100   14900

108050300 722208233723  2    1000     800     200

170040200 722286076951  1    3000     200    2800

204120103 721201488651  1     400     100     300
          721201488661  1     400     100     300
          721201489231  1     400     100     300
          721201489241  1     400     100     300
          721201499441  1     400     100     300

208060107 722248487691  3    1200    1800    -600

208060109 722248487512  8    4800    4000     800
          722248487572  8    4800    3300    1500

208060111 722248487991  1     400     150     250

208570100 722248454311  6    2400    1200    1200

245080126 722206841531 10    1500     150    1350

245080134 722218940611 20    8000    1400    6600
          722218940951 20    5000    3300    1700

245090107 722206833251  1    1200    1700    -500

245090109 722206834281  2    4000    1000    3000
          722206849251  1    1600    1200     400
          722206849261  1    3000    1400    1600

245090115 722206833261  1    1200     850     350

245090116 722206833261  1    1200     750     450

245090117 722206832811  1    1600     750     850

245090122 722206848601  1     400     100     300

245100113 722206840761  1     400     100     300
          722206840771  1     400     100     300
```

```
          722218940951  1     300      50     250

245100119 722206854491  1     400     700    -300
          722206854751  1     400     150     250
          722206854761  1     400     150     250
                            -----  ------  ------
                            77000   35800   41200
       86 preparation hours                 -8600
                                          =======
                                            32600

Period: October 1991      Conven-          Profit
Commiss.                  tional  CADCAM  due to
Number    12NC         Qty  Costs   Costs  CADCAM
--------- ------------ -- ------- ------- -------
107158100 722211416917  8    6400    2500    3900

204198501 721202500331  2     800     850     -50
          721202500341  2     600     200     400
          721202500351  2     400     150     250

208060109 722248487522  8    4000    4800    -800
          722248487542  8    2000     400    1600
          722248487552  8    2000     400    1600

208060110 722248488791  2    3200    2600     600
          722248489091  2    1000     800     200
          722248489101  2    1600    1000     600

208060111 722248488731  1     300     300       0
          722248488911  1     200      50     150
          722248488921  2     300     100     200
          722248488941  1     200     100     100
          722248488951  1     150     100      50
          722248489051  1     100      50      50

208060113 722248489711  1     600    1500    -900

208290132 722248480321 12    3600     350    3250
          722248480331 12    1800     350    1450
          722248480501 12    3600     350    3250
          722248480641 12    3600     350    3250

208570137 722248454441 10    4000    3000    1000

208570142 722248452801  1     200     300    -100

245080136 722206841641 10    3000     400    2600
          722206842661  1    1600    1200     400
          722218944251  2     400     480     -80
          722218944481 14    2800     650    2150

245090136 722206842551  6    1800     200    1600
          722218944411  1    1600    1250     350

245100111 722206841641  1     200      40     160

245100113 722218944701  1    2000    2000       0
```

```
716312201 822271631221  1     800    400    400
                           ------ ------ ------
                            54850  27220  27630
       65 preparation hours               -6500
                                        =======
                                          21130

Period: November 1991      Conven-       Profit
Commiss.                   tional CADCAM due to
Number    12NC         Qty  Costs  Costs CADCAM
--------- ------------ -- ------- ------- -------
157405003 722218264041  4     400    260    140

165057000 762255616921  1     800    600    200

208060113 722248487931  1     800   1100   -300

2082901-2 722248480312 24    1440    300   1140

208290132 722248480402  1    1600   1100    500

208370101 722218941551  8    3200   1000   2200

208570101 722248452802  1     400    250    150

208573535 722218940641 10    3500    500   3000
          722218940952 10    2000    350   1650

234030122 722218940432  1     400    150    250

245060105 722206837331  2     800    400    400

245080109 722206833701  1    1600    700    900

245080131 722218943811 35   42000  31500  10500
          722218943821 11    8800   6500   2300

245080136 722206841581  1    3000   1600   1400
          722206841711  1    3000   1300   1700
          722206841741  1    3000   1300   1700
          722206842651  1    3000   1600   1400
          722218944441  1    3000   1200   1800
          722218944471  1    3000   1600   1400
          722218944491  1    3000   1300   1700
          722218944531  1    3000   1200   1800
          722218944551  1    3000   1000   2000
          722218944581  1    3000    600   2400
          722218944601  1     800    250    550
          722218944641  3    2400    750   1650

245090136 722218944281  1    2000    600   1400

245100115 722206841951  1     800   1500   -700
          722218944631  1     800    250    550

245100121 722206862501  1     400    200    200
          722206862511  1     400     50    350
```

```
245120103 722206823841   1     300     400    -100
          722206824011   1     300     400    -100
          722206824061   1     400     400       0

245130101 722206826561   2    1000     250     750
          722206826571   2    1000     250     750
          722206826581   2    1000    1000       0
          722206826661 122   24400    4000   20400
          722206826691 122   12200    3000    9200
          722206826862   2    3200    1600    1600
          722206826892   2     800     200     600

245337703 722206863481   2     800     200     600
                           -------  ------  ------
                            150740   72710   78030
      174 preparation hours                 -17400
                                           =======
                                             60630

Period: December 1991     Conven-           Profit
Commiss.                   tional  CADCAM  due to
Number    12NC         Qty  Costs   Costs  CADCAM

--------- ------------ -- ------- ------- -------
152054500 722218937311   3    1800    1500     300

208290132 722248480251  12    1800    1800       0

245100127 722206855251   1    2000    1500     500
          722206855261   1    2000    1500     500
          722206855311   1    2000    1500     500

245130101 722206826642  22    2440    2500     -60
          722206826651  22   24400    5100   19300
          722206826721  22    1464    1500     -36
          722206826731  22     488     500     -12
          722206826881   2    1000     200     800
          722206826991  22    2074    2000      74

581166200 722218262971   1     400     300     100
                            ------  ------  ------
                             41866   19900   21966
       48 preparation hours                  -4800
                                            ======
                                             17166
```

Summary

During the period of August to December 1991, 2103 hours of DfMASS manufacturing have been executed, in which dfl. 184.326,- has been saved, compared to Manufacturing conventionally. For preparation activities and aftercare, 25% need to be added to the manufacturing hours.

A summary of the results is presented in Fig. 7.4 in Section 7.1.

2B: ADDITIONAL ORDERS, Evaluation

This table represents the results of the orders, which have been produced by third parties, during September, October and November 1991. A summary of the results is presented in Fig. 7.4 in Section 7.1.

X[1]	Commiss. Number	12NC	Qty	Conventional Costs	CADCAM Costs	Profit due to CADCAM
M	208573528	72224845164	150	40500	17600	22900
M	545897	72220682656 72220682657 72220682658 72220682686	122	177000	149500	27500
M	545861	72224845444	150	41250	19500	21750
				-------	------	------
				258750	186600	72150
P	491466	72221894381	15	18000	7560	10440
		72221894382	41	20500	12915	7585
				------	------	------
				38500	20475	18025
E	401318	72221894437	9	21600	16200	5400
E	401416	72221894174 72221894158 72221894265 72221894266	17	51000	22100	28900
E	401424	72224848040	11	17600	14300	3300
E	401318	72221894462 72221894464	17	13600	10200	3400
E	401297	72224894396	1	3500	2300	1200
E	401392	72220682319	122	120000	89000	31000
				-------	------	------
				227300	154100	73200
				=======	======	======
				524550	361175	163375

---

[1] Code of the company.

TABLE 3 : Evaluation of Manufacturing Families

This list has been derived from Table 1. Only the rows, containing Manufacturing Families from Table 1, have been copied to Table 3. The Manufacturing Design hours in Table 1 contain already family advantages, because some components are derived from families. In Table 3, the hours in column 2 have been adjusted as if no family relations had existed between the different components. In column 3 the Manufacturing Design hours have been estimated based upon a Manufacturing Family had already been available for these components.

Codenumber	MD hours real	MD hours families	number of set-ups convent'ly	number of set-ups in DfMASS
7212 014 8865	3	1	1	1
7212 014 8866	3	1	1	1
7212 014 8923	3	1	1	1
7212 014 8924	3	1	1	1
7212 014 9944	3	1	1	1
7212 025 0033	3	1	1	1
7212 025 0034	3	1	1	1
7212 025 0035	3	1	1	1
7222 068 2666	6	2	2	1
7222 068 3370	3	1	5	1
7222 068 3416	3	1	5	1
7222 068 3470	3	1	5	1
7222 068 3733	3	1	1	1
7222 068 4076	3	1	1	1
7222 068 4077	3	1	1	1
7222 068 4171	23	5	6	2
7222 068 4174	23	5	6	2
7222 068 4195	23	5	6	2
7222 068 4255	23	3	1	1
7222 068 4265	23	5	6	2
7222 068 4266	23	4	6	2

Codenumber	MD hours real	MD hours families	number of set-ups convent'ly	number of set-ups in DfMASS
7212 014 8865	3	1	1	1
7222 068 4860	3	1	1	1
7222 068 4927	3	1	4	1
7222 068 4928	3	1	4	1
7222 068 4929	5	1	4	1
7222 068 6250	3	1	1	1
7222 068 6251	3	1	1	1
7222 189 4043	3	1	1	1
7222 189 4064	23	1	3	1
7222 189 4428	23	4	5	2
7222 189 4441	23	5	5	2
7222 189 4444	6	2	5	2
7222 189 4447	4	2	5	2
7222 189 4448	2	1	2	1
7222 189 4449	6	2	5	2
7222 189 4453	6	2	5	2
7222 189 4455	6	2	5	2
7222 189 4458	6	2	5	2
7222 189 4460	6	3	1	1
7222 484 8799	3	1	1	1
	323	77	122	53

Time savings due to Manufacturing Families: 76%
Set-up savings due to DfMASS: 66%

Appendix M

Potential problem analysis of DfMASS

Analysing problems, which may appear, is a method for estimating the quality of an idea. The following potentional problem analysis tries to predict the problems which may appear if implementing DfMASS. These potential problems have been considered during the study and, as much as possible, the method has been adapted to avoid or solve them.

Is small lotsize Design and Manufacturing suitable for CADCAM and NC?

CADCAM and NC are successful in the area of complex expensive parts, like dies and molds. CAD in this area is used to optimize the shape of the parts, also by finite element calculations and extensive surface modelling. Work preparation for those parts normally take several hours. By CAM functionality the costs can be decreased and the quality improved.

For small lotsize mechanical parts, CAD modelling and drafting is expensive compared to the drawing board, due to the simplicity of most parts. Sometimes NC programming can not compete against conventional milling and turning. Especially if existing drawings are evaluated for NC production, it appears that set-ups, tasks and tools, needed to produce the parts, would be numerous [51]. However, if the whole working method has been optimized, as with DfMASS, manufacturability, redundancy of activities, standardisation and single sourcing create a competitive edge for DfMASS in Mechanical Design. From present experiences of reasonable production quota at Philips Lighting this statement has been demonstrated. Besides, following trends will improve NC applicability:

- NC machine tools will become cheaper,
- labour expenses will increase,
- decrease of needed labour by automated NC production.

The possibility to "distinguish by technology" disappears for workshops

In conventional practice workshops can distinguish themselves by producing faster than others. They accept an order, based on a calculated price and try to earn extra money by smart production. In DfMASS, the technology is built in the NC dataset, delivered by the design office. The workshop can not easily change the process planning or the technology anymore. This aspect of DfMASS, however, can not be seen as a potential problem.

A partial decrease of leadtime has no advantage

Suppose a part of the manufacturing components follow the DfMASS method (with short leadtimes) and the rest of the components will be manufactured conventionally. In that case the DfMASS components are no longer on the critical path and thus the organization can not benefit from the leadtime reduction. This situation will pass by, when the majority of parts will be manufactured following the DfMASS method. This can be reached, because all (milling) parts, which are produced conventionally, can be produced via DfMASS. There is no restriction in type of parts for DfMASS. By the progress of DfMASS implementation in an organization, up to 100 % of the milling parts can be produced by this method. In small lotsize mechanization, milling parts are often critical in leadtime.

Each designer has his own working method

To make a success of DfMASS, a single, unambiguous working method needs to be used by the entire organisation. Designers, being creative people, do not like to work with strict procedures. However, in modern large organisations there is a need to standardize informal communication into formal communication. DfMASS will help management to introduce standard procedures, because computerized procedures are standards in itself. A link can be drawn to administrative automation, where the struggle for standardisation was a topic years ago. Today standard procedures are normal practice.

Is the designer prepared to be restricted in his creativity?

It is a common opinion that designers do not want to be restricted. In practice it shows that designers prefer to save their creativity to Functional Design. They like to invent mechanical solutions for the system functions, while it is rather annoying to elaborate all the details. Therefore standardization and automation of details is welcomed by to the designer.

Obtain sufficient manufacturing know how in the design office

Bringing back manufacturability in Design is an important aspect of DfMASS. Of course, this is an evolutionary process, from which the organisation will profit in the long end. Current workshop skills have to be tought to the designers by the craftsmen. These teachers may grow into manufacturing technologists, stationed in the design office. In the future, creating manufacturing solutions for specific problems will be a specialism of manufacturing designers in the design office. It is almost impossible to store all manufacturing know how into the brains of designers. Therefore the following measurements have been taken to simplify the technology choices:

- restriction in applicable standard machine tools,

- restriction of tools,
- Manufacturing Families,
- automated manufacturing technology in databases or expert systems,
- standard pre- and post-treatments.

A same situation of obtaining manufacturing know how outside the workshop appeared when NC programming departments were founded. In the beginning NC programming departments are located nearby the workshop, when they grow bigger, they move into office environments, sometimes far away from the machine tools. Still these departments are able to obtain sufficient manufacturing know how.

Does automated operations planning lead to efficient production?

The computer will not always define the most efficient operations planning. The rules in the technology database will not always produce the best solution for a specific circumstance, only a good solution. However for small lotsizes, the optimization of operations planning is just a small aspect of the total process efficiency. Complete automation of operations planning yields more advantages than optimal manual operations planning does. In the design of mass products it may be efficient to put a lot of manual effort into optimal operations planning, because the time saved in production time is multiplied by the number of products.

Workshop skills will disappear

Manufacturing organizations are very careful in retaining skills in their workshops. Sometimes they are very proud of their craftsmen, who have their individual working methods. It is hardly possible to document these methods, because they are often a matter of personal feeling during manufacturing. These kind of skills are difficult to retain. Therefore, professional know how should not be based on personal feeling and should not differ between people. Technology should be built by theory, calculations, testing, experience and careful optimization. Once defined, the new technology will be stored in the FAST-CADCAM technology database and applied in all future sessions of Manufacturing Design.

By larger lotsizes the process planning is different

If components will be produced in larger lotsizes, it is essential that the manufacturing designer takes consideration with it during modelling. In those cases, he should spend more time in optimizing the manufacturability of the component.

Alternative technology may overtake DfMASS philosophy

The following trends are expected to develop in the future.

NC control becomes more intelligent

DfMASS does not use the intelligence of NC control, because the CADCAM system generates only elementary NC statements.
Using intelligent NC control in NC programming will cause numerous logistic problems:

- One has to know the machine tool before NC programming,
- In repeat production on another machine, reprogramming is needed,
- One needs to know the typical functions of the specific NC control,
- Less flexibility in buying different brands of machines,
- NC controls still have far less computer power (CPU, storage, datacommunication) than CADCAM computers.

In DfMASS the postprocessor takes care of the difference between machine tools. It is possible to execute postprocessing for different NC controls, if only elementary statements are used. Therefore DfMASS requires simple NC control and high quality of mechanical machine tool precision. By higher standard precision, less special tolerance and roughness requirements need to be specified during Manufacturing Design.

Feature recognition

A lot of research has been done to realize a form feature recognition system. Such a system should be capable of recognizing geometry as form features [5, 29, 49]. Because the designer is used to being very creative in defining geometry shapes, a recognition system will have to cope with a large number of different types of form features. Each form feature type needs to have technology data in the system to create NC datasets from. The attempts to create such a system have proven to be very complex and extensive. Besides, it can be of a great advantage for the whole process to constrain the designer in the variety of shapes that may be applied. If it is possible to fulfil the design needs by a limited amount of shapes, it will lead to a high level of standardisation, less software development in form features, less needed technology, less needed tools etc.

Therefore DfMASS is based on feature based design instead of feature recognition.
By an ideal feature recognition system, it seems unnecessary to restrict the designer by feature modelling. This is untrue, because, if features are choosen by manufacturability, it stays efficient to design by features.

Design features may override manufacturing feature technology
DfMASS uses manufacturing features (shapes which are defined from a manufacturing view point). Current CADCAM trends are in the direction of design features (shapes which are defined from a design view point).

> An example of design features are rims in an aircraft structural component. Rims are used to reinforce the component with maximum structural efficiency (minimum weight). If four rims are positioned in a square, the realization of these design features is by cutting a pocket by which the rims remain. Here, four design features are realized by one manufacturing feature.

However, to transfer design features into manufacturing features is a complex technology which does not have sufficient applicability in practice yet. In the DfMASS method, this translation process takes place in the mind of the manufacturing designer. If the technology of transferring design features into manufacturing features becomes available on the commercial market, this human process may be taken over by the computer. The principles of the DfMASS working method will still remain. However it is questionable, whether the designer will still keep sufficient considerations on manufacturing when the manufacturing features are automatically created from design features.

Automated process planning
A lot of studies and practices draw an important role to the Process Planning as the link between Design and Manufacturing [49, 50]. They leave Design independent of the process planning. Therefore they are forced to interpret the design model and try to find a sufficient process plan to manufacture the design. The need for an expert system to find a process plan is obvious, because the designer has not taken into account the process plan constraints of his model. By automated process planning it may seem less necessary to consider manufacturability during Design, because the automated system could be able to handle all kind of models. Even if automated process planning is available, it is still efficient consider manufacturability during Design.

Manufacturing planning and control systems
By designing with less manufacturability considerations, the required parts will lead to a complex routing problem in workshops. Currently, those problems exist and are subject of study [7]. The automation of routing problem solving only solves a created problem. DfMASS avoids routing problem solving.

Data exchange of form features

In general, for interfacing data between CAD and CAM systems four possibilities are present:

- IGES, the international standard interface format. All kind of geometry can be interfaced with often less errors. Specific features, like drafting entities[1] are not sufficiently supported. It depends on the quality of the IGES postprocessor of the sending system and the preprocessor of the receiving system.
- DXF, the interface format of AUTOCAD, has become a world standard as well, because of the wide spread of AUTOCAD around the world. For PC systems it often supplies better functionality than IGES, however it does not supply functionality for Form Features.
- Specific interface, between two specific systems. Such an interface is often written, on demand by the user. Thus the interface can cover the required functionality, although it may be an expensive alternative, because it has to be developed tailor-made.
- In the German automotive industry, another standard has been developed for exchange of 3D surface models, called VDA-FS. Systems focussed on the automotive market use this interface.

To exchange 3D CAD information in which form features are defined, to other CAD/CAM systems, the interface protocol FFIM (Form Feature Information Model) [35] is presently in development as a part of STEP. As long as this development is not finished, other standards are not available. Without a dedicated interface to the receiving CAD/CAM system, feature based CAD information can not be exchanged.

In the near future the successor of IGES will be STEP, which will cover more functions than IGES. But it will take some years before the CAD and CAM systems will have written pre- and postprocessors for STEP.

However in DfMASS this kind of interfacing is not relevant. The interface is defined at the end of the Manufacturing Design process, where the NC dataset is the interface. This dataset contains standard NC statements and can be interfaced to a number of CAM systems.

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[1] E.g. intelligent dimensioning functions, special characters

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Stellingen

behorende bij het proefschrift van

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1. De werkwijze bij het ontwerpen van mechanische onderdelen voor enkelstuks en kleinserie produktie, zal in de komende jaren fundamenteel veranderen door de toepassing van CAD-CAM methodieken.
   Dit proefschrift, hoofdstuk 8

2. Door alle technologische beslissingen ten aanzien van het maken van onderdelen in de ontwerpfase te nemen, zal de organisatie van de werkplaats drastisch veranderen.
   Dit proefschrift, hoofdstuk 6

3. Door het opgaan van Process Planning in Geometric Modelling wordt een optimaal uitgangspunt geschapen voor Design for Manufacturability.
   Dit proefschrift, hoofdstuk 5

4. Voor mechanische onderdelen in enkelstuks en kleinserie produktie, is het in volle breedte toepassen van CAD zonder CAM net zo min rendabel als CAM zonder CAD.
   Dit proefschrift, hoofdstuk 3

5. DfMASS maakt de inzet van NC machines economisch rendabel in enkelstuks en kleinserie fabricage van mechanische onderdelen.
   Dit proefschrift, hoofdstuk 7

6. De trend om manufacturing features te vervangen door design features levert geen voordelen op in het ontwerpen van mechanische onderdelen.

7. De universiteiten in Nederland kunnen een bijdrage leveren in het vergroten van de concurrentiekracht van het bedrijfsleven door te participeren in het industrieel toepasbaar maken van innovatieve ideeën.

8. Het, in het kader van voorontwikkeling, ruimte geven aan onorthodoxe innovatieve ideeën, waarin velen lange tijd niet geloven, kenmerkt een innovatief bedrijf.

9. Door het verkorten van doorlooptijden in het produkt creatie proces wordt het aantal tussentijdse wijzigingen verminderd.

10. Werkmethodieken volgen uit de gestelde doelen van een proces. De uitvoering van het primaire proces moet niet louter een uitvloeisel van bestaande werkmethodieken zijn.

11. De implementatie van DfMASS op een eenvoudig computersysteem, zal het midden- en kleinbedrijf voorzien van een efficient gereedschap.

12. De term CAD zal verdwijnen als Computer Aided gemeengoed is in Design.

13. Het stimuleren van milieubewust koopgedrag krijgt meer inhoud als er een milieuvervuilingsindicatie op consumenten produkten wordt vermeld.