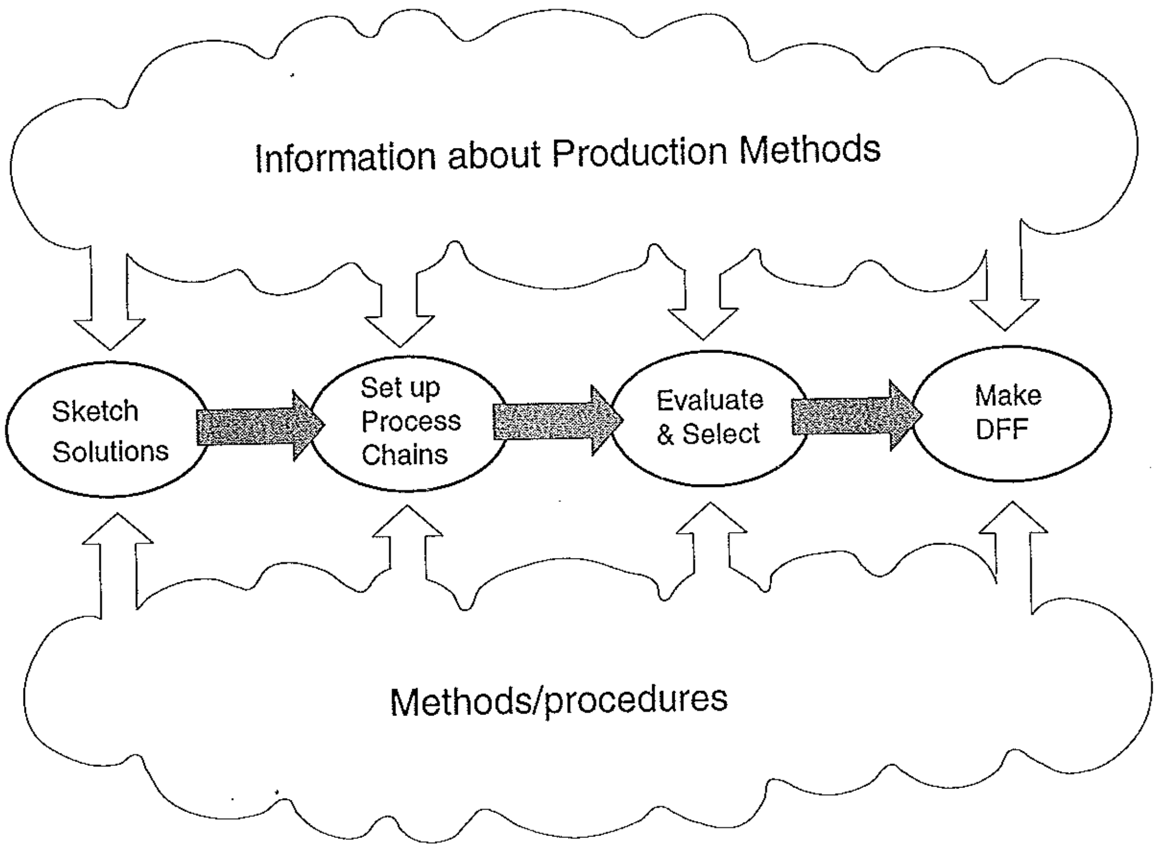
Creating the Basis for Process Selection in the Design Stage

Jan Haudrum

Ph.D Thesis from the research program Integrated Production Systems (IPS) made at the Institute of Manufacturing Engineering, TUD.



INTEGRATED PRODUCTION SYSTEMS

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ABSTRACT

This thesis treats the problem of process selection in design. Through field studies and video tapings the ways in which designers select production methods today were studied. It was realised that designers often select production methods that are familiar to them, and that alternative production methods are seldom considered.

Video-tapings were used to study students solving a design problem. The procedure of these studies (taping and analyzing) is described together with the results of the study and it is concluded that the method is an excellent tool to study how designers select production methods.

Literature on the design domain and the production domain is reviewed and it is concluded that no theoretical basis tailored for the activity: *process selection in design* exists. Earlier research works in the field of process selection are not based on a design methodology.

A systematic method for the embodiment design, where production methods are considered concurrently with function, material and shape, is suggested. This method takes its starting point in a process/material matrix, where all possible combinations are shown. By systematic consideration of these combinations, the designer will cover all process possibilities for his component.

The thesis also treats the upper levels of the design phase and it is suggested that companies run research projects parallel to the product development projects. In these research projects production methods, new to the company, should be investigated for new product solutions.

PREFACE

This dissertation was born out of the hypothesis that designers continue to select the production methods with which they and the company are familiar. Together with the hypothesis that the consideration of alternative production methods would bring new and better product solutions, I have investigated the problem through field studies and have subsequently developed a method for the systematic consideration of production methods.

The dissertation is the result of my Ph.D. study which was initiated in august 1991. It has been a part of the research program, Integrated Production Systems (IPS) supported by the Danish Technical Research Council (STVF). The thesis is intended for researchers in the field of process selection in design, but it has been published in the hope that industry too will benefit from the results.

I should like to thank STVF for their financel support that made this Ph.D study possible, and Professor Leo Alting for placing equipment at my disposal and for being available for discussions throughout the study. I am grateful also to my supervisor Torben Lenau for giving me such a degree of freedom to work with what I considered both important and exciting. I owe a special thank you to my dear colleague and friend, John Christensen for many good discussions on scientific research. I should also like to thank my colleagues from the Institute of Manufacturing Engineering and from the Institute for Engineering Design where Niels Henrik Mortensen and Leslie Kristensen, in particular, have been a great support to me in my work.

During the course of the work I had the pleasure of working with people from the Danish industry and I owe special thanks to Johan Ley and his colleagues of K.E.W. Industries where I spent many extremely interesting hours and likewise Klavs Tvenge and his colleagues at Wodschou A/S, who supported my work by allowing me to redesign one of their products. I also want to thank Lise Busk Kofoed and Niels M. Christensen of AUC for our cooperative work with the video-tapings. Finally I must thank the students who have inspired me by joining as volunteers in the video-tapings and as students in the course, *Design for Production*.

I owe my girlfriend, Lilja a special dept of gratitude for her loving support and extreme patience during the difficult periods.

Lyngby, August 1994

Jan Haudrum

RESUMÉ (in Danish)

Denne afhandling behandler problemstillingen omkring valg af fremstillingsprocesser i konstruktionsfasen. Gennem empiriske studier er det undersøgt hvordan konstruktører overvejer og vælger fremstillingsprocesser i dag. Det er blevet klarlagt, at konstruktører ofte vælger de fremstillingsprocesser som de og virksomheden har tradition for at vælge og dermed er fortrolige med.

Video-optagelser er blevet anvendt til at studere studerende løse konstruktionsopgaver. Fremgangsmåden (optagelse og analyse) i disse studier er beskrevet sammen med resultaterne af undersøgelsen, og det er konkluderet at video-optagelser er et fremragende værktøj til at studere, hvordan konstruktører overvejer og vælger fremstillingsprocesser.

Relevant literatur om konstruktionsdomænet og produktionsdomænet er beskrevet og diskuteret og det er konkluderet, at der ikke findes en decideret teoretisk basis, som kan danne grundlag for forskning indenfor procesvalg, og at tidligere arbejder indenfor området ikke er koblet sammen med konstruktionsmetodik.

En systematisk metode for overvejelse af fremstillingsprocesser i komponent design fasen er blevet udviklet og præsenteres. Denne metode tager udgangspunkt i en proces/materiale matrix, hvor mulige kombinationer er repræsenteret. Ved systematisk at overveje disse kombinationer sikrer konstruktøren sig at han overvejer alle fremstillingsmuligheder for den komponent han konstruerer.

Afhandlingen behandler også de tidligere stadier af konstruktionsfasen, og det er bl.a. foreslået, at virksomheder gennemfører forskningsprojekter parallelt med produktudviklingsprojekter. I disse projekter skal fremstillingsprocesser, som er nye for virksomheden undersøges og videreudvikles i forhold til virksomhedens produkter og produktløsninger.

CONTENTS

1 INTRODUCTION

1.1 Problem statement

General issues in manufacturing

Competition

Companies these days are facing an increasingly competitive situation. This is due to several factors, not least the intensive exploitation of advanced technology, including computer technology, which results in the vastly more effective exploitation of resources. According to CHRISTENSEN 93, the falling barriers in Europe (EU's single market and the East European block's transition to a market economy, not to mention the opening of China), have created a global market much more characterized by competition, while at the same time, the volume of potential customers on the consumer market has substantially increased.

Complex products

Customers make greater demands as to the functionality of products, a factor which involves increased complexity in the products themselves, while at the same time, on account of competitive pressures, companies are compelled to launch new products on the market at increasingly short intervals.

Individuality

The market demands *individuality* and in order to capture the greatest possible number of target groups, the producers must increase the number of variants. Similarly, market expectations as to a high level of service, a favourable price/quality relationship as well as environmentally-friendly products, force companies to adopt new methods of realizing product development and manufacturing processes. At present, not only new forms of organization, but also new technologies and new forms of working procedures are for the first time seeing the light of day.

Types of issues in product development

Specialized departments

The complexity of the tasks that must be solved by a company in developing, producing and selling products has forced a narrow specialization in various fields, and usually a company is split up into different departments each with its own individual speciality and forte. In consequence, the process of bringing a new product from development to market introduction must include collaboration between several departments.

Sequential procedure

In a traditional company these departments are: research & development, production, economy, purchasing, marketing, management etc. Traditionally the product development procedure was sequential, as shown in Figure 1. In a sequential

***Figure 1** Traditionally the product development procedure was sequentiel.*

product development procedure, the marketing department puts up specifications for a new product, the research & development department develops a product that fulfils these specifications and sends the final blueprints to the production department. The production department takes over, fabricates the product and the

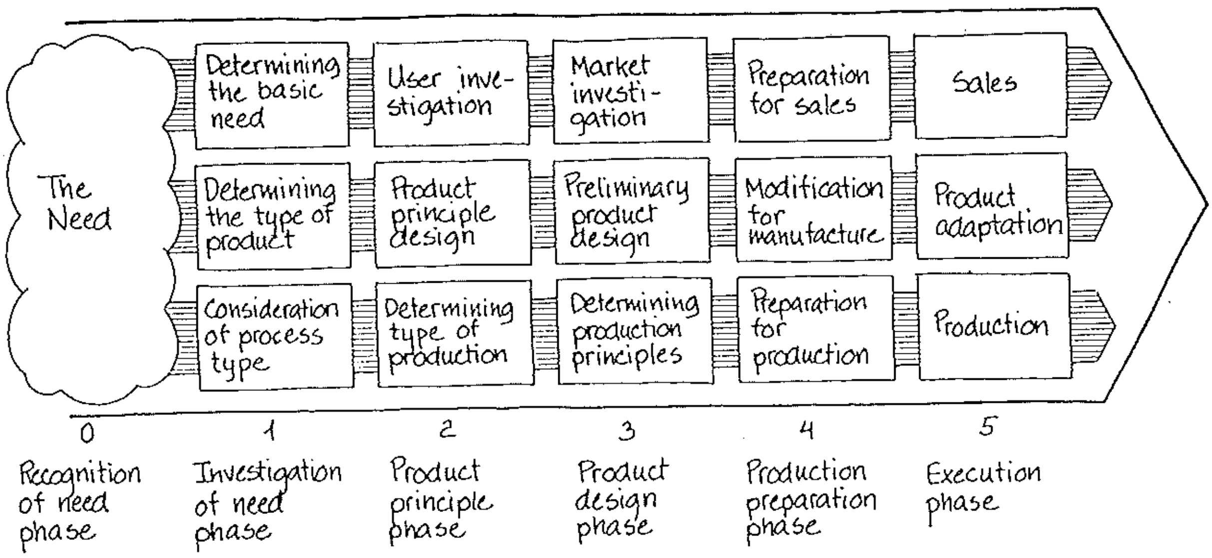

***Figure 2** The phases and activities in integrated product development.* ANDREASEN & HEIN 87.

sales department can subsequently put together some marketing material and start a sales campaign.

Disadvantages

The sequential way of developing and manufacturing products has a number of disadvantages:

- the time taken to reach the market (or the time to earn money) is protracted and often fraught with delays
- the consequences of the designers' decisions are invisible to him
- the employees in the later systems have no influence and thereby no responsibility for the product developed, etc.

Concurrence

The growing competition on the international market, a market which frequently demands new products, is forcing companies to change their development procedure. To decrease development time, the sequential activities mentioned above must be carried out more or less simultaneously, thereby achieving a shorter time to market for the product. The terms Concurrent Engineering, Simultaneous Engineering and Integrated Product Development all focus on developing a product in a concurrent way. Figure 2 shows the phases and activities in integrated product development.

According to ANDREASEN 92B, concurrent engineering has three dimensions, Figure 3: *Simultaneous activities*, which means synthesizing aspects related to market, product and production at the same time. *Integration*, which means treating relevant aspects in the product development process in the right phases. *Providence*, which means bringing aspects involved in future life phases of the product into focus in the (early) design phases.

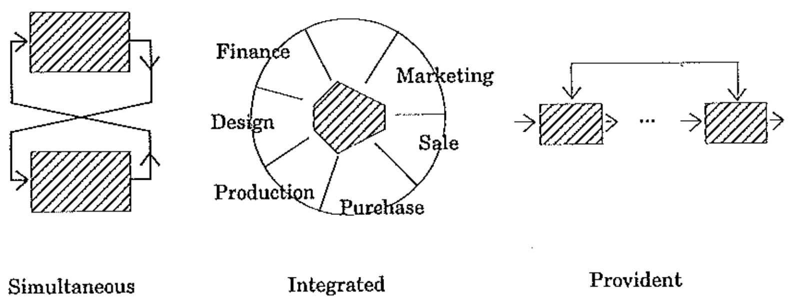

***Figure 3** The three dimensions of concurrence.* ANDREASEN 92B.

Design for X

There are several ways of fulfilling these dimensions, for instance: organizational initiatives (team work), activity controlling initiatives (methodologies and rules), technological tools (computer systems) etc. The term DFX (Design for X) is used as a general cover name for the different tools and methodologies that are developed to support the activity of designing for a property or system X. The essential task in DFX is to make sure that the designer is aware of the consequences his decisions have in the systems affected and to provide him with tools to avoid mistakes, such as designing a product that is impossible (or too expensive) to produce, to assemble, etc. Several specific DFX's are seen:

DFA	(Design For Assembly)
DFM	(Design for Manufacture)
DFMA	(Manufacturability and Assembly)
DFPP	(Production Planning)
DFP	(Production)
DFF	(Fabrication)
DFC	(Cost)
DFQ	(Quality)
DFRel	(Reliability)
DFE	(Environment)
DFDA	(DisAssembly)

Several of these concepts overlap, eg, DFMA, DFP and DFM are often used to denote the same idea, while DFQ and DFC run counter to several of the other terms. Figure 4. shows a general picture of the DFX's relevant in relation to this research work, where LCD stands for *life cycle design*. DFPS is a personally-invented term, which stands for *design for process selection*.

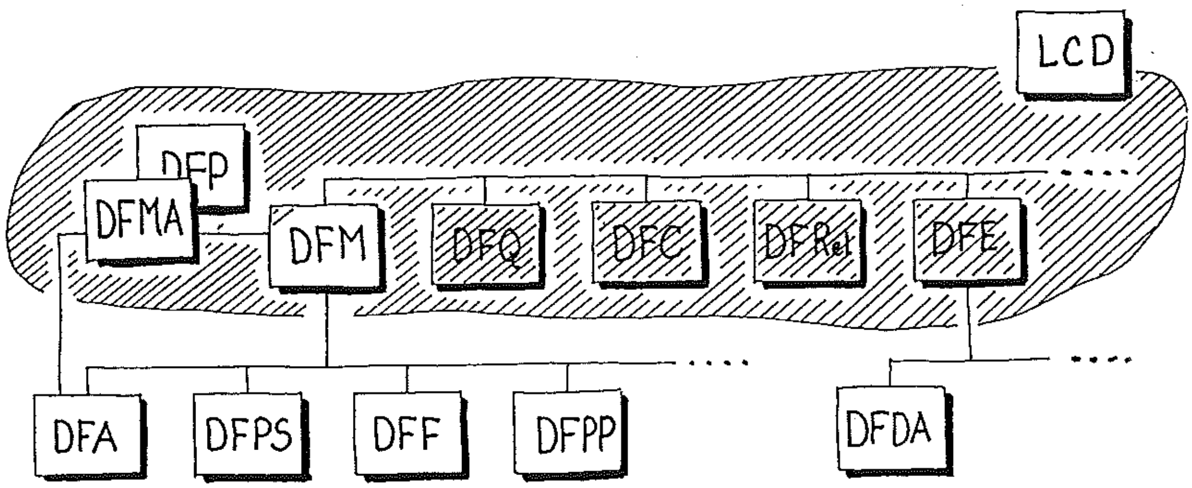

***Figure 4** The DFX's relevant for this research work.*

DFX-tools

In the last few years, many tools have been developed within these areas, STOLL 86. Examples are: assembly analysis (DFA) (e.g. BOOTHROYD & DEWHURST 89, BOOTHROYD 87) who reveal to the designer how appropriate a product is in relation to a given type of assembly system, rules for correctly assembled designs (e.g. ANDREASEN ET AL 88, ANDREASEN & AHM 88) and rules for how to design for a specific production method (DFF) (e.g. BRALLA 86). In the last few years, many attempts have been made within the areas of DFM and DFMA, and these tools have contributed to a better focus on manufacturing issues, but the fundamentals of process selection are not considered and there is still a lack of systematic methods to support the designer in considering all relevant production methods and selecting the best alternative.

General issues related to process selection in design

Process selection

One of the essential keys in designing a successful product is to incorporate the manufacturing considerations early in the design process. Selecting the most appropriate production process in terms of technological feasibility and the cost of a component design is perhaps the most important of the decision-making tasks. In most cases it is discovered, that a number of different production methods can be used for a component, and the selection of the most appropriate one depends on a great number of factors. Its solution requires considerable manufacturing expertise. There is a considerable amount of available data on production methods, but precious little knowledge of how it can be applied to the problem of production method deliberation and selection. Nowadays, most engineers select a production method based on their own intuition and estimations, based on educated guesses. Since different production methods offer different possibilities for a component (functions and properties, forms and complexity, sizes and materials) a more systematic consideration of the alternative production methods during the component design process could bring significant benefits. ALLEN & SWIFT 90, ISHII ET AL 90 and ISHII & MILLER.

An example

Figure 5 illustrates that deliberation on the various different production methods provides opportunities for achieving different solutions with different properties and qualities. The figure shows nine different bottle-openers produced by different production methods (and in different materials). The different production methods result in considerable variations. For example, no. 2 is produced by insert moulding, which has resulted in a handle which is comfortable to hold, as well as an attractive design. No. 3 is stamped out of plate and is extremely cheap, but not so pleasant to have in the hand. No. 6 is extruded in aluminium, a process which makes it so light and compact that it can also be used as a key ring, but on the other hand rapidly becomes worn. It is obvious from these examples that it is crucial to consider several different production methods when a component is in the design stage, since it is here that one can achieve different properties and qualities.

According to BOOTHROYD ET AL 94 a survey of designer´s knowledge of manufacturing processes and materials was carried out by Bishop in 1985 (BISHOP 85). The results showed that designers profess little knowledge of production methods, see Figure 6.

A complex situation

The selection of the optimal production methods for a product is not a simple task, since:

- the total number of production methods is unlimited and it is difficult for the designer to form a general view of the possibilities and constraints
- the available process information is structured by production engineers for production engineers and not for designers
- there are many criteria to consider and the designer is all too frequently not made aware of the company's objectives and the needs of the market.

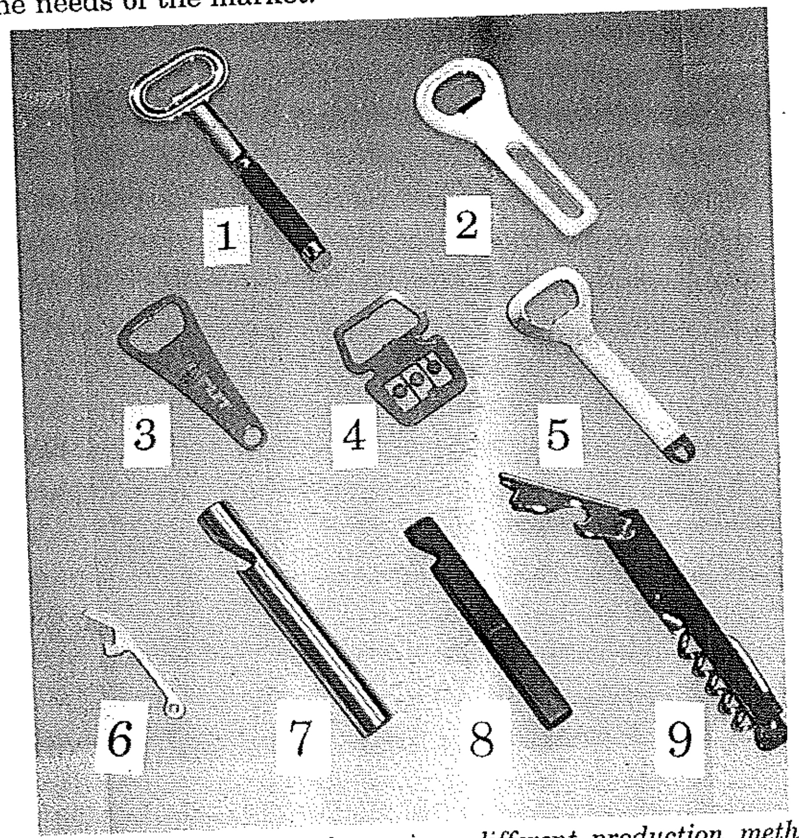

Figure 5 Deliberation on the various different production methods provides opportunities for achieving different solutions.

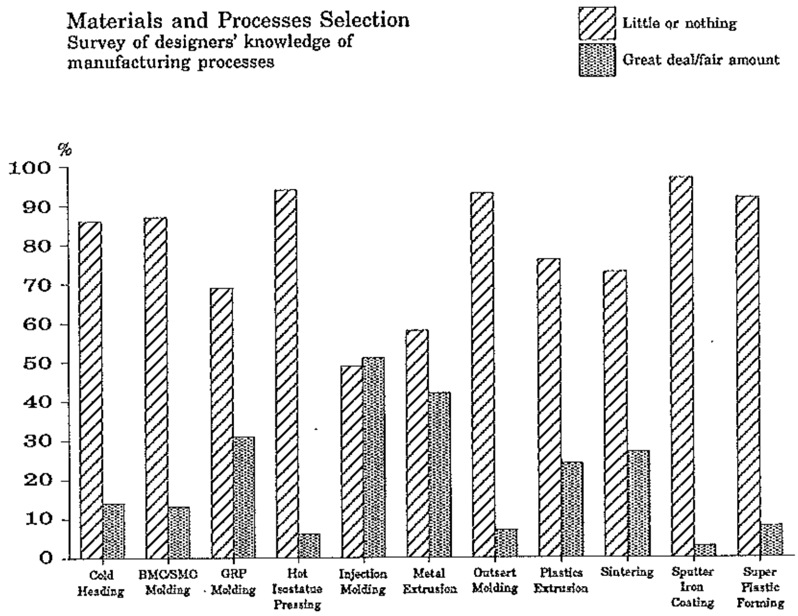

***Figure 6** Survey of designer's knowledge of production methods.* BISHOP *85.*

1.2 Purpose and goals of the project

Hypothesis

Hypothesis

The research work takes as its starting point the following hypotheses:

HY1 Designers consider too few production methods before the final selection.

HY2 Designers do not consider production methods systematically

HY3 Designers select the production methods most familiar to them and seldom consider new production methods.

HY4 More optimal production methods can often be found.

HY5 By also considering production methods not usually employed in the company, the possibilities of new and improved product solutions become available.

HY6 The designer is obliged to consider entire process chains not only single processes before making his final selection.

HY7 To achieve better selections the designer needs more specific information about production methods.

HY8 The information available on production methods does not specifically address the needs of the designer.

HY9 It is possible to find a systematic procedure that makes the designer consider all relevant production methods.

HY10 A systematic procedure can be tailored to the normal engineering design methodologies.

HY11 It is possible to find improved means of presenting production method information.

Objective

Objective

The objective of the research is, through field studies and logical reasoning, to render the above hypotheses plausible. Consequently the work has two aspects, namely:

- *to investigate how the selection of production methods is carried out today, and additionally what is needed by the designer to consider more relevant production methods and how he is to make the selection in a more optimum way.*

- *to develop "a better way", which means to develop a systematic procedure for considering and selecting production methods, and to develop an information model describing the production method information needed by the designer in the early design phases.*

Three levels

As Figure 7 illustrates, process selection can be divided into three levels. The first level is that group of production methods which a given designer in a given company would normally select, because both he and the company are familiar with them and they are the traditional selection in connection with the company's products. Then there is level 2, which constitutes the production methods which, even though they are commercially available on the market, are never selected by the designer,

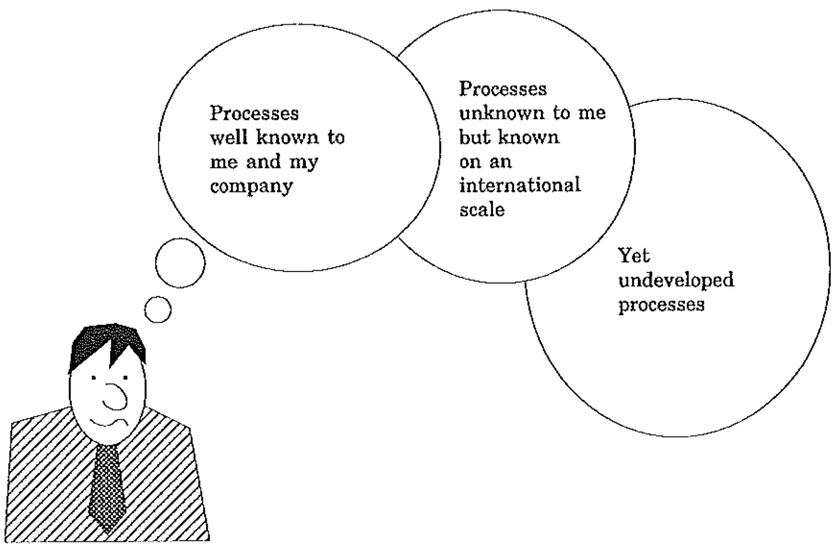

Figure 7 *Process selection can be divided into three levels.*

either because he is not aware of them or because his own or the company's knowledge of them is insufficient. Finally, there are the production methods which have not yet been invented and which, if they are chosen, must be developed along with the product itself.

Task

The main task is therefore to develop a procedure which makes the designer fully aware of all the potential solutions within production methods. The production methods he should consider are those which, on an international scale, are well known and well tried, while for him and his company, unknown and untried, that is to say, "level 2" in the figure. It is therefore not the intention to develop a procedure whereby the designer is supported in the *development* of new and unfamiliar production methods. The fact that the designer considers several production methods for a component will naturally increase his opportunities for selecting alternative materials, functions and forms. The focus here is on the systematic exploration of the potential process solutions. The fact that this provides further opportunities for the selection of the other factors is an extra benefit, but it is not the task of this work to systematize the considerations of material form and function. With regard to this, reference is made elsewhere, including TJALVE 83.

Design levels

The tasks of developing a systematic method and an information model are limited to the design of components (embodiment design). But since the selection of production methods also depends on decisions made earlier in the design phase, the intention is also to give guidelines for the decisions which should be made during these earlier steps in order to ease the consi

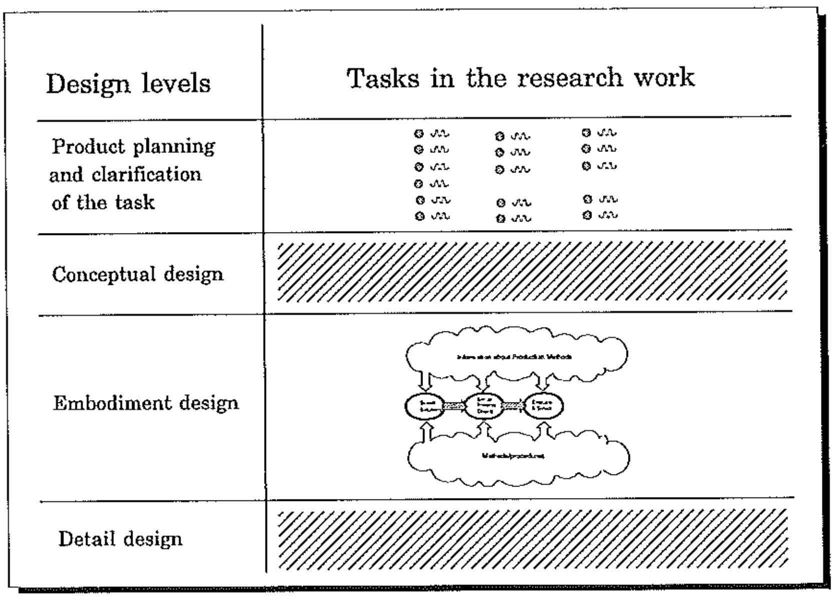

Figure 8 The tasks of the research work.

deration and selection of production methods at the embodiment design level. As argued in Chapter 6, it is not possible to make a direct connection between the conceptual level of design and the production methods, and on the detailed design level the production methods have already been selected. Therefore the emphasis of this research is on the planning and clarification of the task level of design and the embodiment level of design. As illustrated in Figure 8, the task at the first level is to develop methods to support the decision-makers in filling in the product development specification, whereas the task on the embodiment design level is to develop a method for considering and selecting production methods and to develop a process information model that is tailored to this method.

1.3 Preliminary delimitation of the subject

Product types

The tools developed are suitable for mechanical and mechanical/electronic devices, typical examples being household appliances and similar devices. Since the effect of considering many production methods before reaching a final decision is doubtless minimal in the case of small volumes and substantially greater in the case of larger volumes, the emphasis of this study is on the development of tools for devices that are produced in large numbers (thousands). Thus *one of a kind* production is not the focus for these tools.

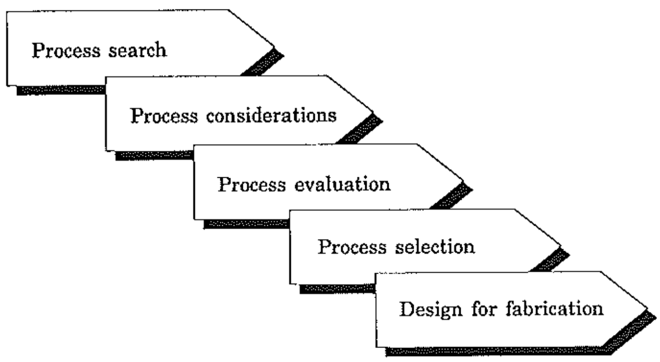

***Figure 9** There are five types of activity which the designer must go through in connection with the selection of production methods.*

Five activities

Process search

Figure 9 illustrates that there are five types of activity which the designer must go through in connection with the selection of production methods. Needless to say, he must first of all look for

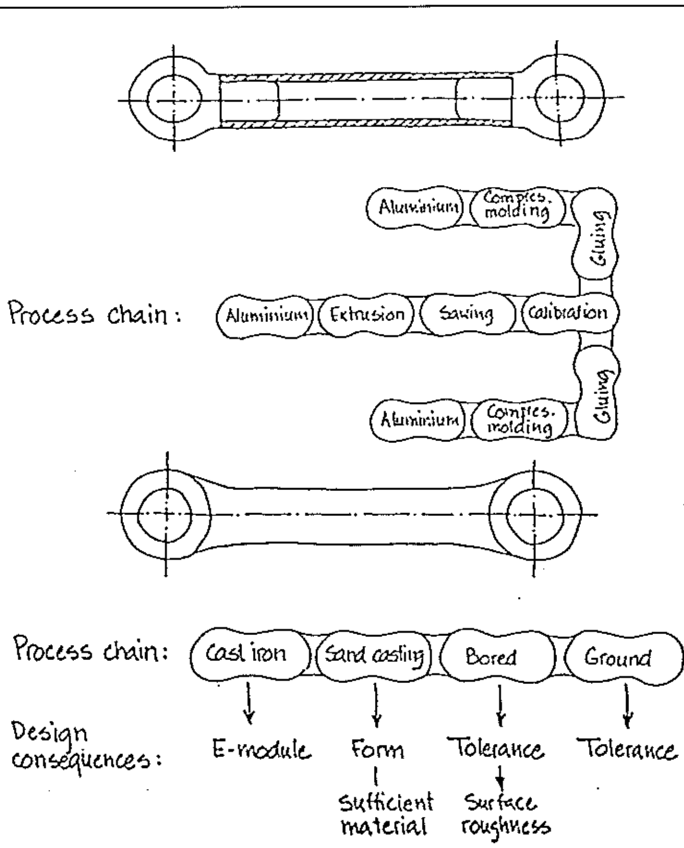

Figure 10 ***A process chain.*** KRISTENSEN 90.

and find relevant production methods. To select a specific production method for a component, the designer must somehow *consider* or *think* of this production method. To consider extrusion, for instance, he must first be aware of the existence of this production method and to sketch solutions he has to know about the possibilities and constraints offered by the production method. The different production methods can subsequently be assessed against each other and the best alternative chosen. In order to select between alternative production methods, he must also be fully aware of the effects or consequences the different production methods have on the criteria he wants to use in the evaluation of the alternative production methods. The final step is the design for fabrication, in which the detailed elaboration of the component is adjusted to the chosen manufacturing process.

Process consideration

Process evaluation

Process selection

Design for fabrication

Primary emphasis

The primary emphasis of the study is on the development of a procedure and a connected process information model for the *consideration* of the main process for a component. The main process is normally a net shape or near net shape process. Since components are most frequently produced with an entire process chain and not just a single process, however, and since the entire process chain and not just the main process can greatly influence the selection of the ideal solution (including that from the point of view of finance), it is necessary that the designer compares process chains and not just main processes. Therefore, the consideration and selection of post processes is also dealt with in this research work. Figure 10 shows an example of a process chain.

1.4 Scientific approach and verification

In a work of this kind it is not easy to verify the results, since we do not have a "before" and "after" comparison. The best indicator that the results are valid is that the methods/models are used by the designer and that he feels that they provide him with a better working procedure which results in good products.

1.5 Research method

Basis

The problem of process selection in design is found in two research domains, namely the field of engineering design and the domain of production process. In the engineering design domain, this study is based on the design theory described by HUBKA 82 ANDREASEN 80 and on the design methodology of pahl & beitz 86.

Terminology

The terminology is based on Hubka and Andreasen, whereas the procedure of designing a product is based on Pahl & Beitz. In the production process domain the study is based on the production method taxonomy advocated by ALTING 78B.

Procedure

The procedure of the research work is shown in Figure 11. From the outset of this research work, it was decided to carry out some experimental work to study the object *process selection* and understand how the selection is carried out in actual design

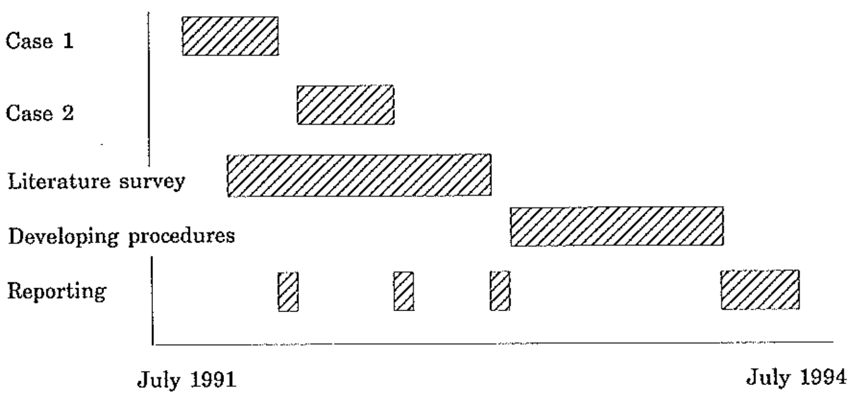

Figure 11 *The procedure of the research work.*

environments. Understanding the environment is a prerequisite for improving it as well as being a study of which levels tools/-methods could be of benefit. Prior to embarking on this study, the author was convinced that the working hypotheses described actually applied and that the designer all too often considers all too few production methods etc, but wanted through field studies to verify these hypotheses.

Literature

Contributions

Production method selection has already been treated by JEPSEN 78B but few researchers since then have treated the subject as a methodological problem. Instead, they are mostly concerned about developing computer systems either for production method information (LENAU & KRISTENSEN 92), cost calculation and selection (ISHII & NEKKANTI 89, YU ET AL 92, ZENGER 93) or design for fabrication (CUTCOSKY ET AL 89). Other contributions in process selection are SIGURJÓNSSON 92 and PETERSEN 92, both published during the period of this study.

Interviews and case studies in industry

Case 1

The experimental work was mainly done through field studies in a Danish company, where designers and production engineers were interviewed. The author also participated in a product development project in the company, in order to obtain an insight into the problem of integrating design and production and in particular into how the selection of production methods was dealt with.

Video-taping studies in laboratory

Case 2

Another part of the experimental work was the video-taping of students from the Technical University of Denmark and the University of Aalborg while they were solving an engineering design problem. Using students in a study like this can be (and indeed was) extremely inspiring, but when using students with no practical engineering experience one has to be particularly careful when analyzing the results retrieved.

Educational projects

Student projects

In the course of the study, the author had the opportunity of working as a supervisor of a student project in design for manufacture, in which the students redesigned products in cooperation with the company. The focus of this project was on redesigning the products for better and cheaper manufacture. The project also provided inspiration and acted as a testing environment for ideas and models.

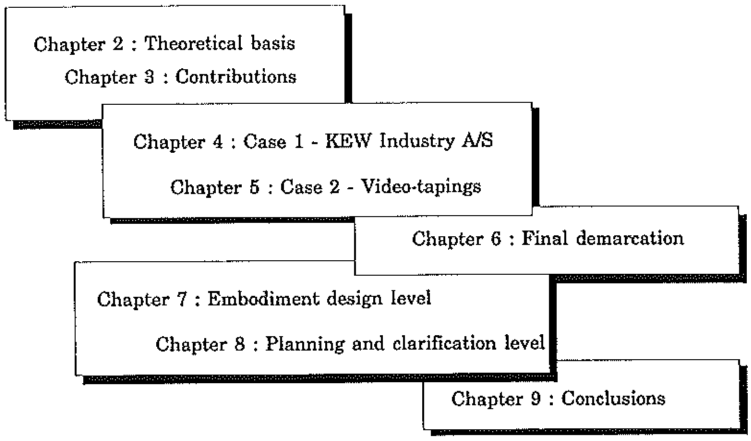

***Figure 12** The structure of this thesis.*

The experimental studies have, throughout the entire research period, been used interactively with the more abstract theoretical work.

1.6 Structure of the thesis and reading guidance

Structure

This thesis has been structured in the same way as the work. This means that the reader, through reading, more or less follows the work process in the project. In order to make the report easier to read, some of the heavier sections, such as descriptions of the literature and procedures have been placed in the appendix. Consequently, in order to gain an insight into the scientific procedure, it may occasionally be necessary for the reader to consult the appendix.

The thesis is structured as shown in Figure 12.

Chapters 2 and 3

Chapters 2 and 3 are on the literature, with Chapter 2 dealing with the theoretical basis within the domains of design and production and Chapter 3 describing earlier works on the concept of process selection.

Chapters 4 and 5

Chapters 4 and 5 describe two different case studies. Chapter 4 describes a case study in which the author participated in a product development project in a Danish company. Chapter 5 describes the procedure and results of a pilot project, in which students were video-taped while solving an engineering design problem.

Chapter 6	On the basis of the literature chapters and the case studies, Chapter 6 describes the final demarcation of the task in this research work.
Chapters 7 and 8	Chapters 7 and 8 describe the ideas and models developed. Although it might seem more logical to describe the ideas and models developed in the order in which they fit into the design methodology, it was decided here to present the methodology on the embodiment design level first (Chapter 7) and subsequently the factors which should be taken into consideration at the planning and clarification of the task level. This order has been chosen because it is easier for the reader to understand the considerations which should be made early in a product development project when the problems inherent in the embodiment design level have been presented.
Chapter 9	The thesis is rounded off with a conclusion in Chapter 9.
Appendices	The appendices contain, inter alia, a description of the procedure in the literature study (Appendix C), empirical methods from the literature (D), as well as some of the articles written by the author in the course of the research (A and B).

Reading guidance

In order to establish an unambiguous mutual understanding between the reader and the author, the concepts central to this work are defined below.

The designer	*The designer* refers both to the design function as an activity and to the designer as a person (or some other person who carries out this activity). In fact several persons could be involved.
Component	*Component* means single parts which are produced without assembly operations. Here can also be mentioned compound components consisting of several different materials when the component has been made through a production method (i.e. insert and outsert moulding).
Production method	*Production method and process.* These terms are used indiscriminately but cover precisely the same content and refer to fabrication processes like turning, milling, injection moulding etc. and not to more detailed processes like ejection, heating etc. nor to assembly processes.

Process chain	*Process chain* is utilized about the sequence of production methods comprised in the fabrication of single parts. In the literature, another term is often used, namely *process sequence*.
Production/fabrication	*Production and fabrication* are used for the same concept, namely to produce components with production methods, while the concept of assembly is not included.
Manufacture	*Manufacture* covers both production and assembly.

THE THEORETICAL BASIS 2

In this chapter, different theoretical contributions in the two areas, engineering design and production, are presented and a basis for this work is selected in both domains. The purpose of the chapter is to present the foundation making clear which theoretical basis and which set of terms are followed by the research described in this thesis.

In this type of research project, it is crucial to have a theoretical foundation. This foundation has two purposes, namely to serve as a springboard and also as a jargon. As a *springboard,* the theoretical foundation has the purpose of ensuring that the researcher is on solid ground, since the foundation is an accepted set of theories and propositions which can not be subject to criticism or question. This means that new contributions to the area of study must be in agreement with this foundation. The theoretical foundation has also the purpose of forming a *jargon* for communication on and around the research work, which with its set of accepted and well-defined norms, ensures an unambiguous mutual understanding between the sender and the receiver of the message, as it were. These fundamental concepts need therefore not be redefined every time a thesis or the like is in the process of completion.

Springboard

Jargon

Two domains

The process selection activity does not have its own domain of theory, but belongs to both the engineering design domain and the manufacturing domain. The development of a procedure and a production method information model to support the designer in the activity of considering and selecting production methods, requires knowledge from both domains. The purpose of going through the literature of this technical area is to enable the author to choose a theoretical foundation for both engineering design and manufacturing engineering, as well as to learn the language and the theory contained within these foundations.

2.1 The domain of production

Theoretical foundations

There are several types of theoretical foundations within the domain of production, as well as a set of theories within each individual production method. There is, for instance, a set of models which describes what happens in the course of a turning process (the way the shavings behave etc). There is also a set for forging which describes the flow of the material in the tool activity as well as the wear and tear on it etc. As the foundation for process selection in the design phase, it is necessary to use another type of foundation, namely a model which in general describes characteristic invariant conditions around all production methods and it is just such a foundation that has been sought and described in this section.

Process information

Information about production methods is vital for engineers in different domains. The information needed by, e.g., a production engineer and a designer is not the same, however. Their interest concerns different subjects at different levels. Many books have been written in order to provide the information needed, mostly by production engineers but also by designers. These books primarily describe the different production methods and materials.

2.1.1 Existing types of production models

General definition of a production process.

A production process is generally defined by ALTING 78B as a transformation of material into the desired result and some waste, by the use of energy and information. The term process describes the basic transformation where the desired shape, hardness and appearance of a part are obtained, Figure 13, left. A part is most often created with more than one production method, or a process chain. ALTING 78B divides the production processes into three phases, Figure 13, right. The phases could be either phases in one production method (e.g., melting, forming, cooling) or phases in the production of a component (e.g., sawing, machining, surface treatment).

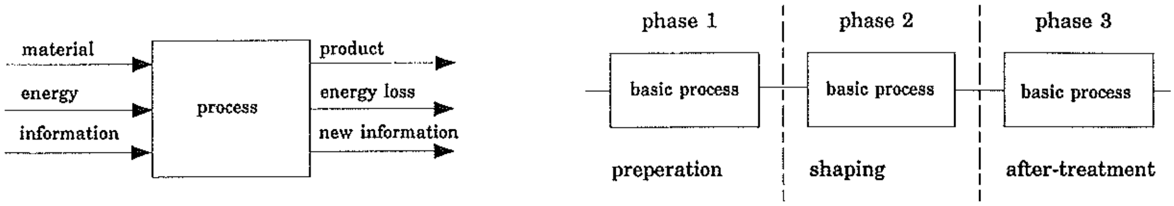

***Figure 13** Left: The general process model. Right: Division of manufacturing processes into three phases.* ALTING 78B.

The morphological process model

The morphological process model of material processes described by ALTING 78B is a taxonomy, from which all production processes can be deduced, see Figure 14. The model is intended to support people involved in process planning and process development. A material process is obtained by choosing a value from each column.

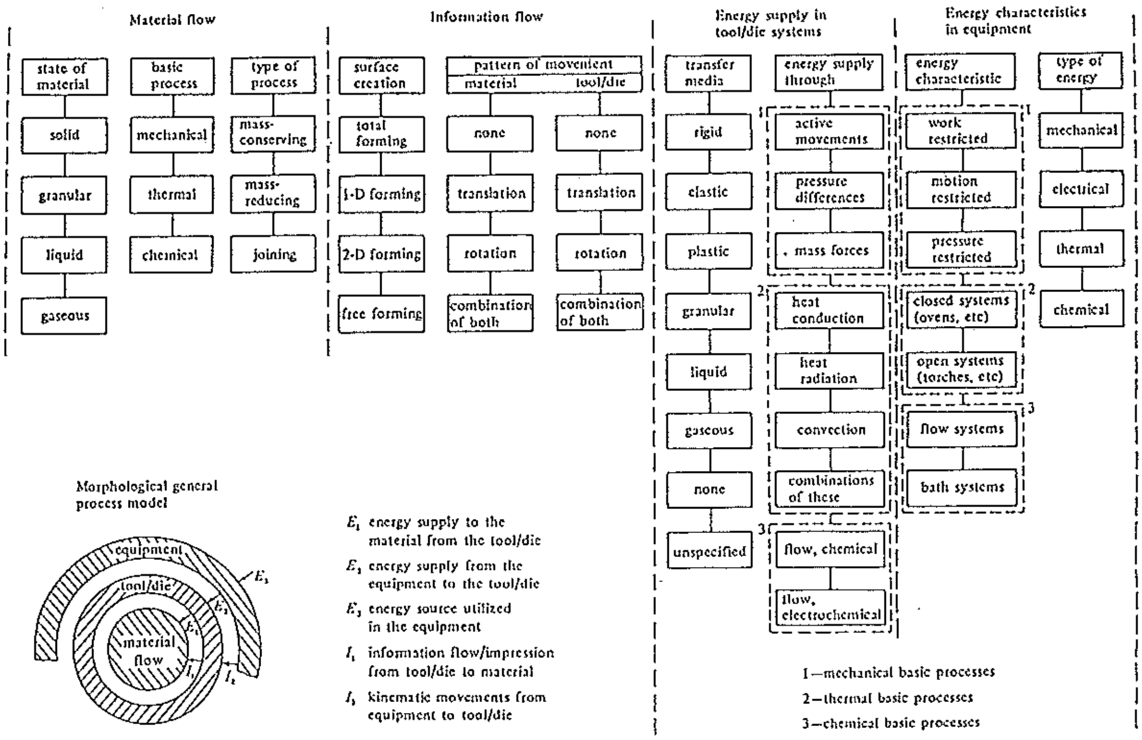

***Figure 14** The morphological structure of material processes.* ALTING 78B.

Books on production processes

Bolz

BOLZ 63 describes production processes. He takes 30 pages at the beginning of the book to present examples of how money was saved by redesigning a part to fit another process. In the remainder of the book, the processes are described under the headings: Metal removing methods, metal forming methods, casting methods etc. Each process is described, including information on; the steps in production, limits in part sizes, production quantities, general advantages, etc. Design considerations are discussed, as well as lists of data for the suitable materials, for example, data for plastics, cost, shrinkage, tensile strength etc. which should help the designer select material.

Degarmo

DEGARMO ET AL 88 describes materials and processes. The philosophy of the book is to provide a solid introduction into the fundamentals of production. The materials are described by first giving an introduction to properties of materials, equilibrium diagrams, heat treatment and subsequently a description of different materials. The remaining two thirds of the book concerns processes, and the processes are divided into groups such as: Casting processes, forming processes, material removal processes etc. Typical products are also listed and presented in pictures.

Allen & Alting

ALLEN & ALTING 86 is a description of some 300 processes. The book has the purpose of giving the designer, production engineer and industrial engineer exemplary information about production methods. The processes are arranged after the taxonomy shown

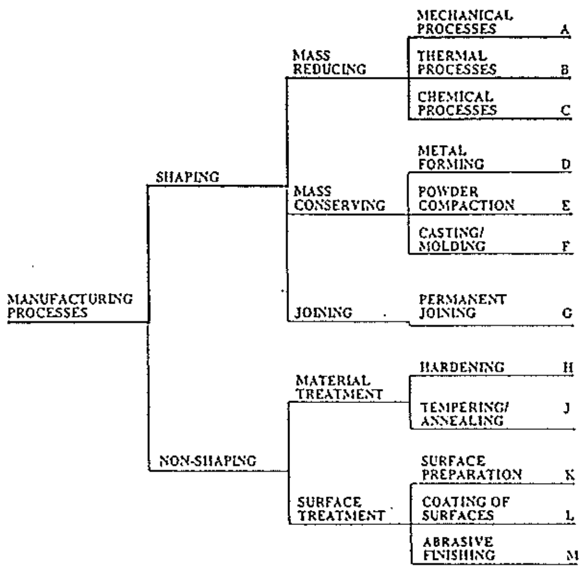

Figure 15 *The manufacturing process taxonomy.* ALLEN & ALTING 86.

in Figure 15, and the information belonging to each process is presented by 24 frames. The first six frames provide a brief introduction to the process and the remaining frames provide data, relationships and rules. All processes are described in the same way, since each frame has a specific content of information, e.g. frame number two includes "setup and equipment". This makes it very easy to find specific information about a chosen process.

Kalpakjian

KALPAKJIAN 89 has written his book with the purpose of teaching students in universities and various technical institutes about production engineering and technology. Kalpakjian describes materials and processes in the same way as Degarmo while also covering subjects such as: Automation of production processes, Integrated production systems and Competetive aspects and economics of production.

Bralla

BRALLA 86 is the book that to the extent of the author's knowledge comes closest to a "Designers handbook of production methods". The purpose of the book is perhaps best described in Bralla's own words in the beginning of the book:

»This book can be used with any of three methods of reference: (1) by process, (2) by design characteristics, and (3) by material. ... The problem with the process-oriented book layout is that it is not adapted to designers (or manufacturing engineers) who are concerned with a particular product characteristic and do not really know the best way to produce it. For example, designers having the problem of making a nonround hole in hardened-steel part may not be aware of the best process to use or even of all processes that should be considered. This is the kind of problem for which the *Handbook* is intended to provide assistence«.

Bralla has seen the problem designers have in finding the right process for a specific product characteristic and the handbook offers tables where different parameters, e.g. surface finishes, maximum surface roughness, dimensional tolerances and commonly used materials are shown for different production methods. The book also includes tables where processes for producing specific features can be found. The features represented are: flat surfaces, two and three-dimensional contoured surfaces, embossed surfaces, round holes, nonround holes and hollow shapes. These tables take up only about 15 pages, however, and the description of materials takes up about 80 pages, while the rest of the book, or about 1000 pages, describes different processes, and although good/bad geometric examples are presented, the book does not fulfil the intention mentioned by Bralla himself.

2.1.2 Concluding remarks about the domain of production

Process information

Information about production methods is structured in different ways in the literature. DEGARMO ET AL 88 and KALPAKJIAN 89 belong in the category where the information about each process is not of the same "type" and is not presented in the same order. BOLZ 63, BRALLA 86 and ALLEN & ALTING 86 present the process information in a more structured way. Bolz and Bralla have at least placed the information under standardized headings. Allen & Alting have gone one step further and chosen a layout where it is easy to find the specific sought-after information.

The designer has two fundamentally different types of questions about processes:

- What can this process deliver ? (e.g. What wall thickness is possible by injection molding ?)
- What processes can deliver this and that ... ? (e.g. what processes can give me a surface finish of 10-15 μm ?)

What can this ...

The books on production information normally only provide the answer to the first question. The structure of the books is process-related and describes each process. In other words, these handbooks are written from a production point of view. Of course the designer needs a structure such as this to answer his fundamental question *what can this process deliver ?*, but some of the information described is too detailed for him. Of what interest is, for instance, spindle speed to him ? Most of the books present information that the production engineer needs but which is of no concern for the designer.

What processes can ...

To reflect the other kind of the designer's fundamental question: *What processes can deliver this and that ?*, he needs another kind of information structure. This structure is to some extend used in BRALLA 86 as promised in the beginning of the handbook, but compared to the number of pages, this part of the book only takes up a minor amount of space.

Also ALLEN & SWIFT 90 have come to the conclusion that the facts usually tend to be process-specific and described in different formats, making the designer's task more difficult.

Theoretical foundation

It may appear somewhat inadequate that a section which concerns itself with the theoretical foundation within the domain of production should describe handbooks on production methods. The reason is that this is actually the closest we can get to a foundation within the domain of production. When the question is an accepted language usage, it is possible to find one, and here it has been decided to use Alting's morphology. Alting's morphology is also sufficient as *an attempt to explain a phenomenon,* but when it comes to a theoretical foundation in the form of a set of accepted propositions, it has not been possible to find one which can be utilized in connection with process selection in the design phase. In given circumstances, such a theory should describe the connection between the phenomenon, a technical system (a product) and the production system (production methods), and the nearest we can come to such are SIGURJÓNSSON 92, PETERSEN 92 and ANDREASEN 91.

Jargon

Unfortunately, these contributions were published after the theoretical foundation in this research work had already been decided upon and it has therefore not been possible to include them, although they are described in Chapter 3, which deals in more detail with contributions to the solutions of problems of process selection.

2.2 The domain of Design

The reading of books concerning design has shown that the domain is divided into two subdomains; the field of *methodology* and the field of *theory*. Some authors go into theory and describe "the facts of the matter" and others go into methodology and describe "how to design". Both design theory and design methodology are extremely important in connection with the selection of production methods in the design phase and therefore this section describes both subdomains.

Different schools

YOKISHAWA 89 presents different schools of design theory: the semantics school, the syntax school, the historism school, the psychological school and the philosophical school. Seen from a product development point of view the two first mentioned are the most interesting ones. The central dogma of *the semantics* *school* is that any machine is something that transforms an input into an output (functionality) whereas *the syntax school* deals with the semantics in a systematic way.

This project needs a design basis, but obtaining an overview of the different schools in order to find out which one to choose would be extremely time-consuming, and consequently the author decided very early on to concentrate on two different design theories (the domain theory by ANDREASEN 80 and the theory of technical systems by HUBKA 82) and two methodologies (PAHL & BEITZ 86 and TJALVE 83). These contributions are described in this section.

2.2.1 Design theory

The domain theory

Four systems

The domain theory described by ANDREASEN 80 and ANDREASEN 92A defines a machine or a mechanical product in four systems: The process system, the functional system, the organ system and the component system.

The process system

The process system describes the transformation of material, energy or information occurring in the machine. A process builds on a correlation between the above-mentioned transformation parameters and the necessary effects (forces, heat effects, movements etc.), which have an influence on the parameter. The effects could be provided by the user of the machine or by the machine itself. A diagram of the technical process *winding a punched* tape is shown in Figure 16.

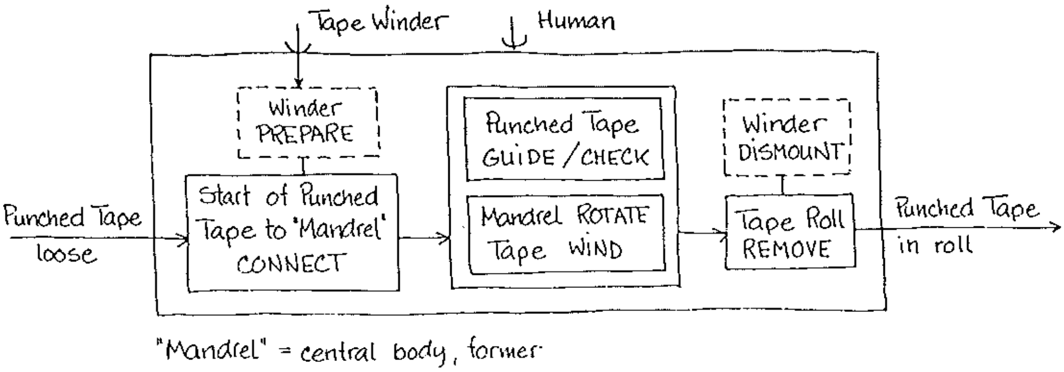

Figure 16. *The technical process for a tape winder. HUBKA ET AL 88.*

The functional system

The functional system is the system of the functions which a machine system should possess. A function is a property of the

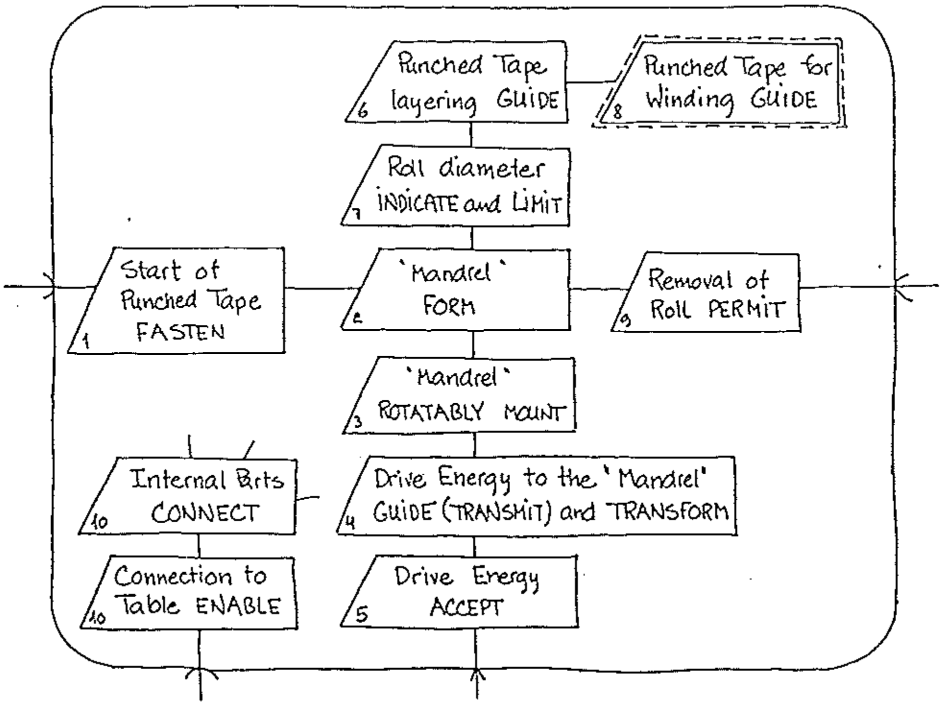

***Figure 17** Functional structure of a tape winder.* HUBKA ET AL 88.

machine. For instance, an electrical resistance can have the function *of increasing temperature* and a tube the function *of leading the water*. The functional structure of the punched tape winding system is shown in Figure 17.

The organ system

The organ system describes the active entities carrying the functions. An organ could be one material area (belonging to one component) or it could be shared between more material areas (belonging to more components). For instance, in a pair of scissors there are three different organs. The cutting organ, the

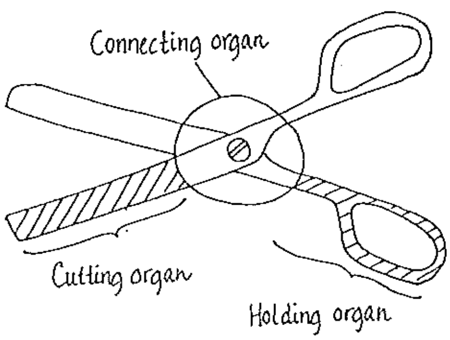

***Figure 18** The organs on a pair of scissors.* ANDREASEN 80

connecting organ (shared between two material areas) and the holding organ (one material area), Figure 18.

The component system

The component system describes the machine regarded as machine parts. One component could carry more than one organ and one organ could be shared between more components, as seen in the pair of scissors example above.

The four systems interrelate in a function/means causality.

The theory of technical systems

Hubka

HUBKA 82 describes a theory for technical systems, where the technical system and its working process are considered as two clearly distinct concepts. Figure 19 illustrates a system like this where an operand is transformated from an existing state to a desired state through a transformation process. The transformation process is realised through effects combined of the human, the technical, the information and the management/goal systems.

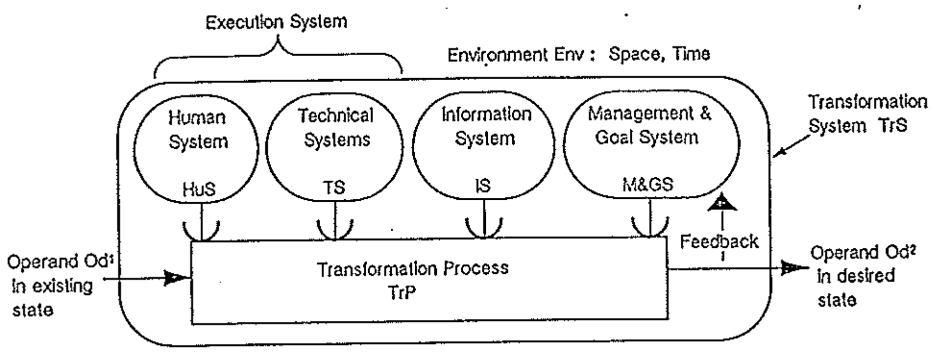

Figure 19 *A general model of a transformation system.* HUBKA 82

The design degrees of freedom

Andreasen & Hein

ANDREASEN & HEIN 87 describe the design degrees of freedom as shown in the triangle in Figure 20. The degrees denote the parameters which must be fixed in the course of a product development. The top 6 are factors which must be established for the whole product as they are part of a functions/means causality. The bottom 5 belong to the individual components. The model does not describe the design process and the design of a product can take its starting point in the formulation of the problem at the apex of the triangle or any where else at all. But functions/means causality means that if the parameters at the lower levels are established, then the parameters which are over

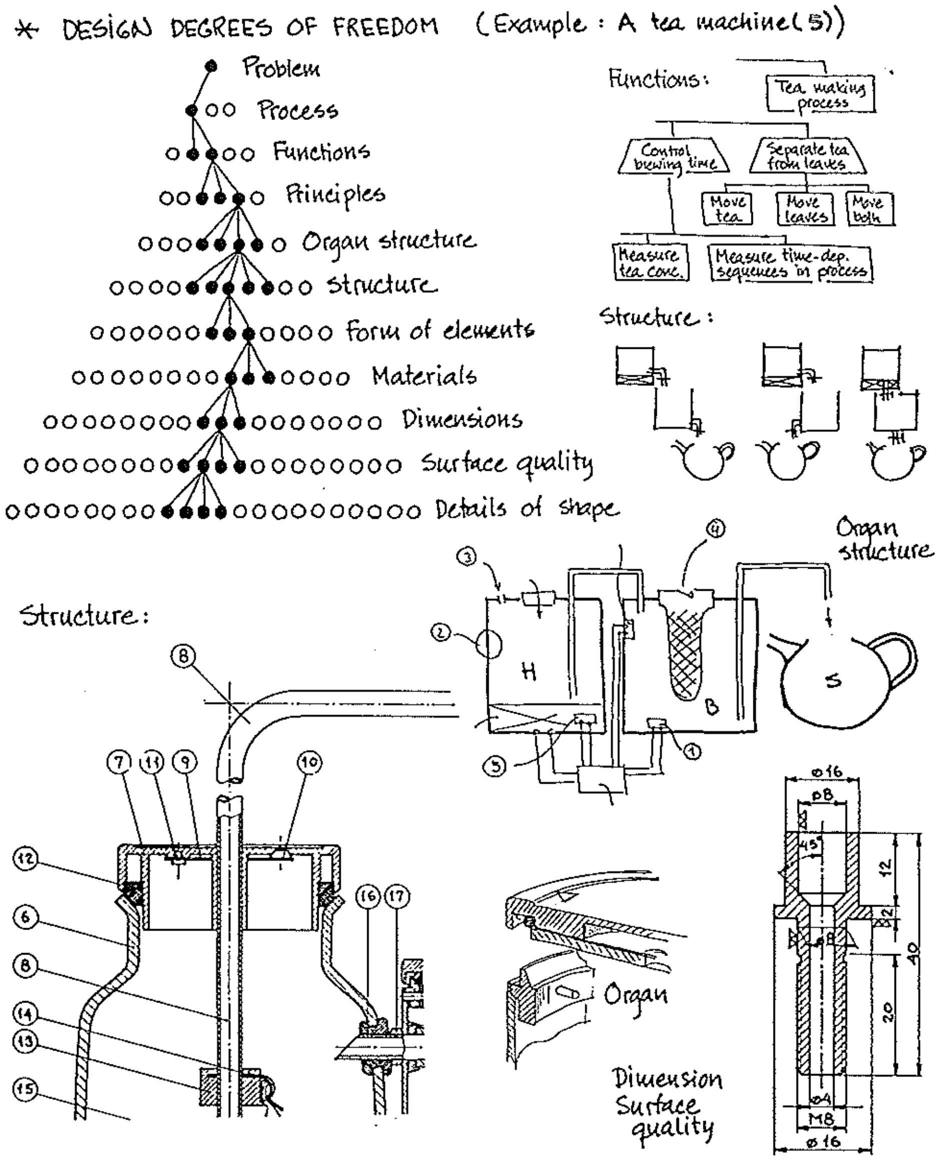

Figure 20 The design degrees of freedom. ANDREASEN & HEIN 87.

in the triangle are similarly fixed (either consciously or unconsciously). In Chapter 3, it is described how PETERSEN 92 and ANDREASEN 91 have utilized this triangle as a starting point for the presentation of the corresponding degrees of freedom for the production domain.

2.2.2 Design methodology

The methodology described by Pahl & Beitz

Pahl & Beitz

PAHL & BEITZ 86 describes a methodology consisting of four main steps: 1. Product planning and clarification of the task, 2. Conceptual design, 3. Embodiment design and 4. Detail design, see Figure 21. Seen from a process selection point of view, all

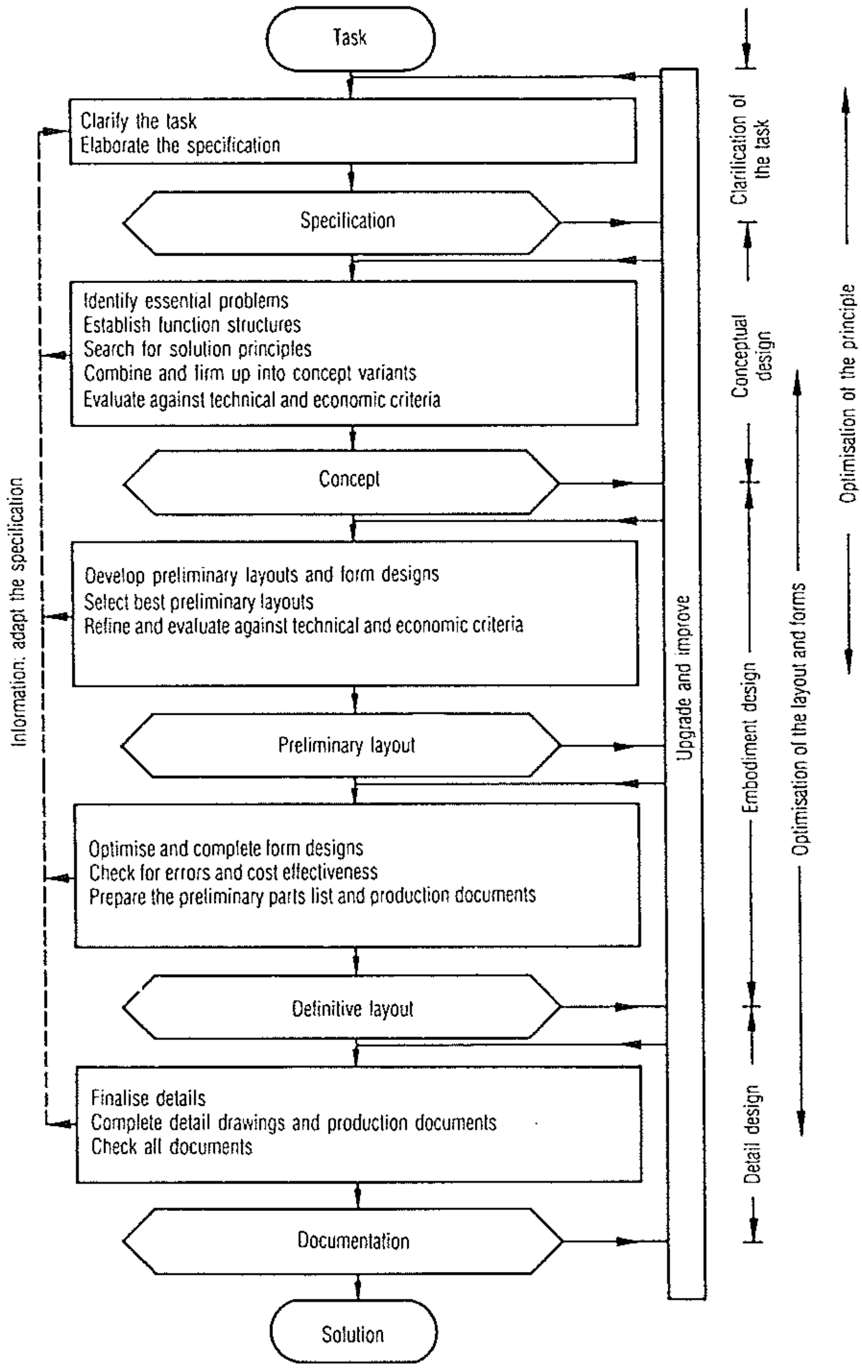

***Figure 21** Steps of Pahl & Beitz′ design methodology.*

levels are interesting since the decisions made at any level will affect the amount of selectable processes at the later levels. The embodiment design level is the more interesting level, however, since it is at this level that the components take form. The four main levels are divided into several substeps and the method seems to be extremely useful in product design and also as a basis for developing procedures and methods for process selection.

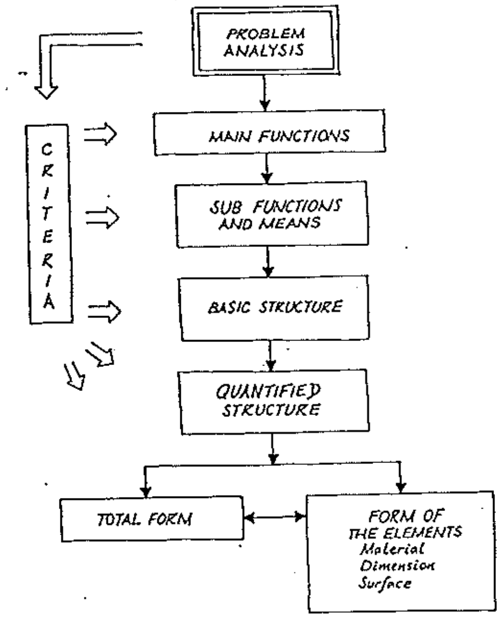

Figure 22 *The stages in Tjalves product synthesis.* TJALVE 83.

Tjalve

The methodology described by Tjalve
TJALVE 83 is, like PAHL AND BEITZ 86, describing a methodology for designers in the product development. The methodology is called "product synthesis" and the stages are shown in Figure 22.

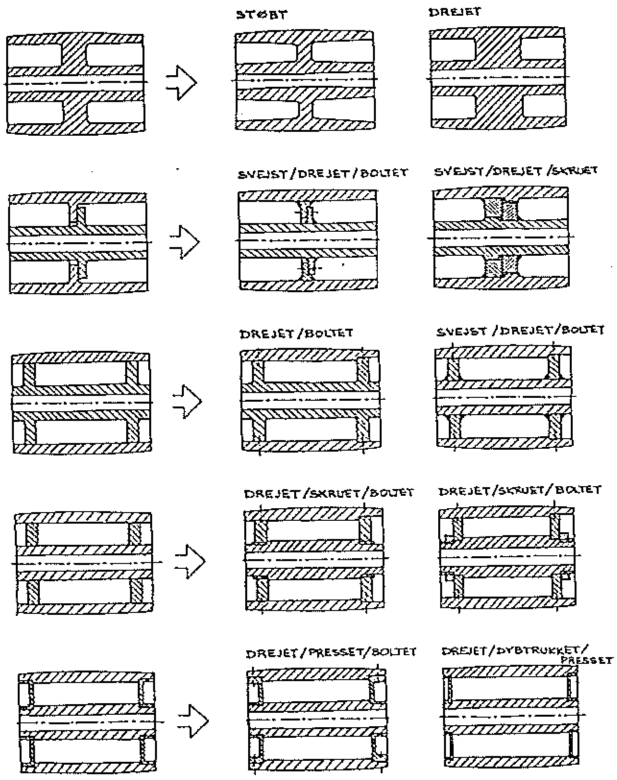

Figure 23. *Form-concepts leading to consideration of different production methods.* TJALVE 83

Tjalve does not go into detail with each stage as PAHL & BEITZ 86 do, but Tjalve presents synthesis methods for some of the later stages in design (e.g. the structure variation method on the stage of quantitative structure and the form variation method on the latest stage). The form variation method is particularly interesting and should be useful in the process consideration activity. Figure 23 shows an example of the form variation method used on a roller.

2.2.3 Concluding remarks about the design domain

Theoretical basis

As a theoretical basis the domain theory described by ANDREASEN 80 and the theory of technical systems by HUBKA 82 are chosen. Tjalve supports these theories with some "tools" for the designer and his work is chosen as a basis as well. When it comes to a description of a systematic design methodology, the one described by PAHL & BEITZ 86 is more formalized and a better tool for a researcher outside the engineering domain. It is therefore used in this research work as a general model for how designers work.

Terminology

The terminologies used by Andreasen/Hubka/Tjalve and Pahl/Beitz are not the same, and as a conceptual world, it has been decided to make use of Andreasen/Hubka/Tjalve´s terminology. The reason for this is that the author, over a period of many years, has become familiar with this terminology and it would therefore only create confusion if another were chosen.

2.3 Summary

In this chapter, the theoretical foundations in the domains of design and production have been described and a springboard as well as a jargon has been chosen in both domains.

Production domain

In the *production domain* it has been decided to utilize Alting's process morphology as jargon, while within the domain of production, it has been concluded that no actual theoretical foundation can be found for use as a springboard in the development of methods for the selection of production methods in the design phase.

Design domain

In the *design domain* it has been decided to make use of Andreasen's domain theory and Hubkas theory of technical systems as theoretical springboard and jargon, while Pahl & Beitz´s as well as Tjalve's design methodologies have been chosen as a general description of how designers work.

Contributions related to process selection in the design stage

3

This chapter describes related contributions to process selection in design. The objective is to uncover the developments, which have already taken place within this subject and thereby review the revelant achievements in this sphere.

In the literature, some authors treat the subject of process selection in design, some deal with a procedure of how process selection should be carried out, others deal with the criteria which should be considered when searching for and selecting processes, and some have implemented procedures and infor-

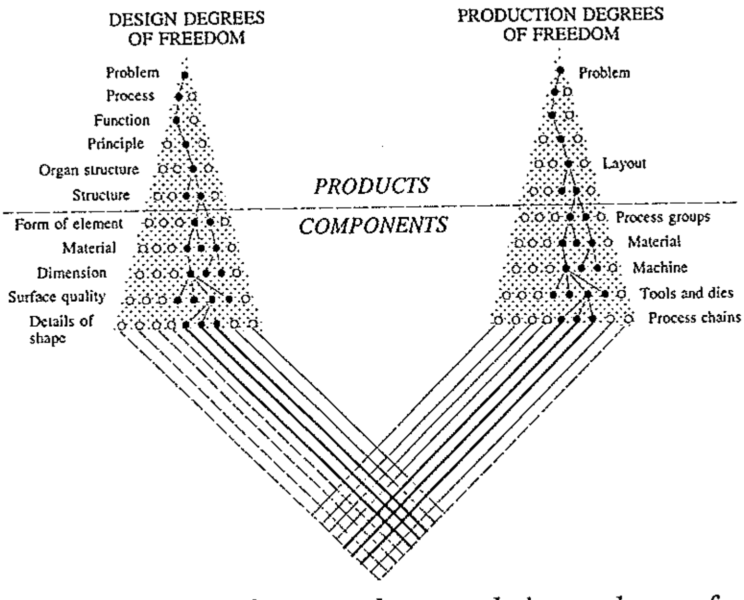

Figure 24 *The common language between design and manufacture.* PETERSEN 92.

mation needed in computer systems. This chapter gives an overview of the procedures, process selection models, process selection systems and cost analysis methods presented in the relevant literature.

3.1 Contributions concerning integration of design and manufacture/production in general

A common language

PETERSEN 92 presents what he calls *a common language* between the domains of design and production, Figure 24. He compares the degrees of freedom in the area of production with the degrees of freedom in the domain of design stated by ANDREASEN & HEIN 87. Petersen wished to confirm a connection, a common language between the degrees of freedom in the two domains, but did not succeed; the dictionary of terms was never invented. The only way a certain connection could be established was through component examples, for which it proved possible to describe parameters applying to both domains. The model presented forms for the basis of the process information system MADED, which is described in Section 3.3.

Andreasens model

ANDREASEN 91 presents a model showing the connection between design and manufacture/production, Figure 25. The model describes how the production system is determined concurrently with the determination of the product itself. This determination is expressed as a chain of events in a pyramid with constructive degrees of freedom from both domains. According to Andreasen the correlations are:

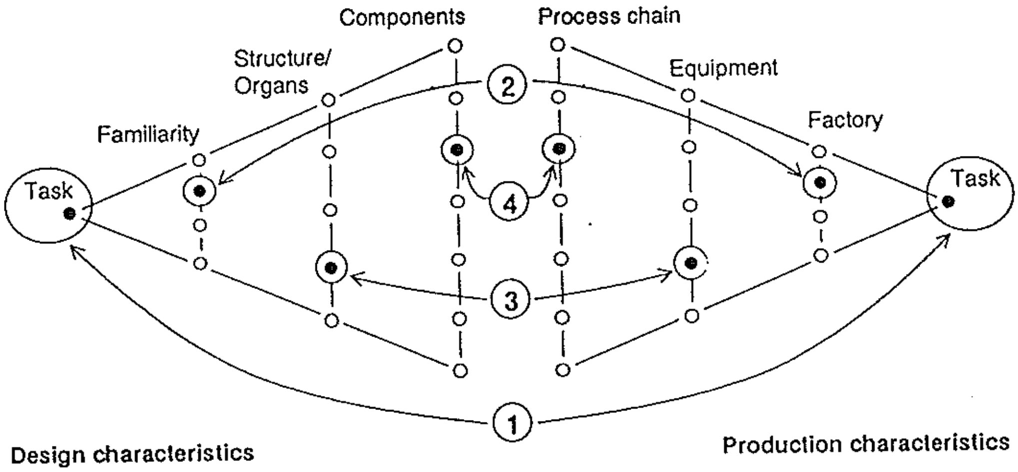

***Figure 25** Andreasens model showing the connection between design and manufacture.* ANDREASEN 91.

Task level

1. At task level: the determination of the product's relationship with other products, variants, as well as the attendant necessary requirements and functional conditions. On the production side, any corresponding relationship with the manufacture of other products is determined etc.

Principle level

2. At principle level: the determination of the principles of the product is counteracted by the already established production types, production principles/manufacturing plant.

Structural level

3. At structural level: the structure of production defines the components and their methods of combination. On the production level, process equipment and layout are also determined (machinery, manufacturing units, cells, transport equipment).

Component level

4. At component level: the component's functional surfaces, features and composition (skeleton) as well as the demands on the component are realized by a selected material and a selected process chain (tools, fixtures, pattern of movement, machines).

The connection is also shown in Figure 26 with an IDEFO resolution re. correlation and recycling. As can be seen, Andreasen assumes that there is a correlation between the design activities: determination of the product concept, product structure, the components and the determination of the production principles/manufacturing plant, process equipment/-layout, process chain/processes respectively.

The author does not agree with this opinion, but believes that although these activities ought to take place simultaneously (in order to shorten development time), there is no obvious connection between product concept/principle and production principle/ manufacturing plant. There is a clear connection between product structure and production equipment/layout when production means assembly, but not when production means fabrication. The connection between components and processes/-process chains is fairly evident. Both ANDREASEN 91 and SIGURJÓNSSON 92 give examples to illustrate the maintained connection, but the author is of the opinion that the examples only illustrate a connection to processes and process chains and neither to production principles/manufacturing plant nor to process equipment/layout. Reference is also made to Chapter 6 for a further discussion on the connection between design and

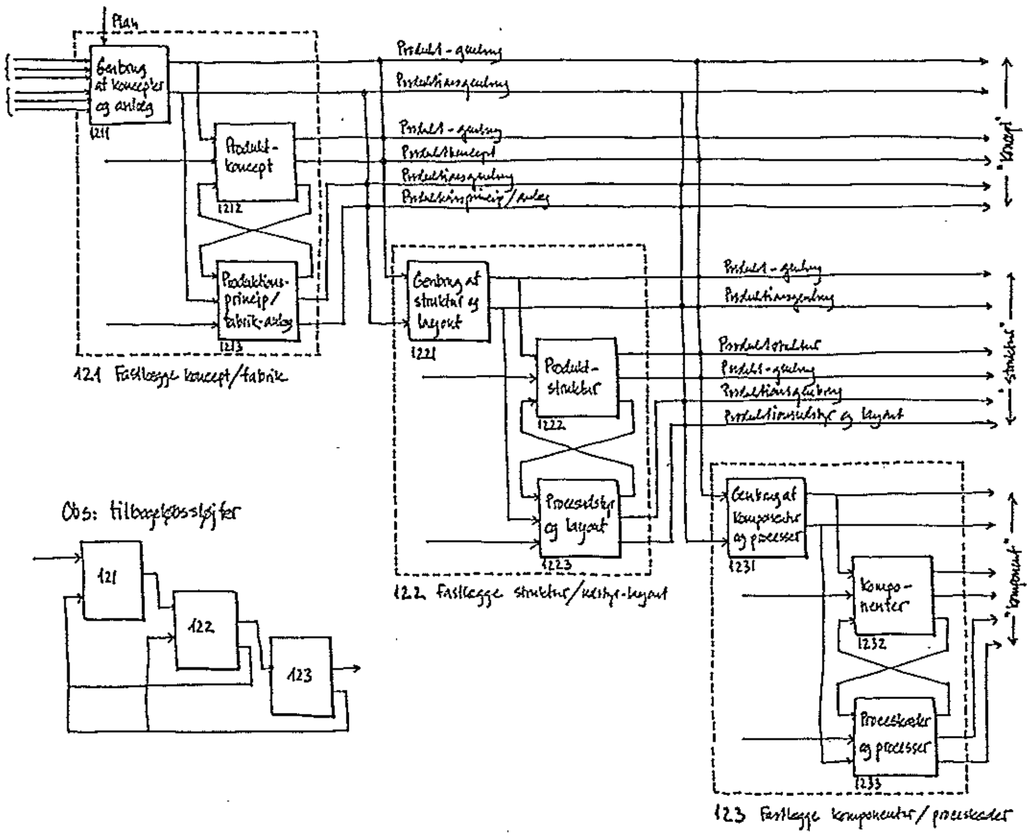

Figure 26 Andreasens IDEF0 model of the connection between design and manufacture. ANDREASEN 91.

production in relation to Pahl & Beitz´s four design levels.

An information model

LENAU & ALTING 92 presents an information model for design support systems, process selection and design for fabrication (Figure 27). It consists of a core surrounded by all relevant information areas. The model is intentionally very loosely structured. It only states that all these types of information are necessary, but a more detailed structure depends on the application.

3.2 Process selection procedures and models

Value control guide

VALUE CONTROL DESIGN GUIDE 63 was made for value engineering, i.e. cost reduction for existing components. The purpose of the guide is to aid the user in obtaining the lowest cost manufacturing process at the very beginning of the design phase. The procedure is in three steps. Classification of the part shape, determination of which processes apply to the part (criteria: raw material, minimum/maximum part size, general tolerance and surface finish) and comparison/selection of a proper process (criteria: production quantity, tooling, labour and material

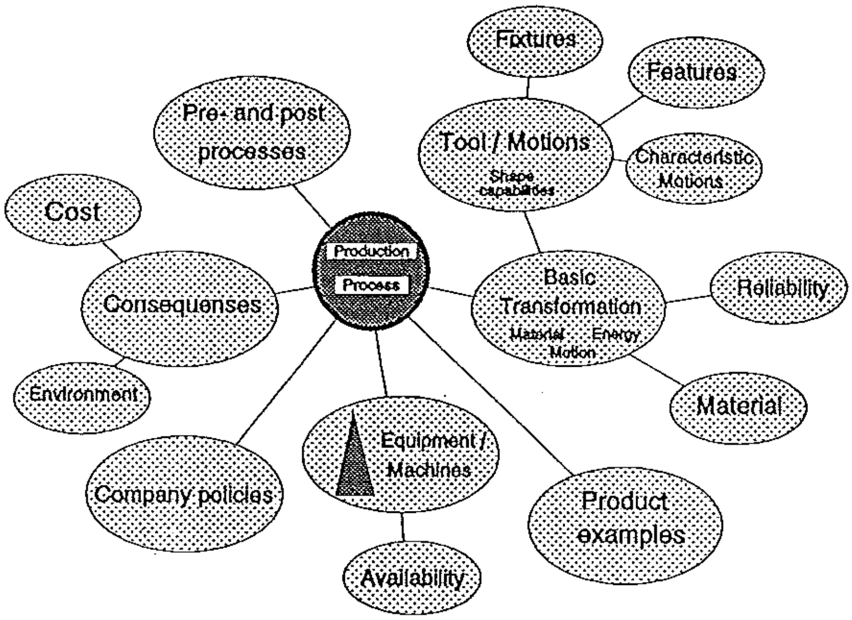

Figure 27 A process information model for design support systems. LENAU & ALTING 92.

waste). The guide has also a section describing different processes.

Ishii et al

ISHII ET AL 90, ISHII ET AL 90/91 and YU ET AL 92 have focused their work on single parts that are to be net or near net-shape manufactured, and they all use the same diagram to describe the dependency between the factors related to product design and process selection, see Figure 28. The diagram does not show, in

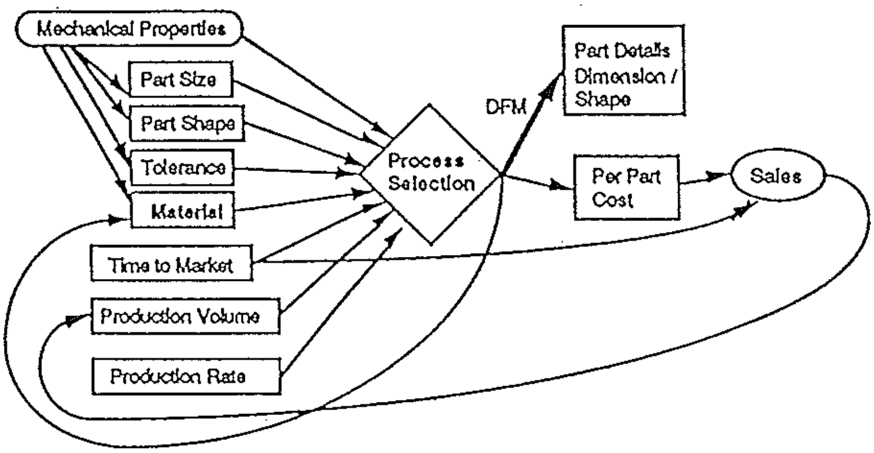

Figure 28 Design dependency diagram. The diagram views process selection as the main decision item, with arrows indicating depencies in the decision process. ISHII ET AL 90/91.

which order the factors should be considered, but they claim that the designer must resolve the eight factors and select the appropriate process simultaneously. They also claim that the detailed design of the part and the determination of process parameters such as machine size and process conditions come after both the material and process selection. They maintain that process selection depends on these eight factors and that it is only *material* that is dependent on the process selection.

Sigurjónsson

SIGURJÓNSSON 92 and SIGURJÓNSSON 93 present a generic information model for components - GCM, Figure 29. The GCM describes the skeleton of the functional surfaces of the component (how the surfaces and features are arranged in space). He suggests three different types of features for identifying possible production methods for the component:

- *overall features* (blocks, sections, netshape) indicate the use of net-shape processes and are related to the whole workpiece.
- *form features* (slots, holes, keys, surfaces, etc.) indicate the use of secondary processes such as drilling, milling, bending and joining.
- *finishing features* (surface texture, surface roughness, corrosion resistance, etc.) indicate the use of finishing operations such as surface treatment, material treatment etc.

Sigurjónsson suggests the use of this limited set of features for the identification of production methods for a component, where the component is described by the above-mentioned GCM.

Jepsen

JEPSEN 78A and ALTING ET AL 79 suggest the same 9-point plan for selecting production methods, Figure 30. Jepsen draws attention to the interrelation between material, form and production method - and to the fact that a process selection is a combination of these three factors. As can be seen in Figure 30, the starting point is the determination of goals and criteria. Subsequently, useable materials and processes are investigated in order to establish possible combinations.

In the same work a criteria function is presented, see Figure 31. Jepsen defines a criteria function as: an abstract mechanism which functions as a method of assistance for carrying out a collective evaluation of the alternatives presented, with a view to selection. After information has been assembled and criteria functions and fabrication methods respectively have been specified, the final sorting can take place and a selection can be made.

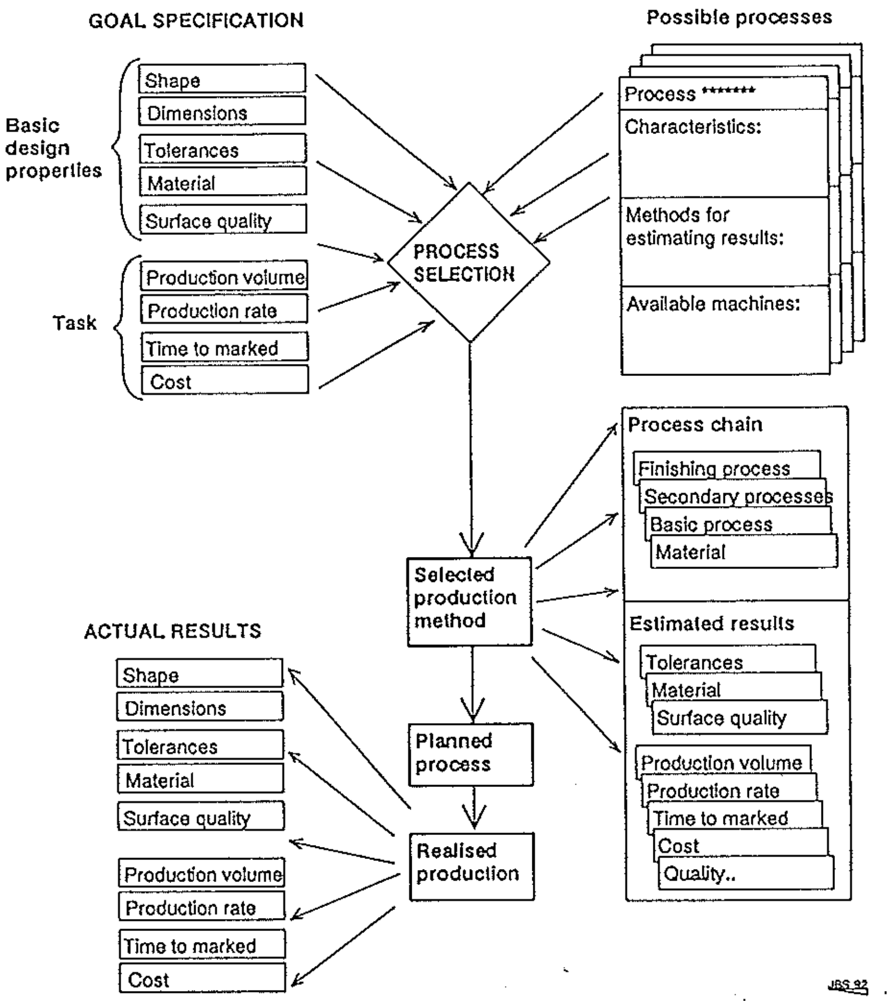

***Figure 29** Sigurjónssons activity model for process selection for components.* SIGURJÓNSSON 92.

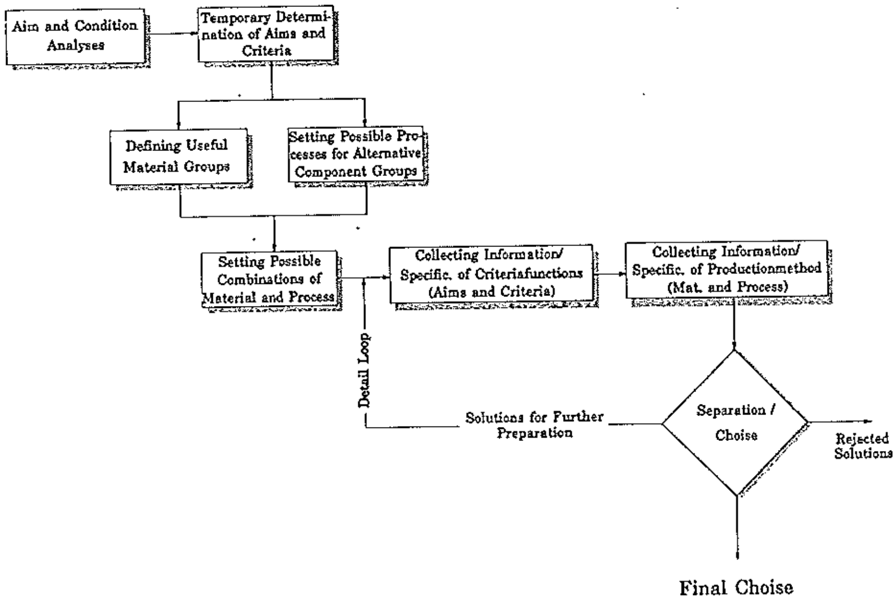

***Figure 30** Jepsens 9 point plan for process selection.* JEPSEN 78A.

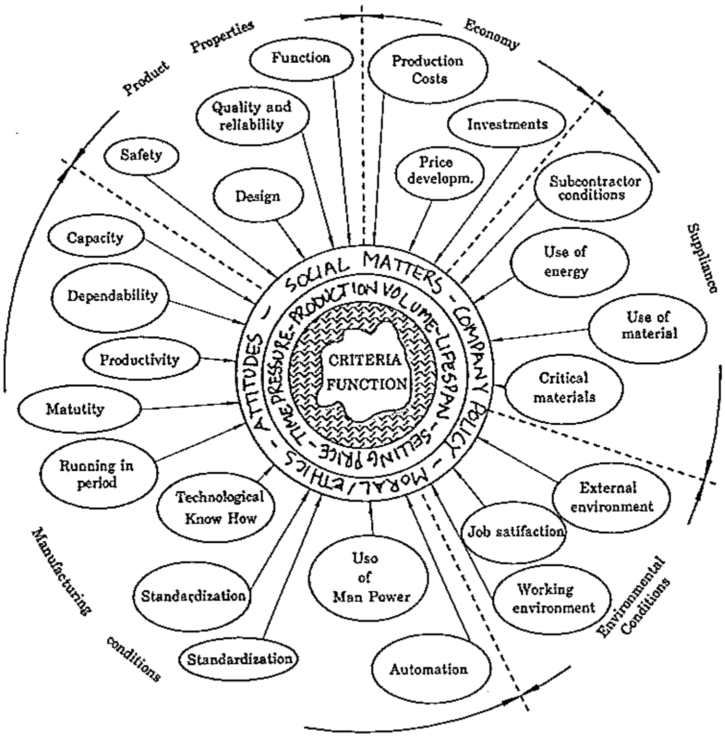

***Figure 31** A criteria function for process selection.* JEPSEN 78A.

Table 2

Size One—Less than One Ounce

Process	Applicable Geometry	Applicable Materials	Minimum Lot Size	Decision Equation for Primary Process
Die Casting	1, 2, 3, 4, 5, 6, 7, 8, 9	2	20,000	$D_t = .0268N + 515$
Investment Casting	1, 2, 3, 4, 5, 6, 7, 8, 9	1, 2	300	$D_t = .3205N + 120$ $D_s = .3043N + 120$
Permanent Mold	1, 2, 3, 4, 5, 6, 7, 8	2	2,000	$D_t = .1955N + 215$
Plaster Mold	1, 2, 3, 4, 5, 6, 7, 8, 9	2	400	$D_t = .2505N + 120$
Shell Mold	1, 2, 3, 4, 5, 6, 7, 8, 9	1, 2	1,000	$D_t = .1475N + 120$ $D_s = .1313N + 120$
Drop Forging	1, 2, 3, 4, 5, 6, 7, 8	1, 2	12,000	$D_t = .0542N + 370$ $D_s = .0350N + 370$
Press Forging	1, 3, 5, 6, 7, 8	1, 2	12,000	$D_t = .0327N + 370$ $D_s = .0338N + 370$
Cold Heading	1, 3	1, 2	20,000	$D_t = .0233N + 265$ $D_s = .0061N + 265$
Extruded Shapes	1, 2, 3, 4, 8	1, 2	1,000	$D_t = .0301N + 140$ $D_s = .0064N + 140$
Impact Extrustion	2, 4, 5, 6	1, 2	15,000	$D_t = .0323N + 260$ $D_s = .0122N + 260$
Roll Formed Shapes	2, 4, 8	1, 2	50,000	$D_t = .0307N + 380$ $D_s = .0077N + 380$
Stampings and Press Formed	5, 6, 7, 8	1, 2	5,000	$D_t = .0342N + 310$ $D_s = .0163N + 310$
Powder Metals	1, 2, 3, 4, 5, 6	1, 2	5,000	$D_t = .0400N + 210$ $D_s = .0150N + 210$
Screw Machine Parts	1, 2, 5	1, 2	5,000	$D_t = .0295N + 95$ $D_s = .0081N + 95$
Electroformed	3, 4, 6, 9	1, 2	100	$D_t = .2124N + 135$ $D_s = .1926N + 135$
Turret Lathe	1, 2, 5	1, 2	500	$D_t = .0967N + 30$ $D_s = .0753N + 30$
Rough Machine from Mill Stock	1, 2, 3, 4, 5, 6, 7, 8	1, 2	10	$D_t = .2017N + 125$ $D_s = .1803N + 125$

***Figure 32** On the basis of the size a table is chosen.* NIEBEL 66.

Niebel

NIEBEL 66 describes an analytical procedure that enables one (industrial engineers, manufacturing engineers, production engineers), in advance of production, to determine the most desirable material, the most desirable basic process, the most desirable secondary operations, and the most appropriate coating. On the basis of the size of the components (8 categories divided according to weight) a table is chosen, as shown in Figure 32 (size one -less than one ounce). The applicable geometry (nine classifications, see Figure 33) applicable materi-

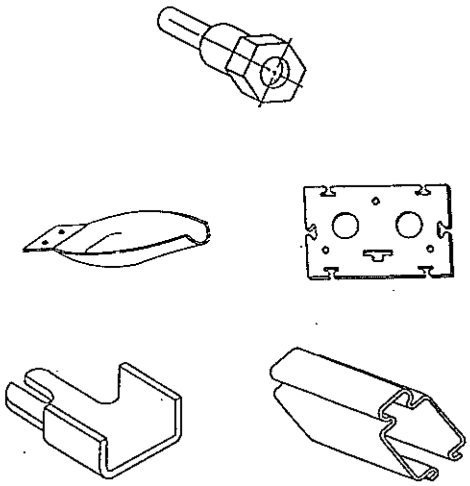

Figure 33 Five examples of Niebels nine geometry classes. NIEBEL 66.

als (four classifications: ferrous, non-ferrous, thermo plastics and thermosetting plastics) minimum lot size (four classifications, 1-10, 10-100, 100-1000, over 1000 pieces) and finally the lowest cost can be calculated from the equation, in Figure 32, where N is the poduction volume, can be read from the table. Tables both for metal processes og plastic processes exist.

3.3 Computer-aided process selection

MADED

MADED (MAnufacturing process Database for Engineering Design) was intended to help the designer with process information needed on a high abstraction level in the design stage. The intention was to establish a so-called "common language" between the design and the process domains. The common language should describe the relation between processes and products on a high abstractual level such as, for instance, on the structural level. But the connection between the product structure and the production parameters was never found and therefore the bridge between the two domains was established by component examples (past designs) in the database. MADED has two different ways of searching for processes (Figure 34), the direct search for processes and the component- based search. *The* *direct search* for processes makes it possible for the designer to find information on specific processes. The information includes: process description, feasable production volumes, batch sizes, pre and post processes, etc. It is also possible for the designer to go the opposite way by entering the system with e.g. a production volume and obtain an output of the suitable processes for this parameter. Currently, powder compaction, aluminium extrusion and pressure die casting are implemented in the system. *The component based search* makes it possible for the designer to find past designs in several design-oriented parameters such as: function, shape, material and process. The functional parameter describes the basic function of the component, e.g. force transmission, cover, hinge, etc. LENAU & KRISTENSEN 92

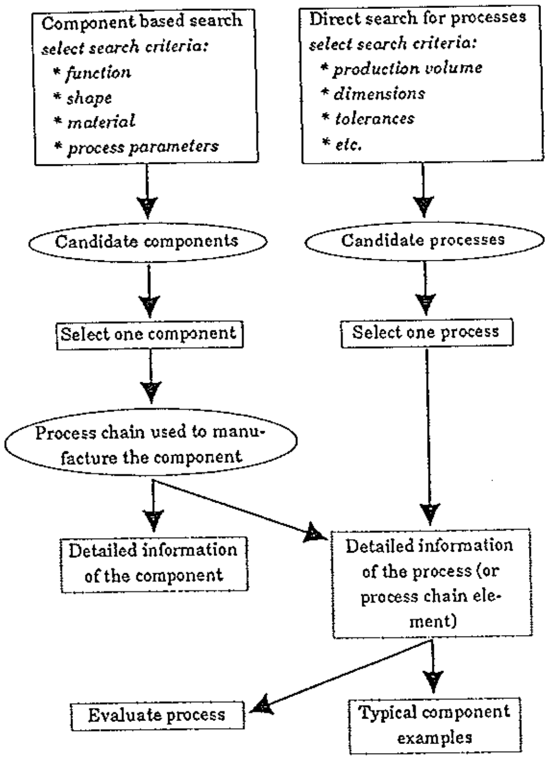

Figure 34 The search procedure in MADED. LENAU & KRISTENSEN 93.

CKB

CKB (Compatibility Knowledge-Base) represents knowledge about design for net shape manufacturing (NSM). There are two methods of using the CKB to help designers. *The first method* is the CCS (Compatibility-based Classification System) which, given the functional requirements of the part and the process constraints, searches through the data bank (CKB) of past designs for a set of candidate designs (characterized by: material selection, geometry and tolerances) which satisfies the user requirements (Load carrying capacity, deflections, size

CCS

restrictions, surface finish, tolerances) and process constraints (Type of process, production quantity, machine capability and process parameters). *The second method* is DCA (Design Compatibility Analysis). This system asks the user to give a full or partial description of the requirements, process constraints and the proposed design; these parameters constitutes a case. The system then determines how well the proposed design satisfies the specifications. The assessment system compares the case with good and bad examples of the past, which are stored in the CCS. The output from the DCA is a justification for its evaluation and also suggestions for redesign of the component. ISHII & NEKKANTI 89

DCA

In YU ET AL 92 a system called DFPS and in ISHII ET AL 90/91, a system called HyperQ/Process is described. These two systems seem to be exactly the same system, although the user interface may have been changed in the DFPS system. Since the systems in principle seem to be exactly alike, only the DFPS system should be described here.

DFPS

DFPS is a process selection system limited to net-shape manufacturing processes (Hot Forging, Cold Forging, Powder Metals, Hot Extrusion, Sand Casting, Investment Casing, Die Casting, Injection Molding and Sheet Forming). DFPS uses the DCA procedure described above. By giving a part design (e.g. material, minimum dimensional tolerances, production volume, and surface finish), the DFPS uses case-based knowledge (CBK) and DCA to screen each process and suggests alternative processes. These alternative processes are ranked by the system. Designers can perform a detailed DCA for a selected process and thereby identify the key factors producing the rating. Subsequently, the designer can redesign the part. YU ET AL 92

MAPS

MAPS (Material And Process Selection) is a system limited to selection between the plastics manufacturing processes: blow moulding, casting, compression moulding, extrusion, structural-foam moulding, injection moulding, lay-up, machining, reaction injection moulding (RIM), rotational moulding, thermoforming and transfer moulding. The process selection is based on part geometry. The system obtains information on part geometry by asking the designer about the existence of features such as ribs, inserts or moulded-in threads, as well as other questions on geometry, such as: "could a die be removed from the inside of the hollow part ?". MAPS evaluates the suitability of the above-mentioned twelve processes and if no suitable process is found, the system makes suggestions for redesign by listing each process and the features which caused it to be eliminated. LOVRICH & TUCKER 86

3.4 Cost calculation of production methods

A certain number of cost calculation methods are described in the literature. Many methods describe single production methods and only a few methods describe several production methods. This section describes only those methods which have been developed for process selection. For a description of methods for the calculation af cost for single production methods refernce is made to Appendix A, where a paper about the subject written by the author and Torben Lenau is reproduced.

	Machining						Rolled profiles	Injection molding					Powder methallurgy			Forgings	Sheet metalworking		Die castings	Castings		Several production methods		
	23	24	25	26	27#1	22#1	27#2	28	29	30	22#2	31	32	22#3	33	34	35	22#4	22#5	27#3	36	37,38	39	40-42
Input parametres																								
Dimensions	●	●		●		●		●	●	●	●	●		●	●	●			●		●	●	●	●
Material		○		●		●	●					●		●	●	●		●	●		●	●	●	●
Shape	●	●		●		●	●	●	●	●	●	●			●	●					●	●	●	●
Surface quality	●			●				●	●	●	●								●			●		●
Tolerance	●			●				●	●	●	●			●					●			●		●
Volume				●							●	●		●	●	●			●		●		●	●
Area											●	●		●		●			●					
Prod. vol./batch size				●		●	●							●							●	●	●	●
Other parametres			●	●		●							●	●	●		●	●	●			●		
Not mentioned					●															●				
Purpose																								
Process selection				○								○			●						●		●	●
Quotations	●						●						○									○		
Variant evaluation				○				●	○							●								
Design for cost	●	●		●	●					●			●		●	●					●	○		
Process planning			●																			●		
Not mentioned						●					●	●		●			●	●	●	●				

Figure 35 A general view of the in literature presented cost calculation methods and their purposes. The numbers are references in the paper. LENAU & HAUDRUM 94

Comparison of all cost calculation methods / systems

All cost calculation methods found in the literature are compared in Figure 35. The figure gives a general view of the input parameters necessary to use the described cost calculation methods. Some specific input parameters used in the methods are mentioned in the figure as *other parameters*. These are generally parameters which are not known by the designer at the stage when the production method is selected, (e.g. number of teeth on the cutter and cooling ability). Some papers have not described the input parameters, these are marked *not mentioned*. The purposes of the described cost calculation methods are

Other parameters

Not mentioned

shown in the figure as: process selection, quotations, variant evaluation, design for cost and process planning. The filled mark (•) indicates the intended purpose of the method when it was developed, and the open mark (o) indicates the author of this thesis's impression of what the methods could be used for.

Several authors have recognized the fact that the selection of production methods in the early phases of design has to be made with the knowledge of very few and quite rough parameters.

Process selection

This is characterized in the cost calculation methods marked *process selection*. The parameters used in these methods are some basic ones: shape, material, dimensions (diameter/width, length, height, wall thickness) and in some cases, tolerances and surface quality. From these basic parameters, other parameters such as: volume, weigth, area etc. can be derived. Basic production parameters are production volume and batch size.

Quotations

The methods marked *quotations* are methods suitable for subcontractors for cost calculations before giving a price to the buyer. In theory, this kind of method could be used for selecting processes as well, but the input parameters are usually parameters known only to production engineers. The quotations made by the subcontractors can naturally be used as a basis for selecting the cheapest production method.

Variant evaluation

Some methods are useable for evaluating different solutions (shapes) within the same production method, these are called *variant evaluation* methods. The methods are relative methods and can only be used for comparing two alternative solutions for the same component. Thus the methods are of no use when different production methods or different structures of the product are evaluated. The relative methods can only be used for the specific process for which they are developed and thus if the component is produced by a production sequence, a relative result for each production method in the sequence is of no value.

Design for cost

The *design for cost* methods have the purpose of helping the designer make cheaper solutions within a given production method. The methods are of two types. The first one where it is possible to calculate cost, change the component and then make another calculation, and thereby obtain cheaper components. The second one where the system interactively tells the designer which features are the more expensive ones, and which changes would make the component cheaper.

Process planning

In the methods dedicated to *process planning,* the calculation makes it possible to select the cheapest route in the production; the cheapest machines and production parameters.

Description of methods / systems which deal with several processes
Only a few papers FERREIRINHA 85, FERREIRINHA 90, ZENGER 93, and ALLEN ET AL 90A, 90B, 91 describe methods where it is possible to calculate and compare cost for different production methods. And only two of these methods (ZENGER 93 AND ALLEN ET AL 90A, 90B, 91) were intended to be used in the early stages of design as a basis for the process selection activity.

Ferreirinha

FERREIRINHA 85 and FERREIRINHA 90 describe how the HKB-system can be used for cost calculation. Included production methods are: turning, milling, casting, welding, forging, sheet metal forming and plastic parts. Inputs to the system are component parameters (shape, dimensions including tolerances, surface quality, heat treatments, quality features) raw material parameters (material, pre-processes, shape, maximun sizes, pretreatments) and production parameters (batch sizes, number of clampings). It is claimed in the papers that the method is useable in the embodiment design phase, but regarding the input parameters, it is unlikely that the system is developed for early estimates and it would be unable to support the designer in the early calculations of production method alternatives.

Zenger

ZENGER 93 presents a system for the comparison of different production methods on the basis of cost. With a few inputs such as: production volume, average batch size, basic part dimensions, volume and simple geometric complexity values, the system is able to present comparable cost analyses for different combinations of material and a production method for a given component, but it is only possible to calculate combinations which are actually realistic. The system includes five different casting processes as well as machining, injection moulding and sheet metal working. The material selection is made by general class such as aluminum, cast iron, copper, zinc, etc. The system is able to give different outputs to the designer: the cost is listed in order of least to most expensive combinations or a curve showing cost per part versus production volume for all combinations. How close the analysis is to the actual production cost is not mentioned.

The programme developed by Zenger is very close to the author of this thesis´s idea of how a cost calculation method for process selection should be formulated. He is aware that the designer has to consider whole process sequences before selecting a solution, although this ability is not implemented in the system yet. The best part of the output is the curves showing cost per part versus production quantity for all investigated process/-material combinations, since these curves make it possible for the designer to see the sensitivity of changing the production volume. On the basis of both the above-mentioned paper and a personal discussion with Dr. Zenger on ICED'93, it seems that all process/material combinations are calculated on the basis of the same component shape, and obviously this means that the shape does not have the same level of producibility for all combinations and therefore that the calculations could be misleading. An important point in this thesis is precisely that the close connection between material, form and process makes it untenable to evaluate the same form in relation to different processes. The only points that can be compared are solutions in which the form is arranged according to one specific process/-material combination.

Allen et al

ALLEN ET AL 90A, 90B, 91 present a technique for evaluating processes in the early stages of design. The papers give an overview of the concept and shows that the predicted costs lie very close (within 16 per cent) to actual costs (for plastic moulded and pressed sheet components). The papers do not describe how the method is used, but a personal meeting with Mr. Allen has clarified the following: The cost is calculated through material cost and process cost, where the process cost is determined using a basic processing cost and a design-dependent relative cost coefficient. The basic cost, derived from the production method, the production volume and the relative cost coefficient, is derived from material-process suitability, shape complexity, tolerances etc. The user does not have to have detailed information about the different processes utilized to produce a component, for example, when evaluating a design, but has only to select the primary process; any secondary processing is automatically accounted in the metrics, and thus the designer has only to select the primary production method and is simply made aware of the fact that it will be necesssary to employ secondary processing for the design in its current form. The method seems to be extremely useful for designers in the selection of production methods.

Boothroyd/Dewhurst

Boothroyd and Dewhurst are represented in the literature by several papers on cost calculation (BOOTHROYD 88, BOOTHROYD &

REYNOLDS, BOOTHROYD & RADOVANOVIC 89, DEWHURST AND BOOTHROYD, DEWHURST & BLUM 89) but since these papers only describe fractions of the calculation methods, they are not described here. Instead, it has been decided to describe their computer system, where all these calculation methods have been realized (BOOTHROYD & DEWHURST). The system for cost calculation includes modules for five different production methods: metal sheetworking, injection moulding, die casting, powder methallurgy and machining. Although Boothroyd and Dewhurst in their papers often mention that their cost calculation methods are intended to be used at the early stages, it seems that most of the modules included in the cost calculation programme could not be used at the level before the selection of production methods. The machining and the die casting module, however, seem to be useable for this purpose.

3.5 Summary

Bridging design and manufacture/production

In the literature, some attempts have been made to describe the interrelation between design and manufacture/production (PETERSEN 92, ANDREASEN 91). Both contributions take their starting point in the design degrees of freedom in the design domain and try to set up corresponding parameters in the production domain.

Procedures and process selection models

JEPSEN 78, NIEBEL 66 and VALUE CONTROL DESIGN GUIDE 63 are methods for process selection. Jepsen describes how the designer should act to consider different fabrication possibilities. Moreover, the Value Control Design Guide describes how to select a process for a (given) component. It is not quite clear from NIEBEL 66 what the procedure can be utilized for, but Niebel states that it in general should be used by production engineers. It is, however, a method which can certainly be used as a form of inspiration in this work.

The weak point of these procedures is that they are not based on a design theory or methodology. To be useful and reliable, a procedure must be compatible with a design methodology.

ISHII ET AL 90, ISHII ET AL 90/91, YU ET AL 92 describe process selection parameters interaction, and not really how process selection should be carried out. SIGURJÓNSSON 92, 93 suggests that the possible production methods for producing a component can be identified through the arrangement of the functional surfaces in space (skeleton) and a limited set of features (overall features, form features and finishing features).

Process selection systems
Among the above-mentioned computer system, only DFPS can be classified as a genuine process selection system. MADED and MAPS can be classified as process information systems. Where MADED and MAPS are limited to process suggestions, DFPS is able to rank the suggested processes, and thus DFPS is actually the only system supporting the activity process selection. The five process selection activities mentioned in Chapter 1 are supported by the following: *Process search* by MAPS, MADED and CKB, *Process considerations* by MADED and CKB. *Process evaluation* by DFPS and Value Control Design Guide, *Process selection* by DFPS and *Process detailing* by MAPS, CKB and DFPS. Most systems do not include process chains but focus on single processes, although it is often necessary to use pre and post processes to fabricate a component (in MADED the past design informations includes process chains)

Cost calculation methods / systems
As can be seen from Figure 35, only a few methods/systems deal with several production methods and can consequently be directly utilized for process selection. The methods/systems which have been developed to support the designer in process selection (ALLEN ET AL 90A, 90B, 91 and ZENGER 93) have each some good individual features, for example, Zenger's system can show cost curves for different material/process combinations (unfortunately only for the same shape) and they both take complete process chains into consideration (Zenger's has not yet been implemented, however). In BOOTHROYD & DEWHURST's software package, the input parameters for most production methods are so detailed that the programme can not be used by the designer for cost calculation before the process selection.

3.6 Conclusion

After a review of the literature, the following conclusions can be reached:

- The procedures (VALUE CONTROL DESIGN GUIDE 63, NIEBEL 66, JEPSEN 78) described in the literature are not based on a design methodology.

- The works which deal with theoretical models for process selection (SIGURJÓNSSON 92, PETERSEN 92) do not describe how the processes should be considered and selected.
- All studies deal with process selection at component level.
- Most studies deal only with main processes and only a few with entire process chains (SIGURJÓNSSON 92, LENAU & KRISTENSEN 92, ZENGER 93) and, of these, none describes how process chains can be arranged.
- There are concepts for cost calculation methods, but none of them are completely satisfactory.

These points mean that the author can legitimately engage in the task of developing a procedure to support the designer in the systematic consideration and selection of production methods (main process as well as entire process chains), a procedure which is coupled to all levels (and not just component design level) of Pahl & Beitz´s design methodology. At the same time, there is a gap in the literature on the designer's need for information in his consideration and selection process.

There is also a case for developing a better concept for a cost calculation method/system. A good starting point for such a concept is to utilize the best points from both (ALLEN 90A, 90B, 91 and ZENGER 93) and to further improve the weak points inherent in both these systems (see discussion on this in the reproduced paper in appendix A).

CASE 1 - PARTICIPATING IN A PRODUCT DEVELOPMENT PROJECT IN A COMPANY

4

This chapter describes one of two field studies which were carried out during the research work to verify the first 8 of the 11 working hypotheses described in Chapter 1. The chapter describes the actual company and the component examples which were analysed in connection with the project. The author, through participation in a product development project in the company expected to achieve the following:

- Gain an insight into the problems involved in process selection in the design phase.
- Gain experience in the collection of empirical data through field studies.
- Verify the first 8 working hypotheses.
- Form the basis for the final problem definition and delimination of the research work.

4.1 The company and its products

The company

A/S KEW Industry

The first case was carried out at the Danish company A/S KEW Industry. The company turnover in 1990 was 472 million DKK. The company has 4-500 employees (in Denmark) depending on the season. A/S KEW Industry develops, manufactures and markets high pressure cleaners, industrial washing systems, carpet cleaners, vacuum cleaners (wet and dry) and cleansers. It develops and designs the majority of the components contained in the products, and the components are subsequently produced by subcontractors and are delivered to the company as either semi-manufactured or finished articles. The company works up purchased semi-manufactured components. The assembly of the components into products is carried out internally in the company.

Product development

Today

Today the product development is carried out as integrated activities, where experts from different domains are working in project teams during the design and manufacturing of the new product. This has been characterising product development for the last couple of years, but one does not have to go many years back in the past to find quite a different way of developing new products.

Previously

Previously, product development was carried out in a separate building with a code lock on the door. The activities in this building were extremely confidential and only the designers were allowed to enter the building. When the product was designed and the drawings were finished, they were delivered to the manufacturing department, where they could then start designing the manufacturing equipment and finally start producing the product. This created major problems, since the designers had only little knowledge of how to design a producible product, and when the product reached the manufacturing domain with this kind of knowledge, only minor details of the product could be changed.

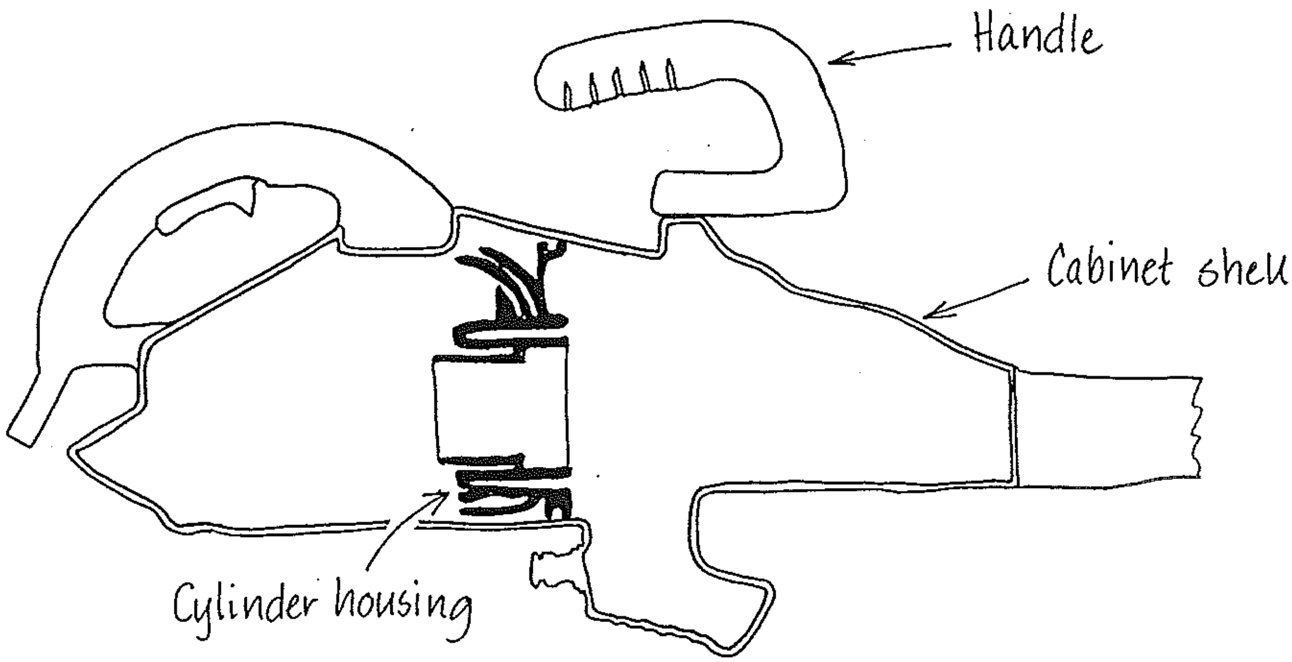

Figure 36 *The hobby cleaner of which a number of components were analysed according to the process selections made. The specific components are shown.*

The products

Hobby cleaners

The company distinguishes between high-pressure cleaners for professional and for privat use (hobby cleaners). The development of these two types is carried out by separate design departments, just as the assembly is carried out in separate factories. In the field study, the author participated in the development of a new hobby cleaner, see figure 36.

The department

The department for the development of hobby cleaners has the following staff: one head of department (engineer) and five designers (of which four were working full time on the project) three technical assistants and two manufacturing engineers. The department has a prototype workshop with a mechanic at its disposal.

4.2 Component examples

It would be unmanageable to describe how the selection of production methods was carried out for all the parts in the hobby cleaner and therefore only certain specific parts were selected. The parts were selected so that the following parameters were represented:

- Different materials
- Different production methods
- Different designers

This resulted in the selection of the following parts:

- Cylinder housing, which is a part of the pump.
- Cabinet shells, which are the housing of the machine.
- A handle for carrying the machine.

Beside these three parts, a number of other parts are described in the following sections.

Cylinder housing

Both *material and production method* were selected on the basis of the existing experience with pumps in the company. No other materials than aluminium and no other production methods than die casting were considered (except for the post production methods which the part undergoes after die casting). The selection of die casted aluminium has obviously a very close relation to a pump; experience and tradition in the company makes this solution "a natural thing". The lack of time because of a fixed deadline for introducing the product on the market is perhaps the essential reason that no alternatives were considered. Injection moulding was considered by the designer later in the design phase, because the die cast shape reminded him of an injection moulded component, but at this time it was too late, and even if plastic had been considered earlier in the design phase, it would have been too risky to actually use it. Furthermore, testing the material would have been too time-consuming. *The shape* was determined from the functional demands, the demands inherent in the production method and in the shared surface with the adjoining parts.

Comments Material and process selection are extremely tied up with the traditions of the company, just as the solution selected was known in advance, since it had been utilized in previous products. It is difficult to decide *who* chose the material, production method and solution. In order to demonstrate the fact that it is worth considering alternative production methods, the author examined the question of which other production methods were possible when it was assumed that the material was aluminium. The only ones that could be considered were forging and powder methallurgy. This would naturally have demanded changes in the forming of the component so the question was if it would be at all possible to select another process without also having to change the adjoining components. This shows that if alternative manufacturing processes are to be considered, this must occur before the component's final form and material are determined.

Cabinet shells

The industrial designer gave the shells their outer shape. The designer who took over after the industrial designer, explains that from the very beginning, it was "a matter of course" that the part should be injection-moulded plastics, and that no alternatives were considered. The selection of plastics was explained because the housing should be electrical and heat insulating and because it should have an "advanced" shape. It was also determined very early on that the shells should consist of two parts, since the machine had to provide the possibility for service.

Handle
The starting point for the designer was a sketch made by the industrial designer. The sketch described only the contours of the handle. Before the industrial designer selected the contour, the selection of the material had already been made. It is difficult to point out who actually selected the material, and in fact perhaps no one individual person did. No alternatives were considered. As a consequence of the selected material it was "natural" to select injection moulding.

At this stage of design, another designer took over the task of finishing the component. By accident, he saw the air-injection moulding process (CIN-press) being used for a component elsewhere in the company, and he got the idea that the handle could be produced by this process. After a meeting with a contractor, the air-injection moulding method was selected, as it became clear that there were several advantages to be gained from selecting this process compared to injection moulding. These advantages included:

- No sink marks would appear on the surface
- Rigidity would be better
- Price per part would be the same
- Design time would be halved
- Time spent designing for this process would never be wasted, since at any time, without any extra work, one could go back to injection moulding.

Three alternative processes to injection moulding were considered; air-injection moulding, gas counter-pressure moulding and sandwich-moulding. From these three, air-injection moulding was selected, because it would result in a component with the lowest weight. Using gas counter-pressure moulding, the component would become solid, and using sandwich-moulding, the cavity inside the handle would be filled with foam. After one meeting with the contractor, the designer was able to complete the design of the part.

Comments The example shows that the production method and the material were 'given in advance', and that it was only by accident that a more optimum process was considered. The designer would, in this situation, have benefited from a systematic consideration and comparison of alternative production methods.

Bearing disc

The *basic form* was taken direct from existing pumps. The chosen *material* was sintered steel. As regards other materials, ceramics was considered, but only briefly, as the cost is extremely high. The chosen *process* was powder methallurgy. As regards other processes, punching and turning were considered. The turning process would have involved hardening and grinding, while powder methallurgy should hopefully not have to undergo a finishing process. Uncertainty as to feasible objective and form tolerances with punching caused this production method to be rejected. It later turned out that form tolerance can probably not be observed with the chosen production method.

Comments The form was inspired by a competitive product. This means that the basic form was established very early on. The material was apparently chosen on the basis of an expected burden on the disc, which meant that only a few possible materials could be considered. The price was a decisive factor in the selection of material and production method from within the possible alternatives considered.

Planet gear

The idea for the planet gear came from a competitive product, one of which features was a bronze sleeve, and it was consequently expected that a bronze sleeve was necessary. There was, however, a possibility that the bronze sleeve could be avoided by making the planet gear and the sleeve in the same material. The designer was not entirely sure about this and contacted two plastics suppliers, of whom one thought that the solution was possible while the other thought not. Subsequently, experiments were carried out and it became evident that the plastic material melted, whereupon it was decided to keep the two components. One of these was recommended by one of the suppliers to be of POM, while the other was still to be of sintered bronze. POM was later changed to PBT in order to gain chemical constancy against oil.

Comments. The selection of form was essentially taken from a competitive product. The starting point for the *selection of material* was the competitive product. Recommendations from the supplier as well as experiments decided the material. *The selection of process* was a consequence of the selection of material. The planet gear is an example showing that material and process can be radically changed by integrating two components into one or the opposite (disintegrating).

4.3 Summary of how process selection is carried out in the company

The examples described above, as well as further observations made in this Case 1, can be summarized in the following main points:

- Process selection in product development *is carried out by the designer* or by "nobody".
- Only a few (usually only one) production methods are considered before a final selection is made.
- *The selection* is made from among production methods with which the designer is familiar, even when other production methods are possible. Other production methods are perhaps not even considered, and even when they are considered, there is still a tendency to select a familiar production method (subjective criteria are employed).
- The process selection is generally a "natural selection" either in connection with material or based on tradition in the company.
- The so-called natural selection is not always the best selection.
- Alternative production methods must be considered early on, before linkages with adjoining components make an alternative selection Utopean.
- Alternative production methods must be considered early on before the form of components and material make alternative process selections impossible.
- Alternative production methods are discovered "by accident" and not through systematic consideration of the different possibilities.
- In some cases, functional demands on the component (e.g. strength) mean extremely limited possibilities for alternative materials and consequently for production methods.
- Components must sometimes be integrated or disintegrated in order to make possible the selection of alternative production methods.
- The material is usually chosen first and subsequently, only one production method can be considered. For example, for aluminium, the production method is pressure die casting and for plastics, the production method is injection moulding etc.

- Alternative materials and consequent processes will often involve too great risks, since there is no time for a thorough examination of these materials and/or production methods.

4.4 Conclusions

In relation to the hypotheses

Hypotheses 1-5

With a starting point in Case 1, it must be concluded that the method of process selection carried out at A/S KEW Industry confirms hypotheses 1-5. With regard to hypothesis 4, it can be mentioned that in only one case, namely in the case of the handle, a more optimum production method was discovered, but this is probably due to the fact that an alternative production method was considered before the final form was established. With regard to most of the other components, the form and material were already determined before the author appeared on the scene, so it was therefore impossible for the author to influence the designer to look for alternative production methods. Another argument for this is that the author attempted to affect the "objective results" as little as possible by his presence.

Hypotheses 6-8

Hypotheses 6-8 were not confirmed, but this is most probably due to the fact that the author was not involved in the project at the time the production methods were to be considered and selected (see below under evaluation of participant method).

Risk and deadlines

The designer kept to the traditional production methods previously utilized in the company. It turned out that one of the reasons for this was combined time pressure and uncertainty as to the efficiency of alternative production methods, which would involve great risks should they be chosen. If one wishes to include new manufacturing possibilities, it is consequently necessary, simultaneously and parallel with the development project, to carry out research projects, which systematically examine the market for interesting production methods, testing them with different objectives in connection with the company's products. Development projects must be capable of exploiting knowledge from these research projects, so that production principles are known and solutions tested before they are built into the product.

Research projects

Participant method

In principle, the author participated in the roll of designer and, through this, gained a sound insight into the company and the development process. Participation as a method also gave a good insight into the existing problems and, at the same time, a great deal of inspiration to build upon. It was, however, difficult to be active as a designer while at the same time attempting to have the necessary overview to concentrate on the research project, and it must be admitted that that part of the data collected which could be directly utilized, was not commensurate with the amount of time spent.

Process specialist

On the background of these conclusions, it was agreed with the Chief Engineer of the department concerned, that the author should participate instead (in a new product development project) as a "process specialist", where the task would be, in the course of the product development, to take on the roll of the person who would examine the possibilities for alternative production methods. This would provide a good basis for the development of a procedure/process information model for the designer, which ensured that he sytematically considered the relevant production methods for the component. This project was never carried through in the company, so participation was naturally impossible.

When the author came into the project, it was already in its realization phase and there were only a few components where the process selection had not yet been decided upon. The collection of data regarding the components described, was therefore primarily carried out through interviews and not through the author's personal participation. This factor can partly explain the relative paucity in result in comparison with the amount of time spent.

CASE 2 - VIDEO TAPING OF DESIGNERS SOLVING A DESIGN PROBLEM

5

After Case 1 had been carried out at A/S KEW Industry, the conclusion was that participation gave a good insight into the problems as well as inspiration for further work, e.g. asking the right questions in more structured interviews in other companies. But, at the same time, it was also concluded that the amount of directly useable data was not commensurate with the amount of time spent. A decision was consequently reached to find new methods to find out how designers consider and select production methods. The selected method was video-taping. This chapter describes a pilot project of the video-taping of designers solving a design problem, including a description of the design task which was solved, the procedure for implementation and how the video-tapings were analyzed. At the end of the chapter, a discussion of the results is given, as well as an evaluation of video-taping as a method of examining the ways in which designers solve problems, with particular reference to the selection of production methods.

Choice of method

The literature was reviewed in order to find descriptions of different empirical methods, see Appendix D, where the results of the study of the literature are described. After having considered these empirical methods, three suitable methods, from among which a choice could be made, remained, namely: interviews, the examination of questionnaires and video-taping. The disadvantages of questionnaires and interviews were estimated as excessive, since the insight into the problems inherent in the selection of production methods at this point in the project was not sufficiently deep to formulate a questionnaire and because, all things considered, more genuine data could be collected by utilizing a concurrent method such as video-taping instead of a retrospective method. In consequence, vieo-taping was chosen.

Video-taping is not often used in the field of engineering science, although there are a couple of examples in EHRLENSPIEL & DYLLA 91 and KUFFNER & ULLMANN 90. In both cases video-taping is used to observe and map the way designers move along in the development of a product.

A pilot project
In order that the method could be exploited with professional designers, a pilot project had to be implemented. The pilot project should be used to find a suitable design problem, as well as to develop a procedure for the implementation and analysis of the experiments. It was decided that some students should be the subjects of the pilot project. These persons were selected prior to the selection of professional designers because the method had to be developed, and it would be better to test it on students first and then afterwards use the completely developed method on professional designers, who would be the actors in a real situation.

Choise of agents

The objective of Case 2
The objective of Case 2 was to verify those working hypotheses which could be verified by means of video-taping, namely HY1-HY7 and furthermore to determine:

- Which parameters initiate the process considerations.
- Which criteria are decisive for the process selection.

The experiment has been described in detail in the report, "Ten studies of how Process Selection is carried out in the stage of Design - A Pilot Project" by HAUDRUM & MORTENSEN 93.

5.1 The problem to be solved in the video-taping

The actors should solve a problem in product development. The problem should be worked out in such a way that the actors would be forced to consider production methods. The problem should be possible to solve for inexperienced designers yet not be too trivial for experienced designers, and it should be possible to solve it within a time limit of approximately 2-3 hours.

Demands

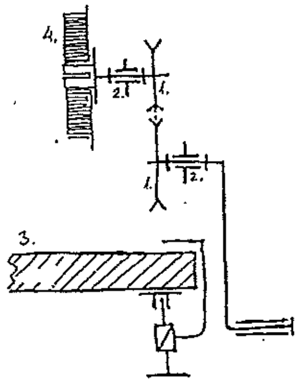

Figure 37 *A principle sketch of the tape winder.*

The problem chosen

The problem chosen for this purpose was: to design the frame for an instrument for winding punched paper tape for NC-machines. The instrument is manually operated and is used for winding up the punched paper tape after it has been read into the reader of the NC-machine. The instrument, shown as a principle sketch in Figure 37, consists of one handle, two grooved pulleys, one V-belt, one winding wheel and one frame, of which only the frame should be designed, the other parts having already been designed in advance. These could, however, be placed differently than suggested, if the designers found it more optimum to structure the parts differently.

The designers were free to change the concept as long as the instrument fulfilled the following requirements:

- The expenses for the instrument including production and assembly must be as low as possible and the end user price must not exceed 500 DKK.
- It must not be possible to trap one's fingers in the mechanical parts.
- It must be capable of use by both left and right handed persons.
- The life span should be at least 3 years.

and the following properties:

- Low noise
- No sharp edges
- The instrument must appear robust.

The designers were asked to describe and give their reasons for the solution selected in the case that the instrument were produced in batches of 100.000 pieces per year over a period of three years. They were informed that the company had no internal production equipment and that they were free to select among all imaginable production methods.

The chosen solution should be drawn as a dimensional sketch to describe how the frame was to be produced and assembled.

5.2 The procedure of the video-taping

This section describes how the video-taping was carried out, how the designers were selected and how the video-taping was set up and executed.

The agents

The number of agents in each video taping was fixed at 2. This was done to make it more natural for the agents to speak their thoughts aloud. All video tapings except team 8 consisted of 2 persons. Team 8 consisted of only one person. The persons participating in the video-taping were final year students, Ph.D. students or unemployed engineers who had not yet found their first job.

Questionnaire

To find the right persons for the video-taping, a questionnaire was sent out to all final year students at the Institute of Manufacturing Engineering and the Institute for Engineering Design (TUD). The intention of the questionnaire was to determine the potential agent's knowledge of production methods. The persons were told that they should imagine themself in the role of an engineering designer and that they should design a part for a given production method. With this in mind, they had to fill in their knowledge about a number of specific production methods. The possible answers were: *familiar with*, *knowledge of* or *without any knowledge of*.

In the questionnaire, they were also asked which courses they had participated in at the two institutes. None of the students from the Institute for Engineering Design wanted to participate, but the questionnaire showed that many of the students from the Institute of Manufacturing Engineering had knowledge of the design techniques taught by the Institute of Engineering Design, and thereforee could fulfil the requirements necessary for the video-taping.

The set-up

The equipment

The equipment applied to the studies was a Panasonic video camera with a 9-54 mm zoom lens and a Panasonic video recorder. The agents were given paper, soft pencils, rulers and compasses but no books.

The set up

As shown in Figure 38, the two agents were placed at a table and only they and the cameraman were present in the room. The camera was placed about 1.5 m from the table. This distance made it possible to obtain a full figure picture of both agents together and to zoom sufficiently close to the table that the texts and drawings became entirely visible. The two chief analysts would sit outside the room and follow the video taping intensively on a monitor. During the video taping, they made notes on what questions they should ask the agents afterwards.

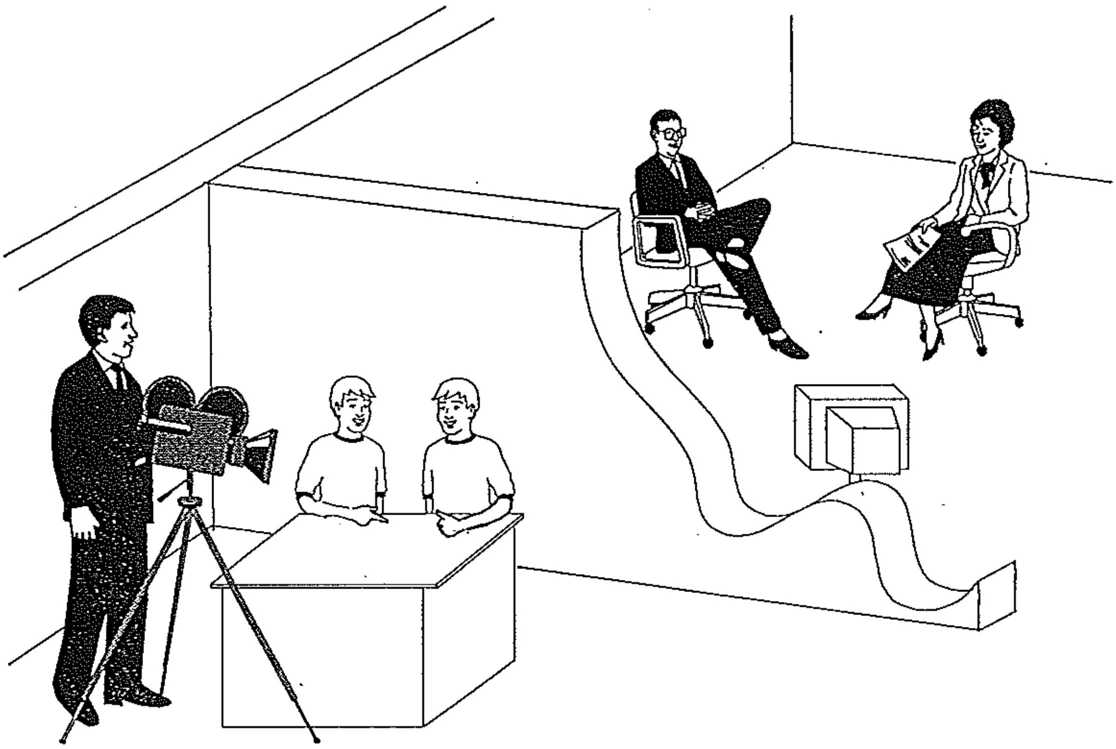

Figure 38 *The agents were placed in one room and only the camera man was present. The chief analysts were placed in an adjoining room where they could watch the play on a monitor.*

Execution
The agents were given a short briefing about what the video-taping was all about, without telling them the purpose of the study. They were told that they should speak their thoughts openly, including any ideas that seemed stupid or irrelevant. After this briefing, they were presented with the problem to solve and they were allowed to read it through.

After solving the problem, the agents were interviewed about general matters, such as: how they felt about the camera/-cameraman, if they had thought of any processes that were not spoken aloud, etc. Moreover, they were also asked to enlarge upon some of the actions that were not clearly comprehensible to the chief analysts. The agents who had not answered the questionnaire at that point were asked to do so and they were all asked to rate the processes of which they had ticked off in the category "familiar with".

5.3 Analyzing the video-taping

This section describes what was done to analyze the accomplished video-taping. For each team a journal, containing a description of the procedure, a summary of the procedure and a general overview of their valuation and selection of materials and production methods, was written.

The journals
The video tapes were viewed and the procedures were typed in detail. A great many of the sentences spoken aloud were typed. Perhaps this seems too laborious, but it proved to be worthwhile, since the word-for-word quotations were needed for the analysis and since it was much more convenient to read through the journal than to find the right place on the tape.

Description of the procedures of the agents
The procedure is not so important for this survey, but it is necessary to give the total picture of each video-taping and therefore the procedures in the video-taping were described. This was done to provide the journal with a more readable format.

Summary of the procedures of the agents
Conceptions

The procedures were summarized, and this proved to be one of the more difficult parts of the analysis. The problem was to determine *what* happened and *when* it happened. To determine and describe *what* happened, one needs to have some specific knowledge of the actions carried out by the agents. It turned out to be extremely difficult to define some conceptions that covered exactly what happened. Should one for instance call it *material selection* when they selected *metal* or *aluminium*, or was it material selection when they selected a *specific alloy*? Was it *process considerations* when they listed seven different processes in a brainstorming or was it process considerations when they discussed what possibilities they had by extrusion.

Selection

Considerations

In this study *selection* describes selection on all levels, which means that both the selection of a specific alloy and more general conceptions such as metal, are regarded as *material selection*. Likewise, the selection of casting or pressure die casting is regarded as *process selection*. There is also no distinction between listing a number of processes and discussing the properties of a specific process, since both activities are named *process considerations*. Another problem was to determine *when* the selection was actually carried out. Often the selection was not spoken aloud, but the conversation showed that the selection had been made. One could also discuss whether a material had been selected when they had reduced the number of possible materials to three.

A set of conceptions

On the other hand, one has to have a terminology to describe the procedure, otherwise one has no possibility of comparing the

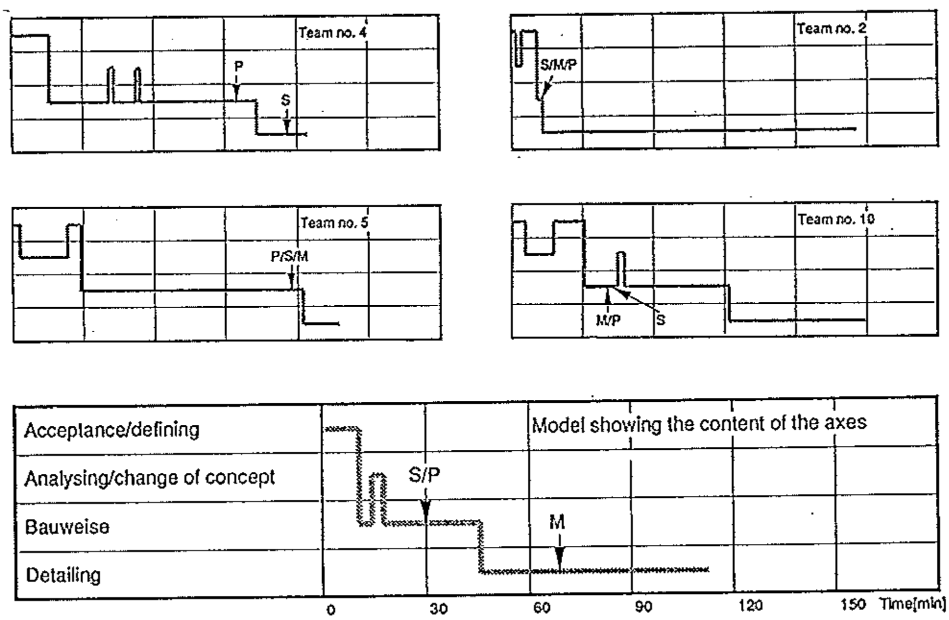

Figure 39 *The solving of the problem passes on on different levels of abstraction. The purpose of the lower figure is only to show the contents of the axes.*

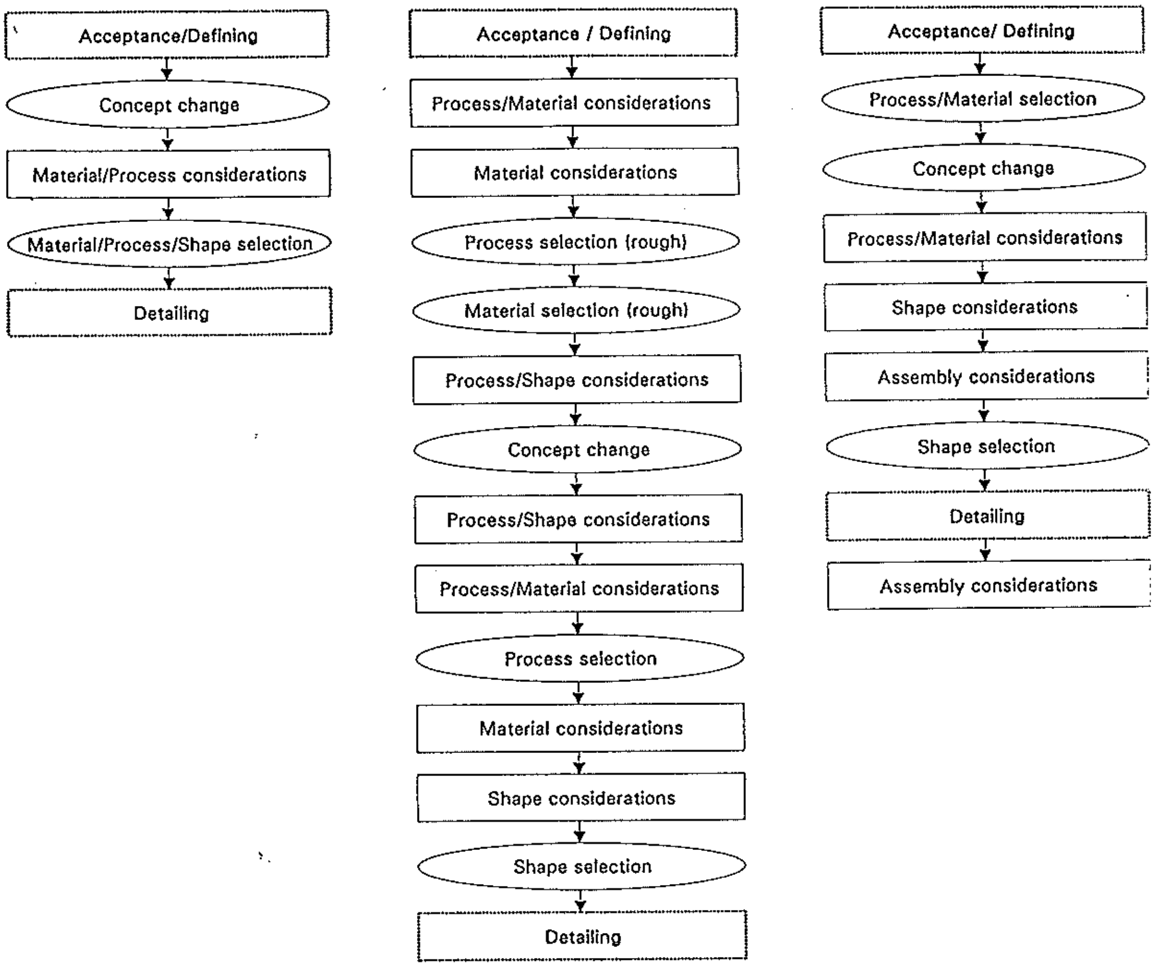

Figure 40 The different procedures for 3 teams.

teams. Thus, a set of conceptions was defined and the procedure of the agents could be described. Two types of descriptions were made. The first described the conceptual levels on which the teams were solving the problem. Figure 39 shows how the conceptual levels were depicted as a function of time for 4 teams. The points where process (P), material (M) and shape (S) were selected were marked on the figure. The second type showed in which order activities such as process selection and material considerations were carried out. Figure 40 shows three examples of these descriptions.

Evaluation and selection of materials and production methods
The processes and materials considered and selected were listed for each team. The comments and arguments connected with the consideration and selection were grouped under each process and material as well as the reasons why the process/material was selected or rejected. An example from one of the teams:

> *Turning/milling was discarded* because of the great waste of material and the number of operations.
> »I don't believe in turning or milling by this production volume« »It will probably be too expensive, you would have to scrap too much material« »Too many operations« »As little machining and assembly as possible«.

One can see that the first line is the researcher's allegation of why they did as they did and the quotations are meant to support the statement.

5.4 Results

This section describes the results of the study. The results are described as pure facts and the author's discussion of the results is presented in Section 5.5. The way the results are presented is a part of the developed method.

Procedures

As mentioned in Section 5.3, the procedures were described with selected conceptions. Figure 40 shows three examples of the procedures. As one can see, they differ greatly. The fact that the procedures are different is representative for all the teams. Some teams considered concepts before they considered and selected process, other teams considered material and process first and then later changed the concept; some because the chosen process made demands on the concept. Some did not change the concept and some did not select material etc.

Considered and selected materials and processes

Since process and material are closely connected, one should not study the process selection without also looking at material selection. Consequently, material considerations and selections are also dealt with in this section.

Figure 41 shows a general view of the processes that the teams considered and selected. Figure 43 shows the frequency of considered and selected processes. As one can see, injection moulding was the most considered (9 teams) and selected process (5 teams). Injection moulding is the only process that more than one team selected. Other processes selected were bending, extrusion, punching and pressure die casting.
One should notice that, even though there are ten selected processes in the figure, the selected processes do not represent

	Team no.									
	1	2	3	4	5	6	7	8	9	10
Extrusion(metals)			*	*	(*)	*)		*		
Forging				*			*	*	*	
Rolling										
Powder compaction				*	*	*			*	
Deep drawing			*							
Pressure die casting	*			(*)		*)	*			
Casting	*		*	*	*			*	*	
Thermo form molding						*	*			
Injection molding	(*)	*	(*)	*	*	*)	(*)		(*)	(*)
Insert molding			*						*	
Outsert molding									*	
Blow molding				*						
Extrusion (plastics)				*	*			(*)		
Die casting							*			
Drilling					*	*				
Milling				*						
Turning				*						
Bending	*	(*)	*	*	*	*	*	*		*
Punching		(*)		*	*					
Welding			*		*			*		
Glueing										
Soldering										
Machining					*		*			

Figure 41 *General view of the processes the teams considered [*] and selected [(*)].*

	Team no.									
	1	2	3	4	5	6	7	8	9	10
Metals			*		*					
Steel	*		*		*		*			
Cast iron	*			*						
Iron				*						
Sheet metal		*		*						
Zink	*			*				*		
Aluminium	*		*	*	*	*)	*	*		
Zirkonia	*									
Titanium					*					
Magnesium								*		
Silumin					*					
Plastics	(*)	*	*	*	*	*)	(*)	*	*	*
Nylon (PA)			(*)				*	*	(*)	
Polycarbonat (PC)					*			(*)		
Polystyrene (PS)					*					(*)
Polyethylen (PE/PEHD)			(*)		*					
ABS								*		
Acryl										*
Reinforced plastics			*							
Rubber		(*)		*	*					
Gypsum					*					
Wood	*			*	*					
Concrete	*									
Carbon fiber/glass fiber	*			*						
Ceramics				*						

Figure 42 *General view of the materials the teams have considered [*] and selected [(*)].*

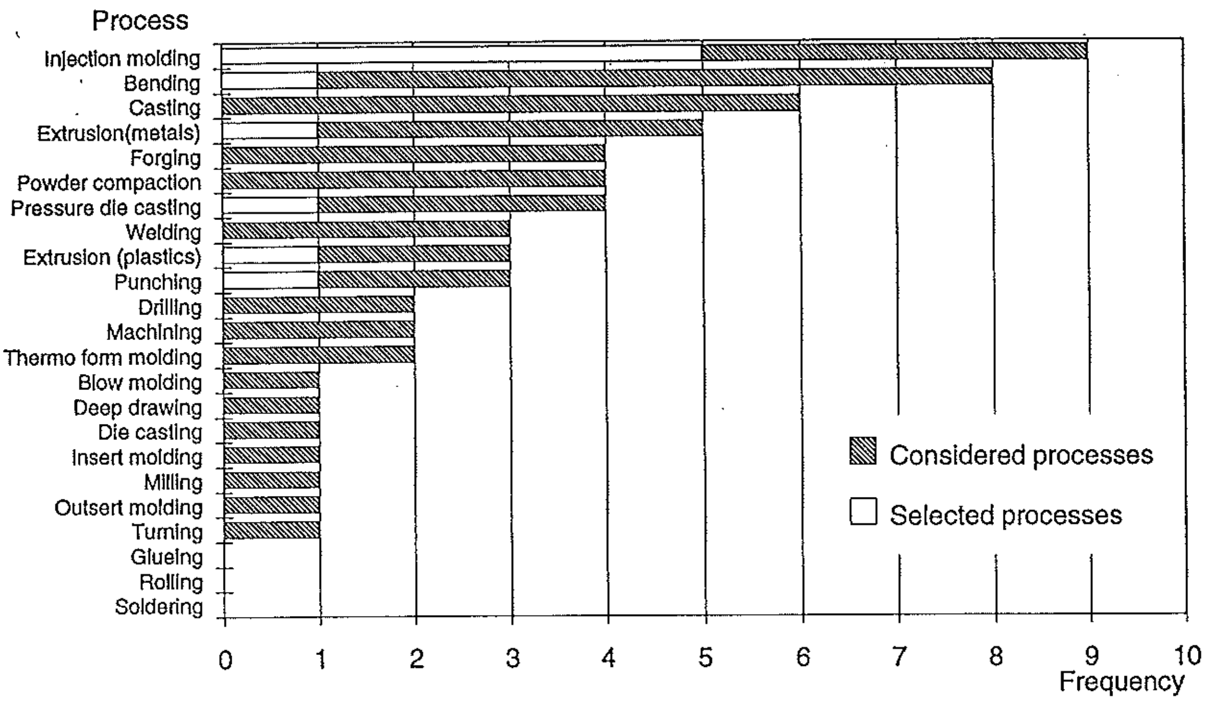

Figure 43 *The frequency of the considered and selected processes.*

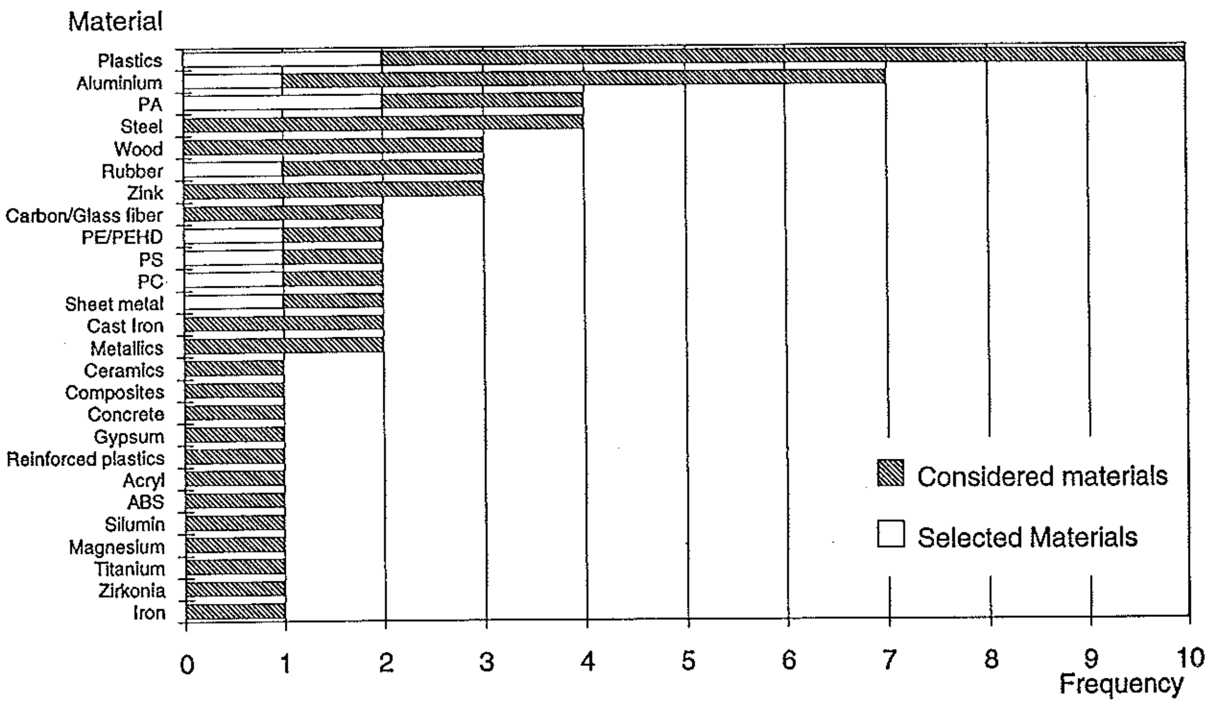

Figure 44 *The frequency of the considered and selected materials.*

one team each, since one team selected bending and punching and another did not select any process at all.
Figure 42 shows a general view over the considered and selected materials. Figure 44 shows the frequency of considered and selected materials. As one can see, plastics were considered by all teams but only three teams selected plastics. The reason for this low number is that some teams went to a lower level and selected what *kind* of plastic they wanted. These numbers are represented by PA, PC, PS etc. Altogether 6 teams selected plastics and it is the only material that more than one team selected. Other materials selected were aluminium, sheet metal and rubber.

Figure 45 shows the number of considered processes and materials for each team. One can see, that the number of considered *processes* varies from 2 to 11 and that the number of considered *materials* varies from 2 to 12.

The questions asked

The questions that the teams asked during the procedure have been listed and grouped under the headings shown in Figure 46. The questions were not all *spoken aloud* as questions, but could as well have been spoken aloud as comments like:

»Our knowledge of the process (powder compaction) is very limited« or
»Plastics, probably hasn't got the strength«

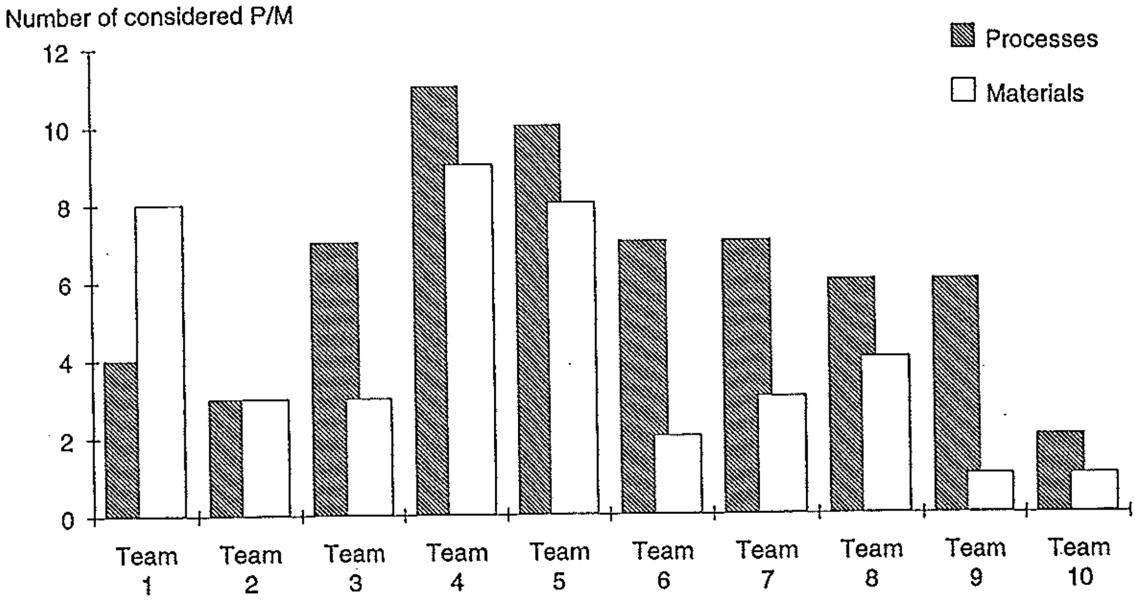

Figure 45 The number of processes and materials considered by the teams.

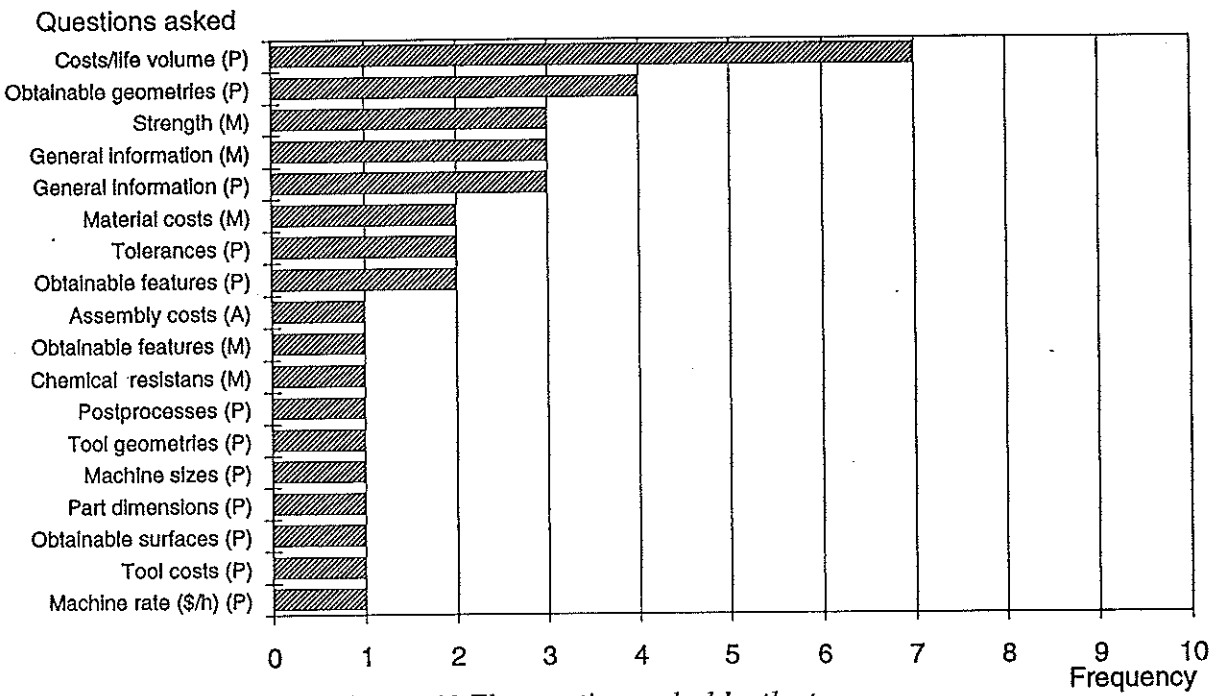

Figure 46 The questions asked by the teams.

These questions were listed to give an impression of what kind of information the designer needs to select between the considered processes. As one can see the most common question is about costs and production volume.

No experience

5.5 Discussion of the developed method

The persons.

The persons who were agents in these 10 studies were final-year students, Ph.D students and unemployed engineers, who had not yet found their first jobs. Naturally, they did not have a great amount of experience as engineers and decision-makers, and furthermore, some of the persons' knowledge of materials, production methods and design methodology left much to be desired, factors which mean that the result of the video tapings must be taken with certain reservations. On the other hand, for the development of the task, the testing of equipment, the implementation and building up of an analysis routine/method, they were the ideal agents. If video taping is to be utilized to comment on a process selection situation at a company, the agents should naturally come from this environment. Although the persons were relatively inexperienced as designers/production engineers, they all had the right background for solving the problems, and it has also proved possible to reach some conclusions on the results, see below.

The task.

The pilot project was meant to develop the task itself, and it must be admitted that the initial task was extremely suitable for the examination of how process selection is carried out. The task was adjusted slightly during the first couple of video tapings, but in general it fulfilled the original requirements from the start. The task was presented as such that there were many different manufacturing possibilities and by and large the teams considered many different production methods in their final selection of solutions, although injection moulding was the most popular. The time taken to solve the task was for all teams between two and three hours, which was mandatory.

Equipment.

The equipment also lived up to expectations. With the video equipment chosen, it was possible to obtain a total picture of both persons, while it was also possible to zoom close to the paper and obtain a picture of the sketches and details on the paper. It was even possible to clearly read the text on the paper (a reason for the white paper and the soft pencils, minimum 2B). It could perhaps be a matter for discussion as to whether there should have been extra equipment such as reference books, drawing boards etc. The answer to this is that it all depends on the objective of the study, while the question of which facilities and resources should be made available must be assessed in the individual situation.

Implementation.
The implementation was satisfactory, but could perhaps have been improved if there had been a fixed introduction sequence, so that all video-taping began with the same starting point. This introduction could be written, or read aloud; the most important factor is that the agents are provided with the same information before they embark upon the task. The implementation itself could also be more standardized, if it were defined when and in which situations the research leader may intervene, and what he is allowed to say/do in these situations. Finally, it would be desirable to have a standardized list of questions which are to be asked after the video taping has been completed.

In these studies, the solution of the set task was not subject to many restrictions, but one can imagine video-taping which is more controlled, e.g. where the agents are forced to consider certain production methods or utilize specific tools etc.

Analysis.
The analysis and reporting of the studies has without any doubt been the most time-consuming part. The video tapes were each watched at least twice, the first time in order to find a standardized method of describing and analyzing the events and the second in order to write the journals and carry out the analyses. The tapes last for 25 hours, and during the reviews, it was often necessary to rewind the tape in order to understand what was being said. Furthermore, it takes longer to write down what was said than to watch the video itself.

Initially, it had been decided not to write down the entire course of action in the experiment journals, but this later proved necessary, as it would have been far too time-consuming to wind the video tape backwards and forwards, just as it was difficult to preserve an overview of the action on the tape without the journals. Therefore, although it was rather time-consuming to write down the entire procedure in journals, it was worth it in the end. It was impossible to predict whether these journals would be of use during the video-taping, so watching the video tapes took precedence. It would be worthwhile to write as much as possible in the journals while taping, since one follows the events in any case in order to ask more detailed questions during the evaluation stage. Apart from this, the analysis part of the study was satisfactory and could be used in a "sharp" situation. The weakest part of the analysis is the opportunity to describe on paper when the individual selection is made.

5.6 Discussion of the Results

The purpose of the survey was to verify the following hypotheses:

HY1 Designers consider too few production methods before the final selection.

HY2 Designers do not consider production methods systematically

HY3 Designers select production methods familiar to them and seldom consider new production methods.

HY4 More optimum production methods can often be found.

HY5 By considering other and, for the company, untraditional production methods, the chance of finding new and better product solutions becomes possible.

HY6 The designer must consider whole process chains and not only single processes before the final selection.

HY7 To achieve better selections, the designer needs a specific type of information about production methods.

In addition, the following points should be examined:

1 Which parameters initiate the process considerations.
2 Which criteria are decisive for the process selection.

Concerning HY1 and HY2

The number

The number of considered processes varies from 2 to 11 for the different teams. The average is above 6 processes. The question is: are these sufficient? According to the way this working hypothesis is formulated, the question is difficult to verify, since it is not directly quantifiable. The author had, however, believed that the agents would consider fewer than 3-4 processes, so in this respect one must say that the teams considered a larger number of processes than expected. Only 3 teams considered 4 processes or less.

The way

It is characteristic of the two teams which considered the highest number of processes that they wrote down a list of processes regardless of materials or solutions. They initiated a brainstorming session, in order to discover all the processes they could possibly think of. Until they had listed all these processes, they did not consider whether the processes were suitable or not. These two teams can be said to have systematically considered the processes, while this does not apply to the remaining 6 teams. For these teams, it was characteristic that the selection of process and material was made late in the sequence and that the phase of detailing was relative short, as seen in Figure 40. The two teams considering the lowest number of processes shared the characteristic that they selected process, material and final solution very early and that the detailing phase was long.

Concerning HY 3

Familiar processes

Seven of the teams selected a process that at least one of the agents was *familiar with.* This is 7 out of 8 teams, since one team did not select a process and the first team did not fill in the questionnaire. In seven out of these teams, both agents were familiar with the process selected. In the last case, one would have to go into detail about the collaboration between the two agents, in order to find out if the person who suggested the selected process was the one who was familiar with it. Only one team selected a process which they both only had *knowledge of.* Since such a large number of the teams selected a process that at least one of the agents was familiar with, one can conclude that the teams preferred and selected a process with which they were familiar.

Concerning HY4

Optimum processes

In order to decide whether more optimum processes could have been found, it is necessary to have a criteria function, in which the individual criteria are weighed against each other. Without such a function, it can only be concluded that the teams chose several different production methods in their final solutions. Consequently, if the same criteria function is applied to all the teams, there will certainly be some teams, which did not select the most optimum process. If one looks at the process most frequently chosen, this was injection moulding, but this is perhaps due to the fact that the majority of the teams were familiar with this process, and not that it was the most optimum process.

Concerning HY5

New processes

When one contemplates the solutions submitted by the different teams, it is obvious that there are several possible solutions when different production methods are taken into consideration.

Concerning HY6

Whole chains

This hypothesis could not be established, since the individual teams chose solutions by estimation and not by objective evaluation of the individual solutions.

Concerning HY 7

Process information

It was obvious that the teams did not have all the information they needed to select the process. As can be seen in Figure 46, the teams posed many different questions, which could all be answered through different sources of information. Only one team came to the conclusion that there was a lack of information which resulted in the fact that the team members did not feel capable of selecting a specific process or material.

Concerning point 1

Parameters

Concerning the parameters which *initiate* the process selection, there are some examples where form or metaphors inspire processes. For instance, one of the teams made a sketch of a 2½D solution and this inspired the team members to think of extrusion. To come up with some good ideas, another team tried to think of a product similar to the instrument they were to design and thought of a die-cast pencil sharpener, which led the team to consider die casting. Several teams used these metaphors to come up with ideas of solutions and to consider whether a process was useable in the given production volume. One example was a team considering forging. They did not know whether this process could be used for high production volumes, but later agreed that, as it is used for producing cranks in cars, the process was suitable for high production volumes.

Metaphors

As demonstrated above, one can use video-taping to uncover some of the initiators, but from a general point of view, one must admit that it is impossible to determine the parameters, since many of these are not spoken aloud but are rather part of a train of thought and therefore inaccessible to the camera. Moreover, the agent could not explain afterwards exactly how his thoughts came to occur. One could say that, though video-taping is the only possible method of uncovering these instigators or triggers, one must accept the inherent limitations of this method.

Concerning point 2

Subjective criteria

All the teams used subjective criteria to select processes. Some of the teams considered objective parameters such as cost, but only a few put figures to the different processes in order to compare them. Most of the teams selected processes with the argument 'We *think* that this process is the cheaper one'. One team considered production volume to eliminate some of the processes but the final selection was a process that one of the agents had worked on for the last three months, which indicates that his criteria were subjective.

5.7 Summary

In this chapter, a pilot project in the video-taping af students solving a design problem has been described, including the design task they solved, the chosen procedure, the method of analysis and the results obtained.

Despite the fact that the persons involved in the project were students and therefore not totally reliable from a scientific viewpoint in the examination of how a professional designer selects production methods, the following statements have been extracted as a summary of the experiments:

- The participants chose primarily well-known/traditional materials and production methods.
- Several of the teams had little confidence in plastics. "That is what is used to make LEGO bricks", whereas other teams were certain that plastics/injection moulding was the only genuine possibility.
- The number of items to be produced was considered an important parameter in the selection/rejection of production methods.
- It was difficult to assess costs for alternative production methods.
- The first proposal concerning material, production method or form was often also the final solution.
- Metaphors were utilized both to consider possible solutions and to evaluate whether the production method could be used (if this or that type of component can be made in this or that way, then this one can too).
- Often, most of the available time in the detailing phase was spent on discussing a single part of the total solution, e.g. to

realize the functions: to avoid trapping ones fingers, the forming of a bearing, the fixing of a frame to a table etc.

- There was uncertainty as to which tolerances alternative production methods could give.
- There was uncertainty as to which surfaces alternative production methods could give.
- Some teams chose a solution early on, but on account of monitoring by the camera, *we must just find some good arguments for our selection* (it was evident that monitoring influenced the agents)
- Production methods were chosen before the actual components existed
- Only a few materials, production methods and forms were considered

5.8 Conclusion

The results

The hypotheses

It must be concluded that most of the working hypotheses could be confirmed by the video-tapings, whereas a few were not quantifiable and were therefore difficult to verify. It is obvious that when students are involved, the results must be taken with certain reservations, since these students are not accustomed to making decisions in a design process. Although the participants were students, however, the implementation of the video-tapings was certainly worth the time spent, since the experiment gave the author a great deal of inspiration and a good insight into the problems of choosing production methods in the design phase. Finally, if one has any analytical sense, one can learn a great deal through watching people choose the "wrong" solutions to problems. This is because it is precisely when other people's procedures do not agree with ones own method of dealing with the problem, that the actions are clarified and characterized and the correct way of acting becomes evident.

Inspiration

Courses at TUD

One important conclusion of this study is that at TUD, it is necessary to teach students how to consider and select production methods in connection with product development. It would therefore be a good idea to start up a course in different production methods, in which students learn about these matters and at the same time are given a description of corresponding processes. This course should not be a thorough review of each individual process, which is TUD's traditional type of course.

Video-taping as a method

The framework works

As a result of the experience gained in this pilot project, it must be concluded that video-taping is a method which can be used for the purpose intended here. It is obvious that, if an actual scientific experiment is to be undertaken by means of this method, first and foremost the persons involved must be replaced with experienced designers. But the framework itself as described here, with a task, its implementation and an analysis can be used for the desired purpose.

Reliability of results

The question of how close video-taping comes to a real situation, can be discussed. It is clear that there will be disturbing elements in the "measuring" (as there are in any measuring situation), which will cause the situation to be somewhat artificial. Is it true to life that two persons are given a problem to solve, or that they must speak their thoughts aloud, or that a cameraman is present, or that a video camera is running, or that they are not allowed to use a telephone, or that the task is a made-up one and as such "just for fun", or that someone is sitting looking at a monitor in the next room, or that the entire process is taped etc etc? But one must ask oneself here: what is the alternative? It will always be an artificial situation when a researcher appears and attempts to observe a work situation, that is of course, unless the camera is concealed and the agent is unaware of its presence.

The pilot project was carried out in order to test and develop the method. After it had been completed, it was decided not to repeat the video-tapings with professional designers. This was because it was believed that the basis for developing a systematic method and a process information model was already present after the first two cases.

6 FINAL DELIMITATION AND PROBLEM DESCRIPTION

This chapter describes the final formulation and limitations of the thesis. The starting point is in the case studies already described (Chapters 4 and 5), as well as in the work already carried out by other researchers in the field of choosing production methods in the design phase (Chapter 3). As previously mentioned, it was decided to make use of the design methodology described by PAHL & BEITZ 86 as a general description of the way in which designers work. Pahl and Beitz´s methodology is described in this chapter and there is a discussion of how process considerations can be fitted in with this procedure.

The hypotheses

Some of the hypotheses mentioned in the introduction have been verified in two special cases (Chapters 4 and 5), and it would not, of course, be feasible to maintain that they are universally valid. On the other hand, there is nothing to prove that the results do not apply. There are grounds for believing that, by implementing video-taping and/or questionnaires in several companies, it would be possible to prove the general application of the hypotheses. A more thorough examination of how production methods are considered and chosen today, could have justified the time spent on the development of a solution to the problems outlined. In order not to waste time attempting to solve a non-existent problem, such a thorough investigation would have been desirable. On account of time limits with the research work and the author's desire to develop a solution to the actual problem together with the results of the two case studies, however, it was decided to give the first eight hypotheses status of assumptions:

Assumptions

AS 1 Designers consider too few production methods before the final selection.

AS 2 Designers do not consider production methods systematically.

AS 3 Designers select the production methods most familiar to them and seldom consider new production methods.

AS 4 More optimal production methods can often be found.

AS 5 By also considering production methods not usually employed in the company, the possibilities of new and improved product solutions become available.

AS 6 The designer is obliged to consider entire process chains not only single processes before making his final selection.

AS 7 To achieve better selections, the designer needs specific information about production methods.

AS 8 The information available on production methods does not specifically address the needs of the designers.

It follows, then, that the problem is assumed to be a genuine one, and that consequently there are grounds for embarking upon an attempted solution to the way the problem presents itself. The remainder of the report will therefore describe the work of verifying the remaining hypotheses:

HY 9 It is possible to find a systematic procedure that makes the designer consider all relevant production methods.

HY10 A systematic procedure can be tailored to the normal engineering design methodologies.

HY11 It is possible to find improved means of presenting production method information.

The author is of the opinion that methodology and process information can not be separated, but should be handled as an entity and must therefore be developed concomitantly, since the method must be supported by a process information model.

> *The challenge is to present the manufacturing process information in such a way that it fits in with the work of the designer as well as to find a procedure that helps him to consider all relevant production methods so he is able to select the most optimum ones for the product he is designing.*

6.1 Design methodology and process selection

Since designers have different ways of designing products, it is important to have a general description of how designers work, which can be used as a basis for the methods and process structure to be developed. As mentioned in Chapter 2, the design methodology described by PAHL & BEITZ 86 (in the following, abbreviated to P&B) has been chosen for this purpose. In this design methodology, the design process is divided into four main steps or levels: Product planning and clarification of the task, Conceptual design, Embodiment design and Detailed design, see Figure 47.

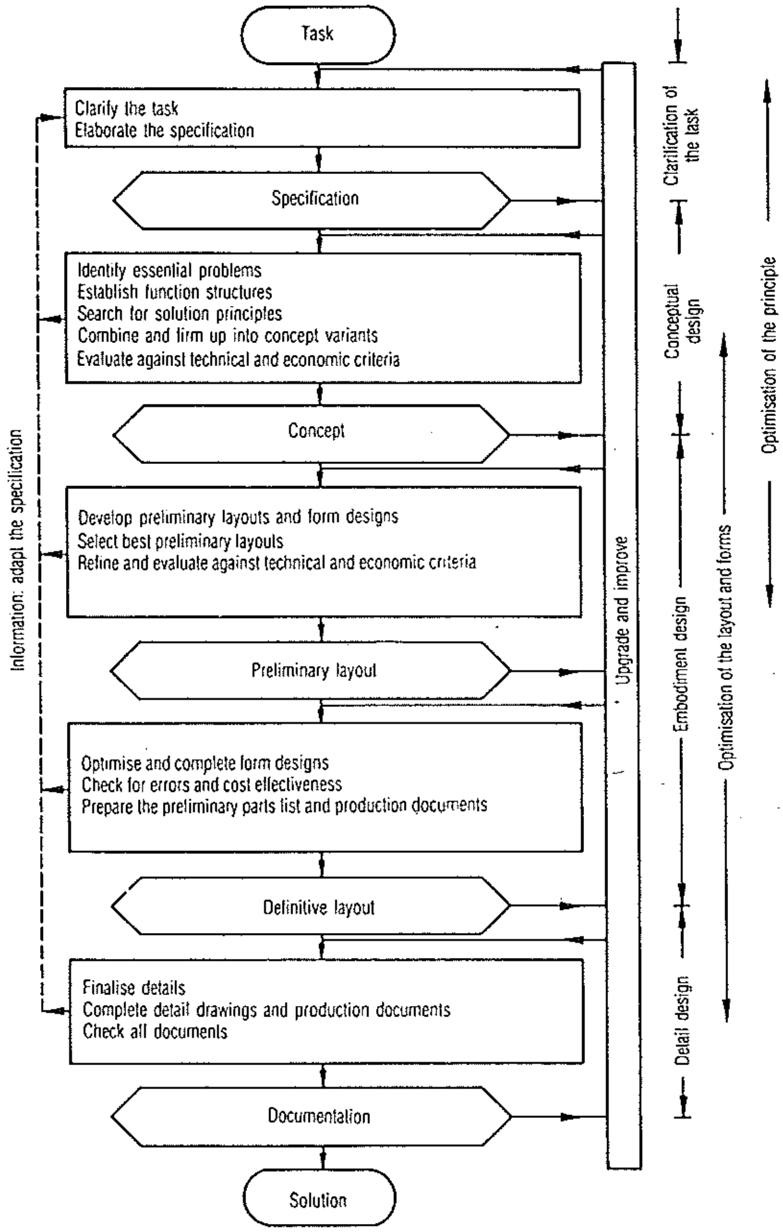

Figure 47 The steps in Pahl & Beitz's design methodology. PAHL & BEITZ 86 *(Figure 3.3)*

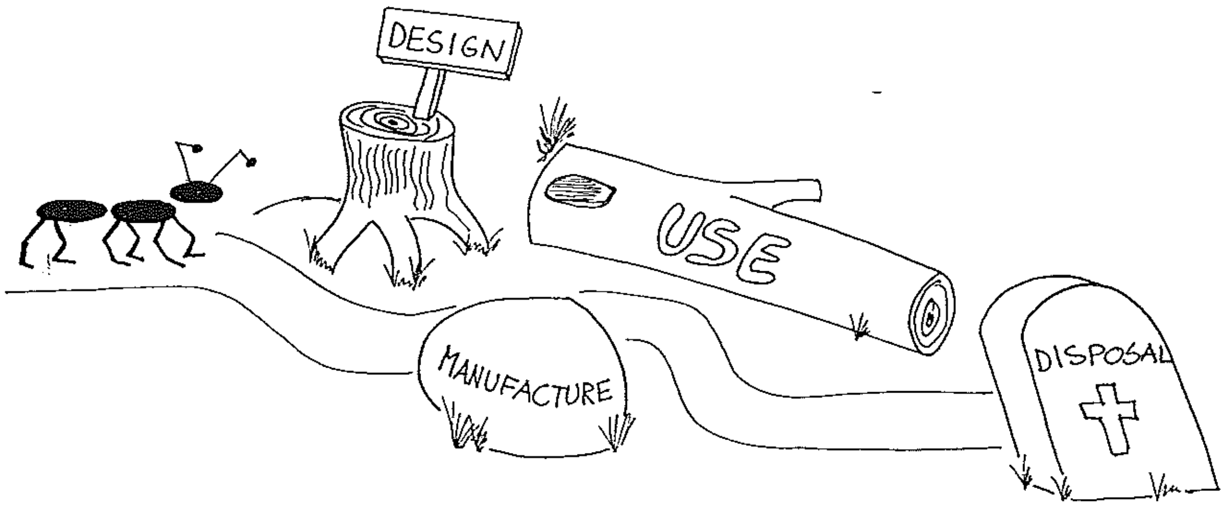

Figure 48 The product meets a number of systems in the course of its life span.

Only the product itself

In general terms, P&B consider only the product and the development of the product. The systems met by the product in the course of its life span, see Figure 48, are only considered to a limited extent. If one compares P&B with the model for integrated product development (IPD) in Figure 2, it can be seen that P&B only represent the middle strip, that is to say, the development of the product itself, and only to a minor degree consider the other domains in the IPD model, i.e. sales and production. This also means that the surface between the product and the production system is only dealt with in a limited way and that the problem of process selection is not even mentioned in the book. At the embodiment design level, rules have been presented for, e.g. the design for fabrication for different production methods, but there is no description of how the consideration of different production methods can be incorporated into the design procedure. Furthermore, apart from the embodiment level, the systems (production, assembly etc) are only dealt with sporadically.

Surface to production

P&B and IPD

It might appear that e.g., the production system, has been omitted from the design methodology, or put in another way, that the P&B methodology does not take integrated productdevelopment into consideration. It is obvious that the task of *bringing a product from the idea stage to the market place* does not only lie in the development of the product itself, but also includes development of the assembly and production systems, see Figure 49. This has also been noticed by others, including SIGURJÓNSSON 92 and ANDREASEN 91. If the selection

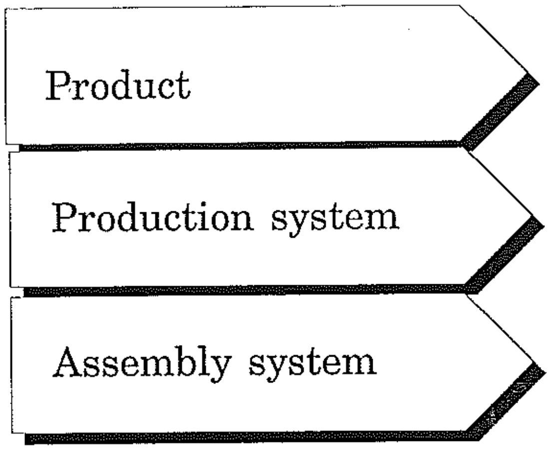

Figure 49 *The development of a product includes simultaneous development of an assembly and a production system.*

of production method is to be carried out in the optimum way, production considerations must be carried out parallel with product considerations, as illustrated in Figure 2, where phases 1 - 4 correspond extremely well with the four levels in P&B. In reality, then, the question in this study is what the first 3 of the lowest boxes in the IPD-model contain, or what is contained in that part of the boxes which represents production methods.

The P&B method is described in this chapter in order to clarify what the individual steps contain and to establish which production considerations will be appropriate in (or parallel with) the individual steps.

6.2 Product planning and clarification of the task.

The first level

The first step in the design methodology is product planning and clarification of the task. In this step, which requirement - which problem - the product should fulfil, must be clarified. The output from this phase is a description of the demands and properties the product must fulfil and possess - i.e. a product specification.

P&B give a check list to set up a product specification, see Figure 50. As is evident, only a few examples of what such a list might contain are given here. Under the main heading *production,* a few points are mentioned: factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances and wastage. The author finds that these are not sufficiently adequate to allow the designer to be capable of

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension.
Kinematics	Type of motion, direction of motion, velocity, acceleration.
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, intertia forces, resonance.
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Flow and transport of materials. Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc).
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct protection systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clearness of layout, sitting comfort, lighting, shape compatibility.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of despatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Costs	Maximum permissible manufacturing costs, cost of tools, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date.

***Figure 50** Check list for drawing up specification.* PAHL & BEITZ 86 *(Figure 4.5).*

selecting/rejecting production methods, and that it would be helpful to supply a more comprehensive list.

Three specifications

Purely schematically, the product specification can be looked upon as three specifications, one for the product, one for production and one for assembly (plus, of course, other life phases not included here). These specifications will naturally be closely connected to each other, and it will probably not be feasible to split them up in practice. Here it has been done to illustrate that it is only the production specification which will be dealt with in this study, and only that part of the production specification which can be directly attributed to those factors limiting the freedom of the designer in the selection of production methods (see Figure 51)

The objective

The objective at the planning and clarification of the task level is therefore: to set up a check list for the matters which must be decided upon early in the design phase, questions which influence the designer's degree of freedom in the selection of

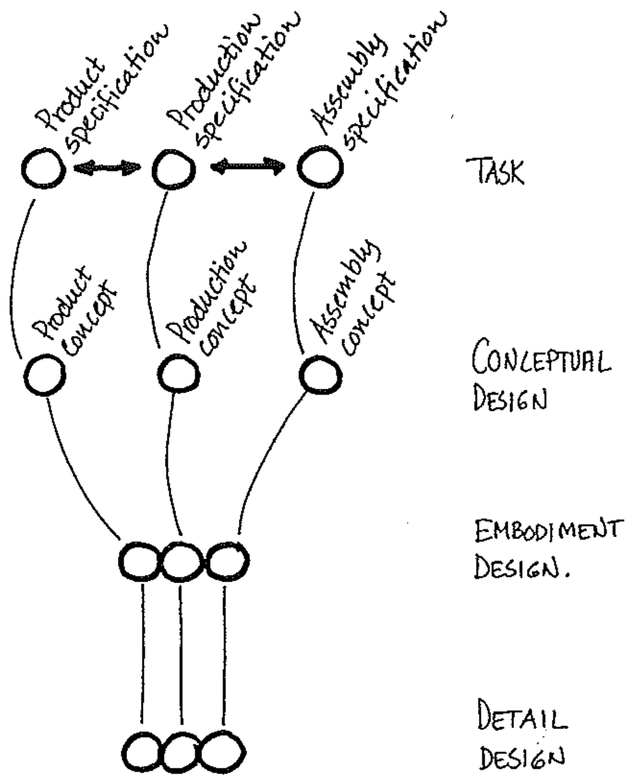

***Figure 51** Purely schematically the product specification is split up into three, one for the product one for assembly and one for production..*

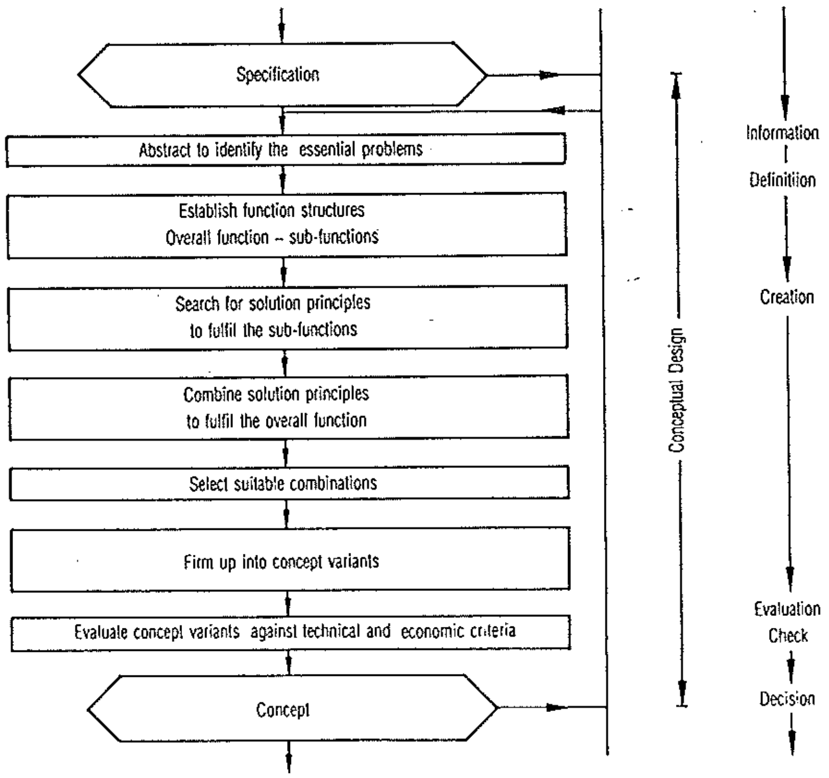

***Figure 52** Steps of conceptual design.* PAHL & BEITZ 86 *(Figure 5.1).*

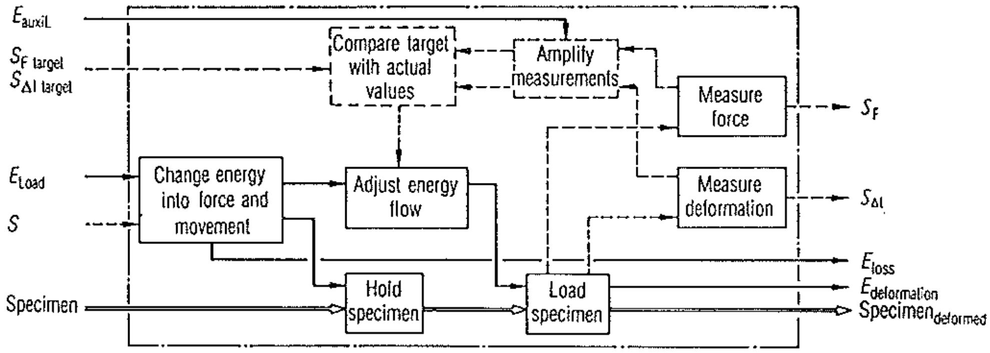

Figure 53 *Completed function structure for a testing machine.* PAHL & BEITZ *(Figure 5.14)*

production methods, and which should be asked before a criterion-related specification for the development of the product is completed.

6.3 Conceptual design

The second level

Functions

The conceptual design phase comprises several sub steps, as shown in Figure 52. The essential problem is identified through abstraction. Subsequently, the function structures are established and overall functions in the product are identified and divided into sub-functions. Figure 53 illustrates an example of the completed functional structure of a testing machine. A functional structure describes, then, the functions contained in the technical system and the time connection between them, but does not describe their spatial placing in relation to each other. In the next step, working principles for the functions are sought and these principles are combined to fulfil the overall function of the product. Figure 54 shows different working principles to satisfy the function *store energy* by varying the type of energy. Suitable solutions are selected and developed into principle solution variants. Finally, the solution variants are evaluated.

Working principles

Links with production

At the level where the functions in the product are determined, it is not possible to determine the links with production methods. It is logical that this connection can not be established until the moment the product is given substance in the form of material and shape. Functions as, for example, *to conduct water* or *to show temperature* have no immediate connection with the production method. It is, of course, possible that we have been there before, that is to say that we have previously found the

Type of energy / Working principle	mechanical	hydraulic	electrical	thermal
1	Flywheel (rot.)	Hydraulic reservoir a. Bladder b. Piston c. Membrane (Pressure energy)	Battery	Mass
2	Moving mass (transl.)	Liquid reservoir (pot. energy)	Capacitor (electr. field)	Heated liquid
3	Pot. energy	Flowing liquid	Magnet (magn. field)	Superheated steam
4	Metal spring			
5	Wheel on inclined plane (rot. + transl. + pot.)			
6	Other springs (compr. against fluid + gas) $\Delta p; \Delta V$			

***Figure 54** Different working principles to satisfy the function "store energy" by varying the type of energy.* PAHL & BEITZ 86 *(Figure 5.31).*

solution to the function of *showing temperature*. And it is obvious that it would be possible to list previous solutions and connected production solutions. It is also possible that for a given function there are several possible final solutions and therefore several possible final fabrication methods, but the connection between function and production method must necessarily go over to a given solution with material and geometrical substance. It is not until the moment that we can imagine a substantial solution to realize the function, that we can go into the fabrication possibilities.

Previous solutions

The same comments apply to working principles, which as those in Figure 54, can be seen to have a somewhat abstract level, which is to say that the solutions have not yet taken on any substance. It is therefore surprising that the check list (Figure 55) for design evaluation during the conceptual phase under the main heading *production,* includes the points: few and established production methods, no expensive equipment, small number of simple components, since from the author's point of

P&B check list

Main headings	Examples
Function	Characteristics of essential auxiliary function carriers that follow of necessity from the chosen solution principle or from the concept variant
Working principle	Characteristics of the selected principle or principles in respect of simple and clear-cut functioning, adequate effect, few disturbing factors
Embodiment	Small number of components, low complexity, low space requirement, no special problems with layout or form design
Safety	Preferential treatment of direct safety techniques (inherently safe), no additional safety measures needed, industrial and environmental safety guaranteed
Ergonomics	Satisfactory man-machine relationship, no strain or impairment of health, good form design
Production	Few and established production methods, no expensive equipment, small number of simple components
Quality control	Few tests and checks needed, simple and reliable procedures
Assembly	Easy, convenient and quick, no special aids needed
Transport	Normal means of transport, no risks
Operation	Simple operation, long service life, low wear, easy and simple handling
Maintenance	Little and simple upkeep and cleaning, easy inspection, easy repair
Costs	No special running or other associated costs, no scheduling risks

Figure 55 Checklist. PAHL & BEITZ 86 *(Figure 5.60).*

Variant / econ. criteria	11	12 / 14	13	15	25	35
1) low material costs	2	2	3	4	4	(1) 2
2) low reassembly costs	2	2	(2) 1	3	3	3
3) Short testing time	2	2	4	3	3	2
4) Possibility of manufacturing in own workshop	3	3	3	3	3	2
Total	9	9	11	13	13	9
$R_e = \frac{\text{Total}}{16}$	0.56	0.56	0.69	0.81	0.81	0.56

(1) Austenitic shaft (2) Torque measuring shaft must be moved

Figure 56 Economic evaluation of concept variants. PAHL & BEITZ 86 *(Figure 5.62).*

view it is quite impossible to make any statements on these factors if one evaluates working principles at this abstract level. This applies also to Figure 56, which shows an evaluation of some abstract principle variants, which are assessed for different economic criteria. It is quite simply not possible to do this either on the basis of the given information.

P&B examples

When they, in their examples, talk about concept variants, which are the basis for their concept evaluation, it is quite clear that

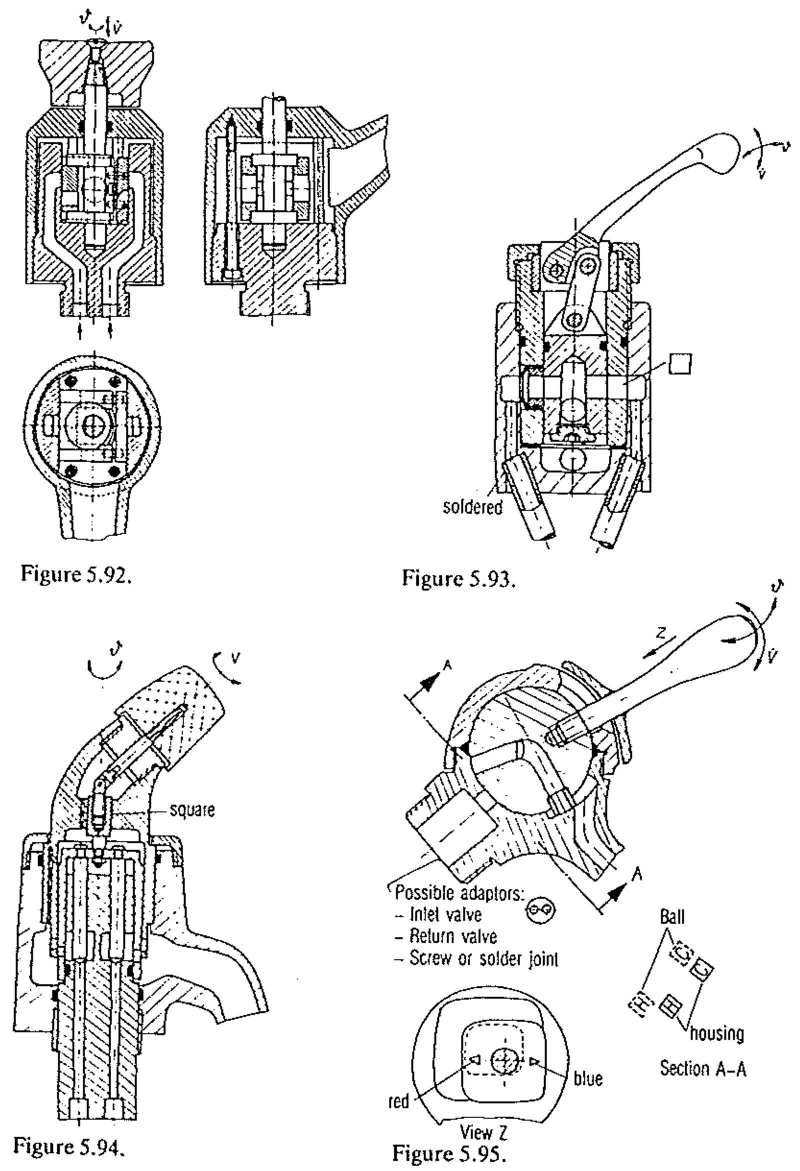

***Figure 57** Concept variants.* PAHL & BEITZ 86.

they are no longer talking about working principles at an abstract level, but that these concept variants are sketched with detailed components and their individual formulations, see Figure 57. They also say themselves that if it is to be possible to evaluate concept variants, then it is frequently necessary to use rough sketches or rough scale-drawings of possible layouts, forms, space requirements etc. And it is evident that it is possible even from these sketches to speak of possible and impossible production methods.

No direct connection

The author must conclude that, with the given descriptions of the conceptual design level, it is not possible to establish a connection with production methods. The fact that it is necessary to go down to the embodiment design level in order to evaluate concept variants is another matter. But it is clear that, parallel with the conceptual design for the product, a conceptual design for the product system can also appear.

Tasks on the conceptual level
Since, seen from the author's point of view, it is not possible to establish a direct connection from conceptual design to production methods, this level has not been dealt with in this research work.

6.4 Embodiment design

The third level

The embodiment design level is the level where the working principles are gone through from a technical and financial point of view. It is at this level that the materials and processes for each component are selected and the components are given shape.
P&B write:

> During the embodiment phase, at the latest, the designer must determine the overall layout design (general arrangement and spatial compatibility), the preliminary form designs (component shapes and materials) and the production procedure, and provide solutions for any auxiliary functions.

Consider processes

Figure 58 shows the individual steps in the embodiment design. It is at step three that the components begin to take shape. A rough layout, derived from the concept, is used to identify the embodiment-determining main function carriers - that is, the assembly processes and components fulfilling the main functions. Subsequently, (at step 4) the first proposals for suitable preliminary layouts are worked out. In the author's opinion, it is here that the first considerations about production methods ought to be incorporated. At this stage, however, it is only the main processes, which are interesting, while the post-processes can be considered later, when the individual components are to be fitted together. The main process has great influence on the structure of the components and consequently on these preliminary layouts for the product, and it is therefore crucial that alternative production methods are considered (systematically) already at this relatively early stage of embodiment design. Moreover, if the layout is fixed without the fabrication possibilities for the individual components having been considered, then the restrictions of the already determined

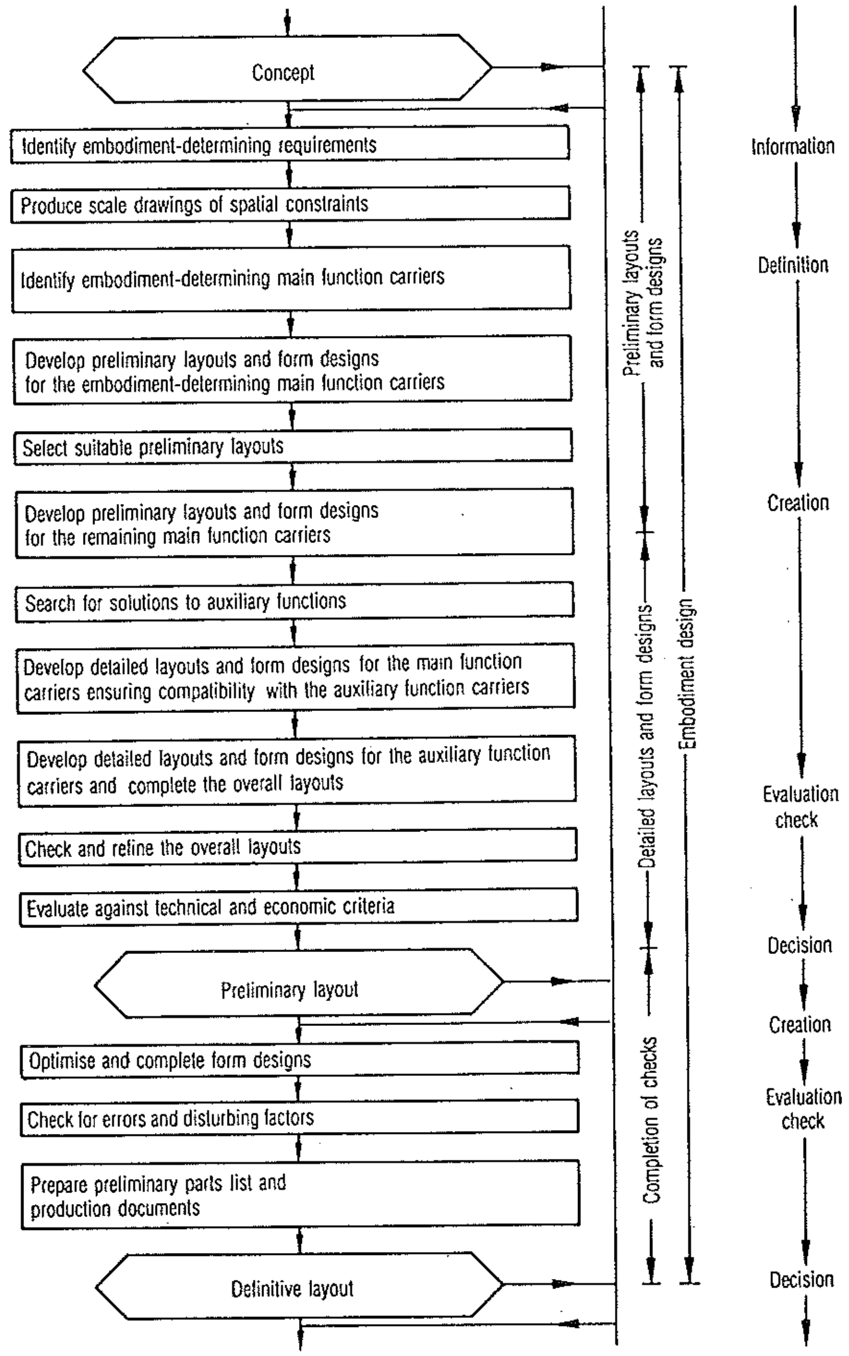

***Figure 58** Steps of the embodiment design.* PAHL & BEITZ *(Figure 6.1).*

form will greatly limit the number of alternative fabrication possibilities.

Process and structure

Figure 59 shows the schematic connection between assembly, production and product. The main process has a great influence on the possible component structures and consequently on the product and product structure, which again is connected to the method of assembly and the order of assembly. At the lower

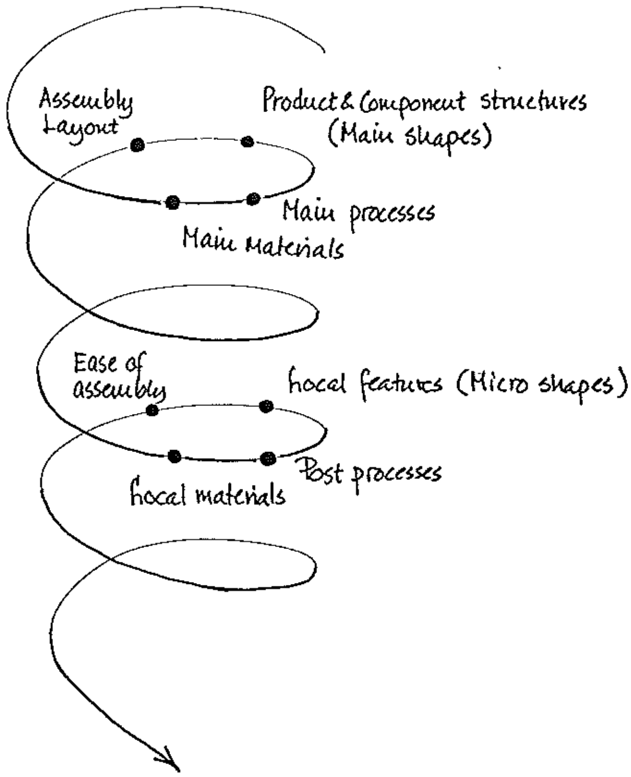

Figure 59 *There is a connection between assembly, production and product.*

levels, where detailed layouts and form designs are developed, it is more a question of considering the post-processes, tolerances and ease of assembly; that is to say, the forming of local features, which make the organs functional and easier to produce and assemble.

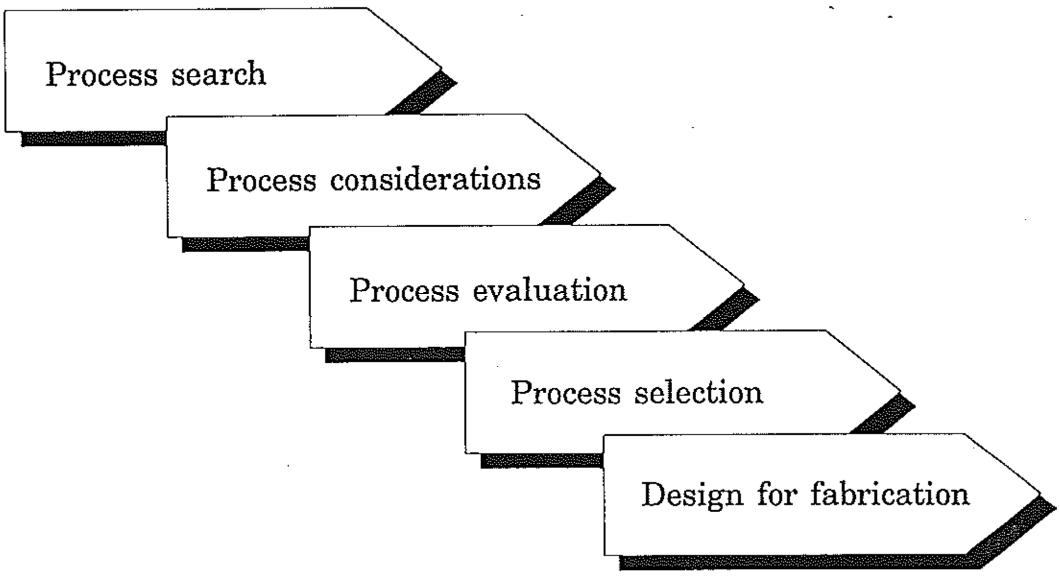

Figure 60 *There are five types of activities which the designer must go through in connection with the selection of production methods.*

Considerations and selection of production methods
Considerations and selection of production methods must, generally speaking, follow the model shown in Figure 60.

Process search

Process search. The first step is to find suitable production methods for the components which are to be constructed. The search for processes itself has the purpose, from the starting point of relevant search criteria, of finding the production methods which can be utilized in the given situation. At the early stages, when preliminary layouts are considered, it will be the main processes which primarily interest the designer.

Process considerations

Process considerations. When relevant production methods have been found, the next step is to consider whether the processes found can be used to maufacture the components to be constructed.

Process evaluation

Process evaluation. The manufacturing alternatives drawn up are compared and evaluated in relation to one another.

Process selection

Process selection. On the basis of the results of the evaluation, the most suitable production methods for the individual components are chosen.

Process detailing

Process detailing. After the production methods have been chosen, the individual components are then designed in detail so that the geometry fulfils the requirements of the production method. This activity is often called design for fabrication (DFF).

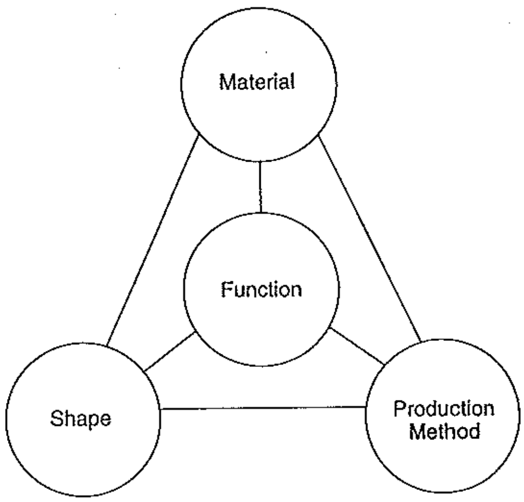

Figure 61 *The interrelation between function, material, shape and production method.* JAKOBSEN 89.

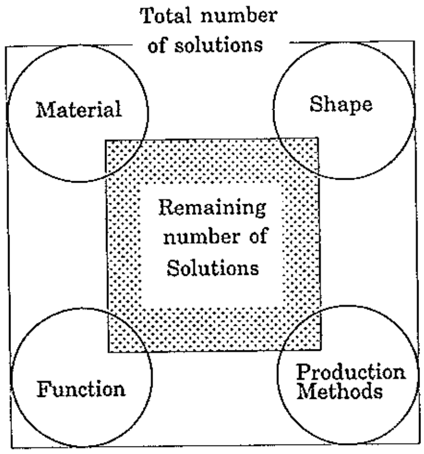

Figure 62 *The interrelation between the shown factors means that if one is selected the possibilities of selecting the others is decreased.*

An interrelation

According to JAKOBSEN 89, there is a close interrelation between the function, material, production method and shape of a component, see Figure 61. This interrelation means that if one factor is selected, the possibility of freely selecting the other factors is decreased. The combinations of these four factors represent the total number of possible solutions, and if the possibility of selecting some of the factors is decreased, the remaining number of solutions is also decreased, see Figure 62. This means that selecting process and material very early on, which is most often what designers do, will reduce the odds for creating the best components and product. It is therefore extremely important that the designer considers a sufficient number of possible combinations of processes, materials, functions and shapes before making the final selection of a solution. The conclusion is: that the designer has to consider, evaluate, and select the four factors as an entity (a component solution) and not as individual parameters.

A component solution

This means then, that the object of the previously-mentioned selection of process activities: search, consideration, evaluation and selection of production method, is not only the selection of the production method, but rather a combination of the four factors material, process, function and form. From now on this combination will be called: *a component solution.*

Life cycle criteria

Another argument for this conclusion is that life cycle criteria such as material wastage, reusability, recycling etc. cannot be directly coupled to the process, the material, the function or the shape itself, but must be coupled to the component solution. How should one be able to assess the amount of material wastage there is for a process, if one does not know the shape of the component ? How should one be able to tell the process' effect on reusability and recycling, if one does not know the material combinations in the component ? And what about cycle times, flexibility, quality etc. Can these factors be evaluated by only considering the process and not the component as a whole? Of course not, and therefore:

> *the designer must consider, evaluate and select solutions and not the four factors as individual parameters.*

Process sequences

Process chain

It is extremely important to realize that components often have to be fabricated by more than one production method, since one process alone cannot give the component the desired properties. Therefore the component is often fabricated by a chain of processes. The processes can be divided into the following groups of processes:

- The main processes, which are the processes creating the main shape of the components.
- The pre and post processes, which give the components the required local or global properties, which the main process is not able to fulfil.

One could say that the main process creates the material connection between the functional surfaces - and if the required properties of the functional surfaces cannot be satisfied by the main process, then a process chain is necessary. The question of which processes can be placed in the different groups, depends on the specific situation (component size, component complexity, production rate etc.), but the usual main processes are netshape and near netshape processes such as injection moulding, casting, forging etc.

Often designers select the production method after only having considered the costs of the main process. This is a great mistake, since the pre and post processes must be included in the evaluation. Alternative process chains, and not only single processes, must be compared before the selection.

The task at the embodiment design level
On the basis of the above, there are two statements which should be taken into consideration before suggesting a procedure for process selection at the level of embodiment design:

Two statements

- Processes must not be selected as individual parameters, but must be seen as an integrated part of a solution. Therefore solutions and not processes must be generated, evaluated and selected.

- Components are most often fabricated by means of chains of processes and not single processes, and therefore solutions comprising the entire process chains should be generated, evaluated, and selected.

The task

At the embodiment design level the task is: to draw up a procedure, which through the sketching of solutions at the embodiment design level, will lead the designer through the consideration of all relevant production methods, as well as to set up a model for the process information required to carry out this sketching process. The main emphasis of the work is on this sketching of solutions, but other objectives are to set up a procedure and a process information model for the consideration of process chains and to discuss the evaluation and selection with special reference to establishing the costs of the selection criteria.

6.5 Detailed design

This is the phase in which the arrangement, form, dimensions, and surface properties of all individual parts are finally laid down, the material specified and all the drawings and other production documents produced. At this level, the production methods have already been selected and thus this level has less interest seen from a process selection point of view. The detailed design level is consequently not dealt with in this research work.

6.6 Summary

Problem
The total number of production methods is vast and it is difficult for the designer to form a general view of the possibilities and

constraints; the available process information is structured by production engineers for production engineers and not for designers; the production methods are related to individual components, but through the shape of these individual components, the production method influences the structure of the product. The influence on the structure is not visible, however, until the shape of the component is generated. The process selection task is therefore an extremely complex and difficult task and the two key-words in the solution to this problem are information and methodology. In order to select the most optimum production methods, the designer needs the right information at the right time and he needs to make the considerations and selections of production methods in the right way.

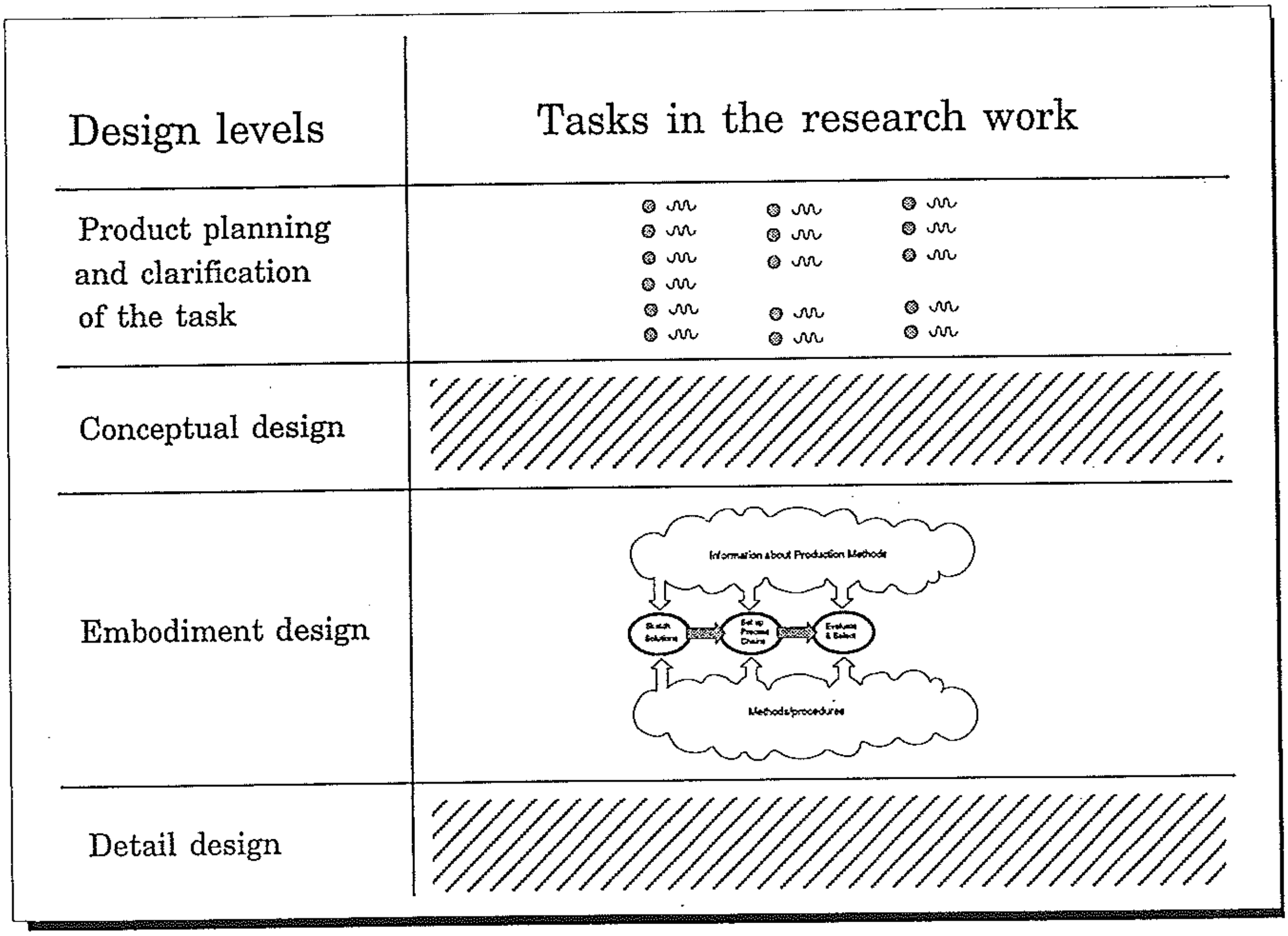

Figure 63 Emphasis is on the first and third level of P&B's methodology.

Task

The task here is that shown in Figure 63, i.e. to develop a method which, combined with the design methodology described by PAHL & BEITZ 86, will assist the designer in the consideration and selection of production methods. The principle emphasis is on the first level (planning and clarification of the task) and the third level (embodiment design) of P&B´s method. Emphasis is on the first level because it is here that the entire basis for the scope of possible solutions is fixed and on the third level because it is here that the components take shape and therefore also here where production methods are considered and established.

Delimination

Planning level

At the first level, guidelines are drawn up for the information which should be included in a criterion-related specification for the product, in order to make the selection of production methods at the embodiment design level easier for the designer. Similarly, there is a description of the measures which can be implemented in order to establish relevant information.

Embodiment level

At the embodiment design level, the task is limited to setting up a procedure and a process information model for the sketching of component solutions. The model contains main process, material, form og function as well as the establishing of process chains and finally the discussing of evaluation and selection, with particular focus on the establishing of cost information.

Demands

For the procedure

The following demands and properties can be drawn up for the procedure:

- It must raise the possibility that the designer is aware of the different production methods he is able to select between.
- It must be based on the *law* that function, material, shape and production methods are closely interrelated.
- It must be in harmony with the design methodology described by PAHL & BEITZ 86
- It must be addressed to designers and should be practicable in use.
- It must inspire the designer (in a systematic way) to consider every relevant production method.
- It must assist the designer in selecting the best production methods for the components he is designing.
- The consideration and selection of processes must be based on process chains and not single processes.

For the info model

The following demands and properties can be drawn up for the process information model:

- The designer should have the relevant information at the right time in the designing process.
- He should have the information that he needs and neither more nor less.
- The information must be presented in a way that is tailored to his way of working.
- The information must be presented in a language that the designer understands.

A PROCESS SELECTION PROCEDURE FOR THE EMBODIMENT DESIGN LEVEL

7

This chapter describes the model for process selection at the embodiment design level, which has been developed in the research work. Firstly, a general model is proposed in which process selection comprises the activities: sketch solutions, process selection comprises the activities: sketch solutions, setting up of process chains and evaluation and selection. Subsequently, the content of these activities and the attached process information model are described.

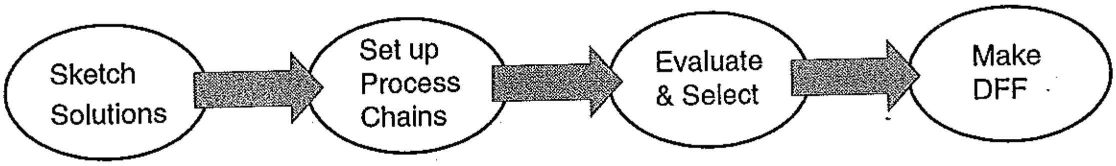

Figure 64 *The author's proposal for a general model for process selection consists of four steps: sketch solutions, setting up process chains, evaluate and select and making DFF.*

7.1 A general model for process selection

The author's proposal for a general model for process selection, which fulfils the demands drawn up in Chapter 6, is shown in Figure 64. As can be seen, the model consists of four steps: sketch solutions, setting up process chains, evaluate & select and making DFF.

Sketch solutions

Sketching solutions means generating a number of component variants with different materials, different macro shapes, different production methods and perhaps different functions. This step is quite different from the design for fabrication (DFF step), since the purpose is to generate component variants and to investigate the total solution space for the component, and not to create a component that is designed in detail for the given process. For sketching solutions, the designer needs information about production methods that are quite different from the information he needs to make the detailed design for fabrication. He needs precisely the information that makes it possible for him to *sketch* solutions without going into too much detail. Going into detail takes time and at this stage it is important that he generates as many solutions as possible without spending too much time on each solution. It is necessary, however, that the components are sufficiently detailed to make it possible to reach a decision as to which solution is the best alternative, which means that:

> *the sketched component solutions must have a certain level of process correctness, and that all component solutions to be compared have the same level of process correctness relative to the respective production methods*

Process chain

After sketching a number of solutions, the next step is to *set up the full process chains* for each solution. This must be done before the evaluation and selection of components are made, since pre and post processes have an influence on the cost and on the main shape. Often, designers select the main process very early and leave the process planning to the production engineer in a later sequence. This is not an optimum procedure, since a component solution that seems to be cheapest when only the main production method is calculated, can turn out to be the more expensive one when the whole process chain is calculated. Similarly, a post process may often make demands as to the form created by the main process, e.g. the fixing sheet for a drilling process, and it is therefore crucial to consider the entire process chain, before the main process is determined. Consequently, process planning has to be incorporated early in the design phase before the final selection of the main process is made.

Evaluate & select

The next step is to *evaluate & select* the best solution. The advantage of evaluating solutions instead of the process as an individual factor, is not only that the solution space can be investigated in a more optimum way. Evaluating component solutions makes it possible to use quantitative selection criteria from the production system such as cycle time and material waste, as well as criteria from other systems in the product life cycle (sale, distribution, use and recycling) which can not be used when evaluating and selecting the process as an individual factor.

Make DFF

When the best solution has been selected, the designer can begin design for fabrication (*make DFF*), where he designs the shape in detail in order to meet the needs of the specific processes in the chain.

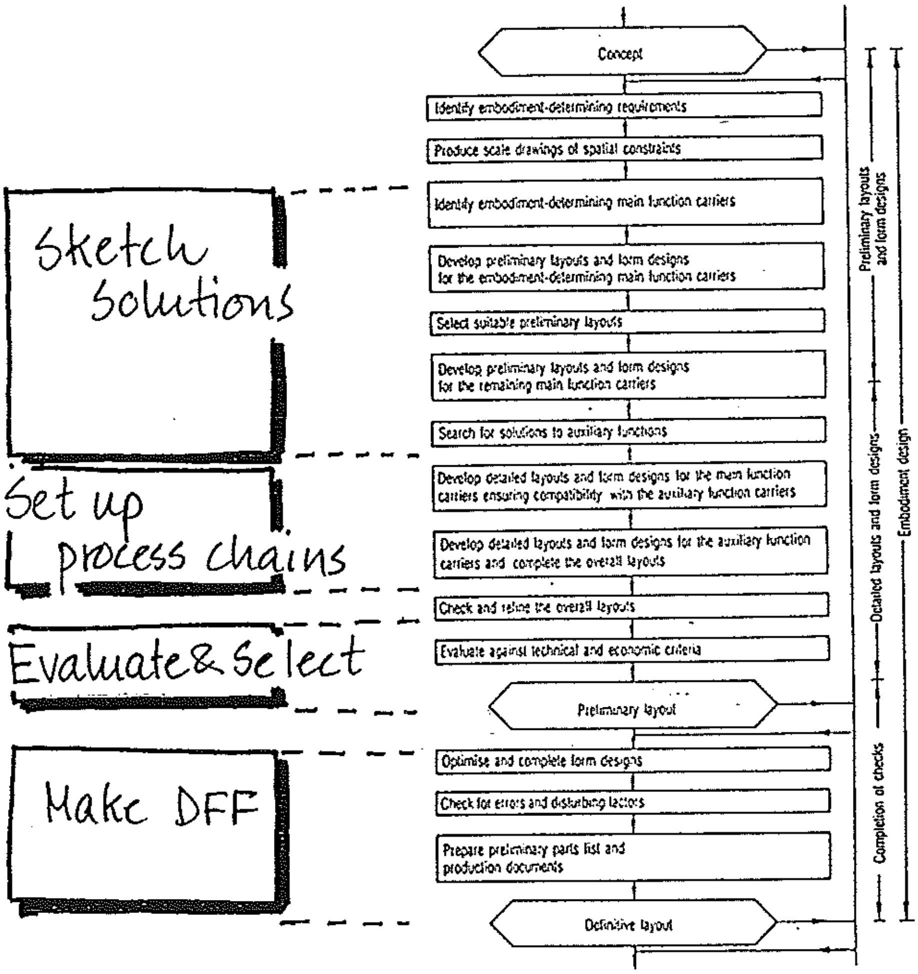

Figure 65 The connection between the suggested procedure and P&B's design methodology.

The connection between the four steps and P&B's methodology is shown in Figure 65. The designer needs information on production processes for each of these steps and he also needs systematic procedures, see Figure 66.

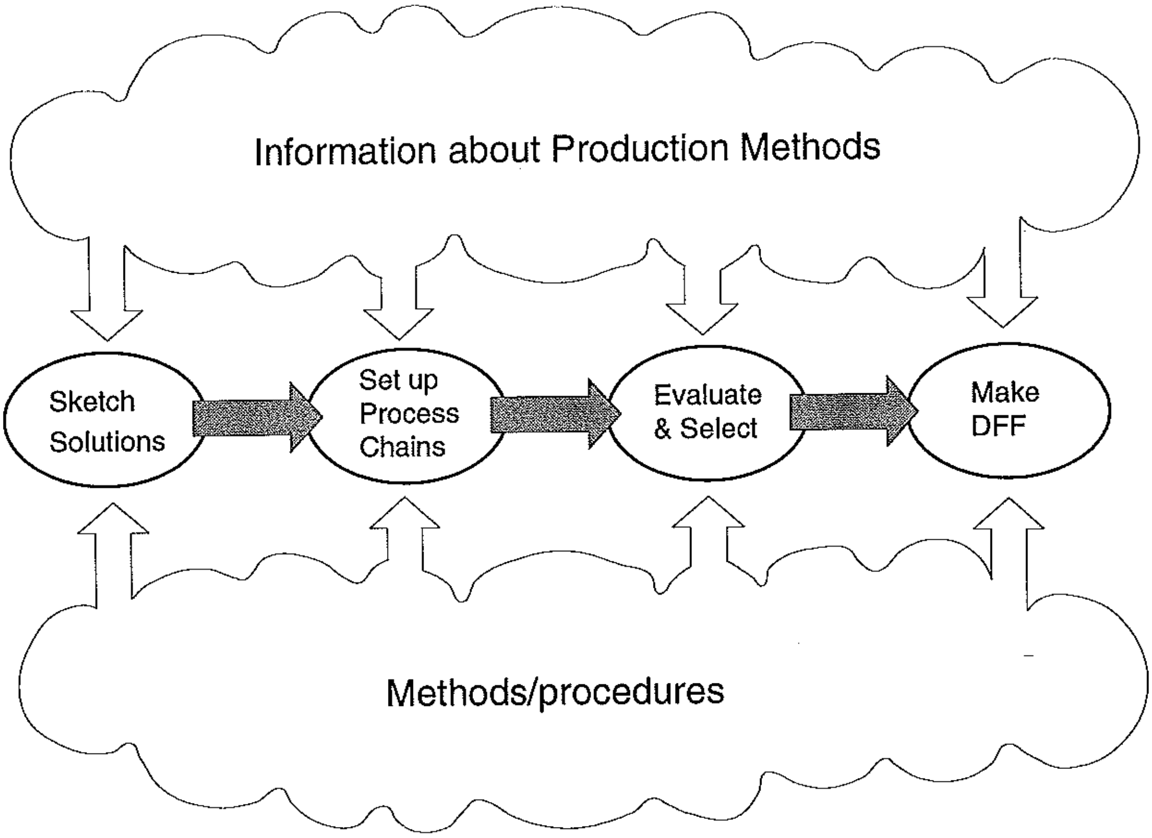

Figure 66 *To each of the steps in the procedure the designer needs a method of how to carry out the activity and he needs differenet kinds of information about production methods.*

The following section in this chapter describes the three steps: sketching solutions, setting up process chains and evaluation & selection (the DFF step is, as previously mentioned, not dealt with in this research work). In the section on sketching solutions, there is a description of how the designer can systematically consider the production processes, as well as a model for the presentation of the necessary process information for this. The section on process chains describes why and how process chains can be set up, and the last section on evaluation and selection of processes gives a discussion of selection criteria with the emphasis on cost.

7.2 A method for the first step: Sketching solutions

In the book "A short course in industrial design", Tjalve describes a *form variation method*. He describes how the shape of acomponent can be variated in a systematic way to thereby investigate the solution space. Tjalve presents, therefore, a method which systematically leads the designer around in the

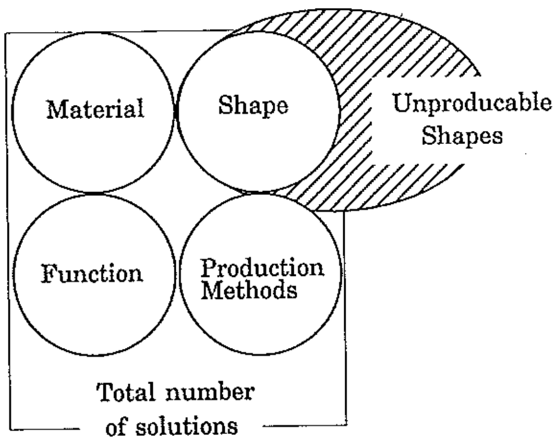

Figure 67 *By systematic variation of forms without considering materials and production methods the designer risks to consider shapes that are impossible to produce.*

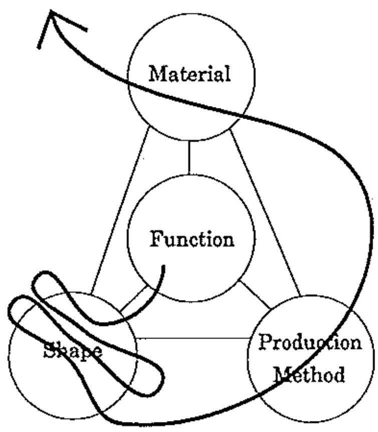

Figure 68 *Tjalve's starting point is the functional surfaces for the components, after which he varies the form. The process and the material must then be adjusted to the forms found.*

solution space for the forming of components and the method is excellent for creating new shapes for component solutions. As Figure 67 shows, the designer runs the risk of finding forms which can not be produced. Tjalve's starting point is the functional surfaces for the components, after which he varies the form. The production process and the material must then be adjusted to the forms found, see Figure 68. Tjalve presents this, among other things, in his book. He maintains that he makes a jump from the abstract form concepts in Figure 69 to the more form-fixed in Figure 70. It is clear how the individual proposals in Figure 70 could be produced so this is either a coincidence, or Tjalve has had these production processes in mind during the

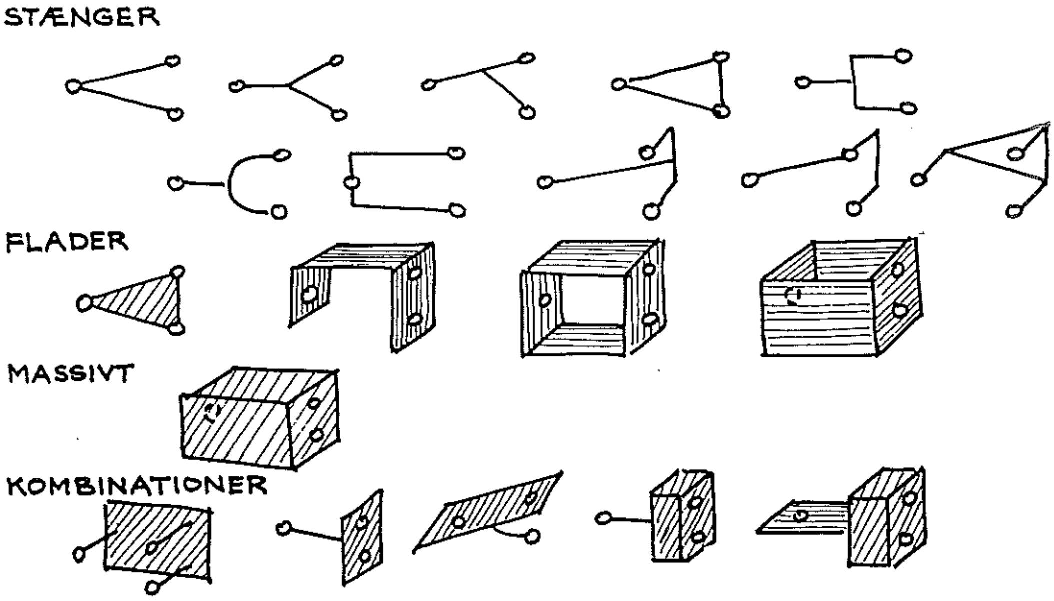

Figure 69 *Form concepts for a fork link at the most abstract level.* TJALVE 83 *(Figure 59)*

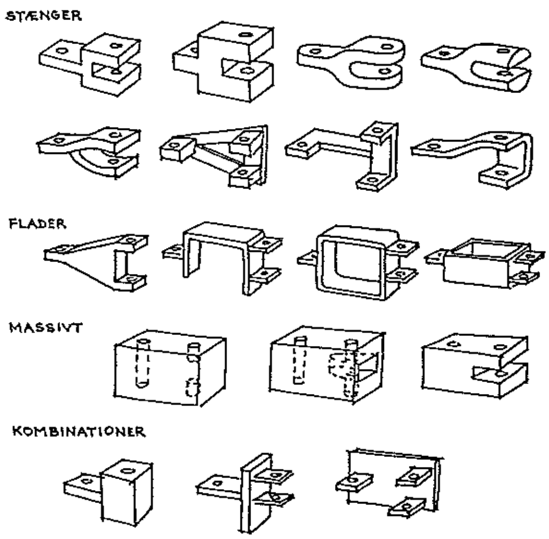

Figure 70 *More concrete form concepts.* TJALVE 83 *(figure 60).*

step between the abstract form concepts in Figure 69 and the more concrete form concepts in Figure 70. As is implied in Figure 70, and as can be derived from Jakobsen's model:

a process neutral shape is impossible to find

a fact that Tjalve also notes, since he writes:

»A prerequisite for being able to select the optimum production process is that the best possible accord between the form and process demands can be achieved. This means that the order mentioned in Figure 94: form concept, selection of production and assembly processes and detailing, must be understood in such a way that the form concepts are set up first, then the process possibilities are examined, and finally the form concept and the processes should be, as far as possible, selected simultaneously. It is therefore normally not sufficient to adjust the detailing to the process, if an optimum-formed product is to be the result.

The problem of selecting production process before the detailing stage has become too advanced, often crops up in discussions between the designer and the production engineer. The designer often tends to forget the production process to such an extent that the production engineer has no opportunity to provide the optimum contribution. The ideal situation would be if the production engineer came into the picture at such an early stage that he could also take part in the evaluation of form concepts at the first level«

Tjalve also suggests that form concepts should be considered first and on the basis of these, production processes, after which form and process should, as far as possible, be selected simultaneously.

7.2.1 The author's suggestion for a method

As previously described in Chapter 1, the intention here is to find a method which provides the designer with the greatest possible chance to explore the solution space, representing the production processes, so that all relevant production processes are considered. With Tjalve's method, only those production processes in which the form accidentally coincides with the possibilities of the process are considered, and this is not all that optimum when the starting point is to consider all relevant production processes. As a supplement to Tjalve's form variation method, the author therefore suggests that component solutions are sketched according to the procedure shown in Figure 71.

The starting point is, as for Tjalve, the assertion that the function of the component is fixed and that the functional surfaces' rough spacial placing is known (sketched).

Step 1 Subsequently, the first step (1 in the figure) is to *primarily* select a process/material combination. With this combination in mind,

Step 2 the form concept (2) for the component is varied, for example by exploiting Tjalve's form variation method. The result will be a number of sketched solutions, which consist of the given process/material combination and a number of different form concepts. Step 3 is then primarily to select a new combination

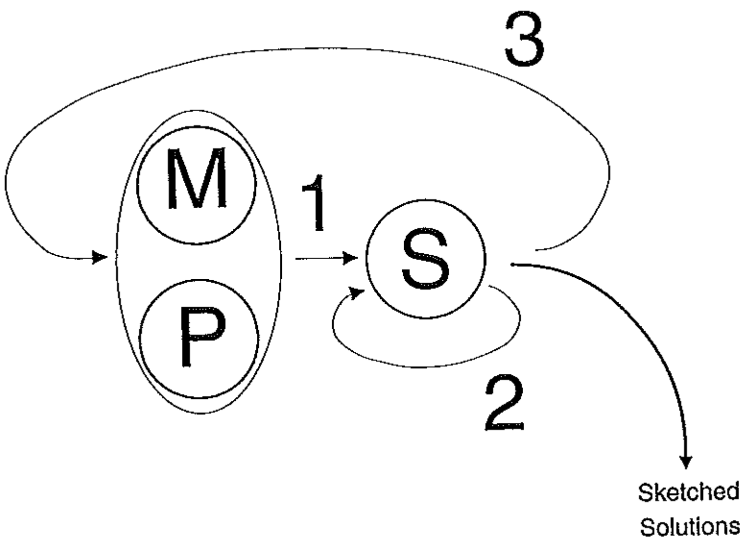

***Figure 71** The procedure suggested by the author.*

Step 3

of material and process and with this combination in mind, to sketch new form concepts. This procedure is repeated until all relevant process/material combinations have been systematically considered. In other words, the designer asks himself the question: "What solutions (shapes) can I think of if the component should be produced by extruded aluminium ? or injection-moulded plastics ? or extruded plastics ? etc.

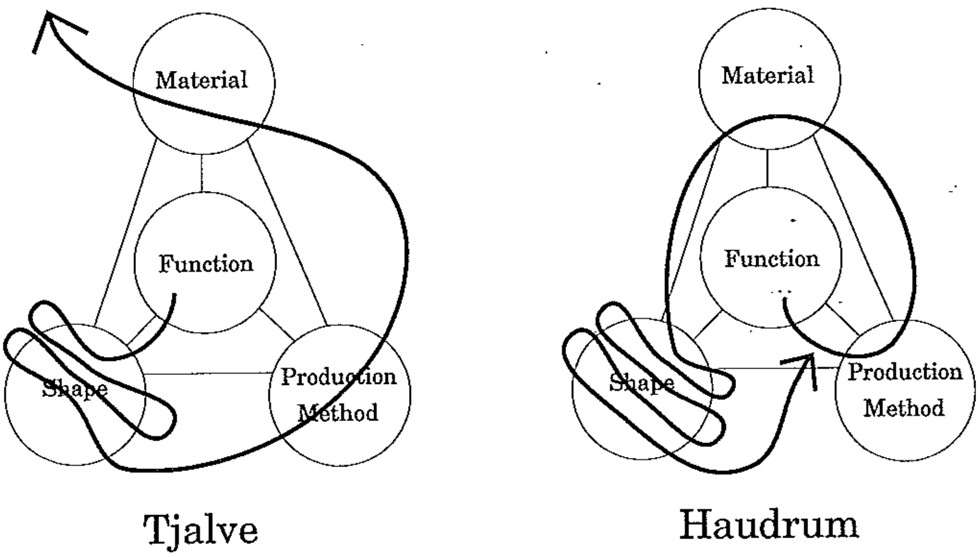

***Figure 72** Tjalves and the authors's methods shown schematically.*

This method has at least two advantages compared to Tjalve's form variation method, namely that:

- The production methods are used as a source of inspiration when creating component main shapes (form concepts).
- Shapes that are impossible to produce are avoided.

Tjalve's objective is the systematic drawing up of alternative form concepts, while the author's method is the systematic consideration of process/material combinations. When these two tools are combined in component design, the designer is able to systematically exploit the solution space for component solutions. Figure 72 shows the two methods schematically.

Figure 73 shows an example of how the author's method has been utilized to set up alternative component solutions for bottle openers. As already mentioned in Chapter 1, numerous different production processes are used in the manufacture of bottle openers. The figure shown here gives a few examples of how these solutions can be systematically set up, when the material/process combinations are systematically considered. Some combinations have been deleted (the grey circles) in order to illustrate that some combinations are unrealistic when the function of the bottle opener must be fulfilled.

Process/material matrix

As shown in the bottle opener example, as a basis for the method, the relevant and possible production methods/materials combinations can be shown in a matrix. In the sketching phase of component solutions, it is initially only the main shape of the component, which is sketched and consequently it is only relevant to consider processes which create the main shape of the components - in the following, called the main processes.

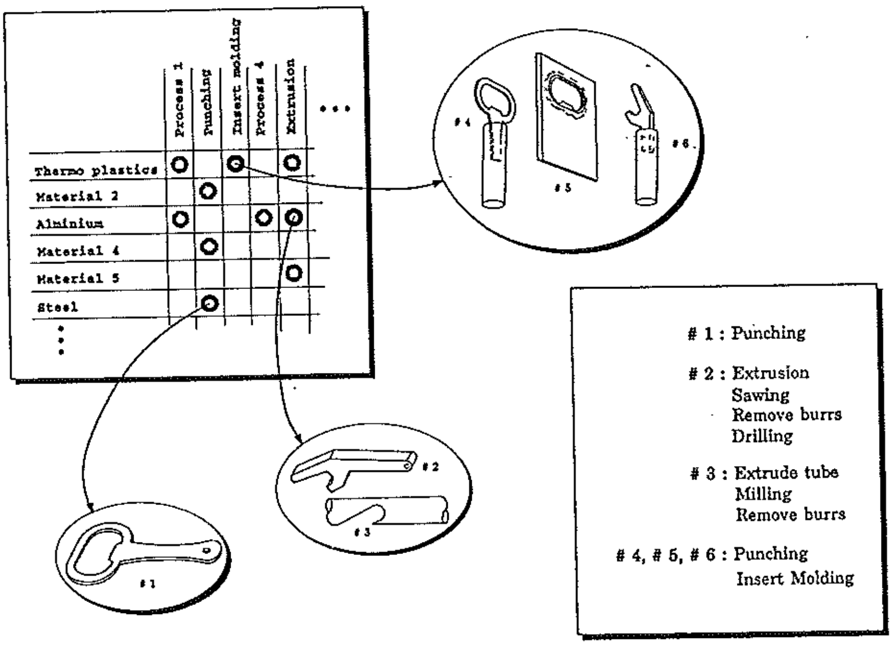

Figure 73 The method used to set up solutions for bottle openers.

Examples of main processes are injection moulding and extrusion. As can be seen in solution #3-6 in the bottle opener example, the solution can appear by combining several of the main processes (here extrusion/milling and punching/injection moulding respectively).

In a practical situation, it will often be possible - with the starting point in the previously described criterion-related specification - even from the process/material matrix to reject processes (and materials) which are unsuitable for consideration (see Figure 74). It is naturally to a certain degree permissible,

> *but the designer ought to make every effort to also consider processes which apparently could be deleted on the basis of the criterion-related specification.*

There is no harm in considering processes and in sketching solutions, and it is possible that some sound solutions will arise from the fact that decisions made earlier in the process are questioned, since these solutions could not have been foreseen at that point.

Psychological effect

An important factor in the utilization of a material/process matrix as a starting point is that the designer is forced to consider all possible combinations. It might be alleged that the designer will just delete the processes with which he is unfamiliar etc, but the author believes that the action of deleting possible combinations in a table has a great psychological effect. With just a small amount of self-discipline, the designer must give arguments (at least to himself) that a combination should be deleted, and this will certainly lead to a mental process relating to the fact that processes can simply "be forgotten" without having to come up with valid arguments for the fact that they are unsuitable.

Relevant production methods to be considered when sketching solutions.
As mentioned above, it is not all production methods that are potential possibilities when sketching the main shape of the components. As a starting point, it is only main processes which are relevant in the sketching of solutions. In the following, the processes which ought to be included in a process/material matrix is discussed, as well as whether it is possible to divide the material/process combinations into types of categories, so

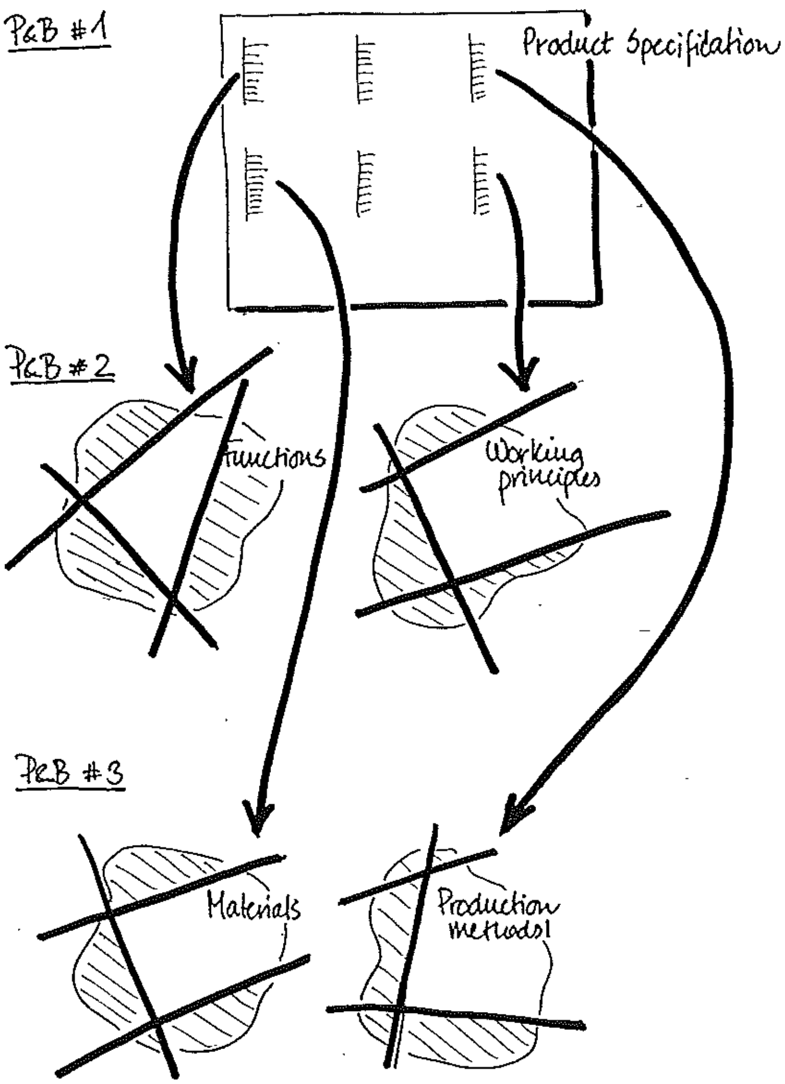

Figure 74 Often it is possible to reject some production methods from the product specification.

that it is only necessary to consider the individual categories. The author has decided to concentrate on metal and plastics processing production methods, which cover by far the majority of the relevant production processes capable of being utilized within the sketched target groups.

Mechanical processes		Thermal processes		Metal forming		Casting/ molding	
Boring..	B	Cavity-type EDM	B	Cold heading	B	Die casting..	A
Broaching	B	Wire EDM	B	Cold forging..	A	Permanent mold casting	A
Drilling	B	Gas/Torch cutting	B	Upset forging	B	General Investment casting	A
Filing..	C	Plasma arc cutting	B/C	Swaging	B	Sand casting..	A
Gear cutting..	B			Thread rolling		Shell mold casting	A
Milling/routing..	A/B			Deep drawing	A/(B)	Plaster Mold casting	A
Parting/grooving	B/C			General stretch forming..	B	Uniaxial powder compaction	A
Plaining/shaping	B			Tube drawing	B	Blow molding	A
Reaming	C			Wire/bar drawing	B	Compression molding	A
Sawing..	B/D			Roll bending/ forming..	A	Extrusion molding	A
Threading..	B			Roll bending (profiles/rods)	A	Filament winding	?
Turning/facing	A/B			Tube bending		Injection molding	A
Abrasive jet machining	B			Brake forming		Rotational molding	A
Grinding..	C					Thermoform molding	A/B
Conventional blanking	B					Transfer molding	A
Nibbling	B						
Piercing..	B						
Edge preparation..							
Shearing	D						
Steel-rule-die-blanking	A						

***Figure 75** The production methods in* ALLEN & ALTING 86 *can be sorted into categories. A: Macro shape creating, B: Micro shape creating, C: Surface treatment and D: Separating processes..*

When using the manufacturing process manual written by ALLEN & ALTING 86, it is possible to sort the production methods described into categories as described in Figure 75. And as can be seen, it is only the following production methods which create main shapes and consequently should be included in the sketching phase: milling, turning, steel-rule-die-blanking, powder compaction, cold forging, deep drawing, roll bending (forming), roll bending (profiles/rods), die casting, permanent mould casting, general investment casting, sand casting, shell mould casting, blow moulding, compression moulding, extrusion moulding, injection moulding, rotational moulding, thermoform moulding and transfer moulding.

Although the manual includes numerous production methods, there are some processes which are not included but which are potential when sketching solutions, namely the metal process extrusion and several plastics processes such as: insert, outsert, multicolor and air injection moulding.

The objective here is not to make a complete list of the processes that should be considered in the sketching step, but rather to point out that it seems to be a good idea to consider all netshape and near netshape processes plus some other processes which can deliver macroshapes, for instance, milling and turning. As a passing remark, it can be mentioned that quite different processes are potential when setting up the process chains.

It must be assumed that the designer can decide at an early stage whether a component is to be manufactured in plastics or metal (or another main category) so it is therefore expedient as a starting point to divide into two matrices, namely one for plastics processes and one for metal processes. In situations where it is not possible to decide whether a component should be manufactured in plastics or metal, both matrices can be consulted.

The level for the description of material is here, of course, for metals such as: copper, aluminium, iron etc, whereas for plastics it is: PE, PS, PA etc. The two matrices are shown in Figure 76.

Plastics processes	Polystyrene	Nylon	Polyethylene LD	Polyethylene HD	ABS·	PEEK	PVC	Polypropylene	Polycarbonate	Acrylic	● ● ●
Injection moulding											
Rotaional moulding											
Blow moulding											
Compression moulding											
Extrusion											
Thermo forming											
Transfer moulding											
● ● ●											

Metal processes	Irons	Steel	Heat and corr. res. alloys	Aluminum alloys	Copper alloys	Lead alloys	Magnesium alloys	Nickel alloys	Tin alloys	Titanium alloys	Zinc alloys
Milling	●	●	●	●	●		●	●		●	●
Turning	●	●	●	●	●		●	●		●	●
Steele-rule-die-blanking		●		●	●		●	●		●	●
Powder compaction	●	●	●	○	●			○		○	
Forging	●	●	●	●		●	●	○		○	
Deep drawing		●	●	●	●						
Roll forming		●	●	●	●						●
Die casting				●	○	●	●		○		●
Permanent mould casting	●	○		●	○	○	●	○	○		○
General investment casting		●	○	●	●		○	●			
Sand casting	●	●	●	●	●	○	●	●	○		○
Shell mould casting	●	○	○	●	●			○			
Extrusion		○	○	●	●	○	●	○	○	○	○

Figure 76 *The two sketched process/material matrices.*

7.2.2 Combination of two main processes

The method for consideration of main processes set up in section 7.2 naturally enough poses the question: "Are all relevant production processes considered in this way and are all relevant solutions found"?

It is obvious enough that the form concepts which occur in Figure 70 through the combination of several main processes (including the component solution marked *) do not appear if one takes ones starting point in either the metal or the plastics process matrix. It is perhaps also somewhat misleading that in the bottle opener example solutions appear, which are a combination of two main processes. The metal and plastics process matrices assume that a main shape is produced by a single main process and this is not always the case. It is therefore necessary to set up a further matrix, which combines different main processes and where these main processes are part of the total process chain, each in its own way, see Figure 77. By means of this matrix, it also becomes possible to place main processes

	Primary main processes \ Secondary main processes	Drilling	Milling	Turning	Steele-rule-die-blanking	Powder compaction	Forging	Deep drawing	Roll forming	Die casting	Permanent mould casting	General investment casting	Sand casting	Shell mould casting	Extrusion	Injection moulding	Rotational molding	Blow moulding	Compression molding	Extrusion	Thermo forming	Transfer moulding
		Metal														Plastics						
Metal	Drilling																					
Metal	Milling	●								1						1		1				
Metal	Turning	●	●							1						1		1				
Metal	Steele-rule-die-blanking	●	●					●								2						
Metal	Powder compaction	●	●	●			○									1		1				
Metal	Forging	●	●	●												1		1				
Metal	Deep drawing	●	●																			
Metal	Roll forming	●	●													1		1				
Metal	Die casting	●	●	●												1						
Metal	Permanent mould casting	●	●	●																		
Metal	General investment casting	●	●	●																		
Metal	Sand casting	●	●	●			○															
Metal	Shell mould casting	●	●	●																		
Metal	Extrusion	●	●	●												1						
Plastics	Injection moulding	●	●			6										3		4				
Plastics	Rotational molding	●	●																			
Plastics	Blow moulding	●	●																			
Plastics	Compression molding	●	●																			
Plastics	Extrusion	●	●															5				
Plastics	Thermo forming	●	●																			
Plastics	Transfer moulding	●	●																			

1) Insert moulding
2) Outsert moulding
3) Multicolor moulding
4) Injection/blow moulding
5) Blow moulding
6) Metal injection moulding

Figure 77 The matrix where main processes are combined.

such as outsert moulding, which is in fact a combination of sheet metal working and injection moulding, but which has been given its own name.

Vertically, there are examples of processes which are the first link in the chain, and horizontally examples of processes, which come in as the second. As can be seen from the figure, it is not all main processes which can be combined, while some processes can exclusively come in as the first process (i.e. extrusion, powder metallurgy) and others as exclusively the second (i.e. drilling). Finally, dependent on which process combination they come into, some processes can be included either as first or second processes. Despite the fact that drilling in isolation can not be considered a main process, it is naturally included here in the process combination matrix, since it is a means of achieving the holes which are part of the form concept for component solutions.

Some of the combinations shown are so well known that they have been given their own names (i.e. insert and outsert moulding). These process combinations are marked in the figure by a filled mark and a number which refers to a footnote at the bottom of the figure. Other combinations have not, to the authors knowledge, been exploited, but could in principle easily be combined; these are marked by an open mark. Combinations which are not marked are impossible.

7.2.3 The process information needed to sketch solutions

The big question is whether it is at all possible to present information on production methods in a simple way that makes it possible for any designer (regardless of his current knowledge and experience) to design a component for the given process? The question is whether this is practicable, or whether the designer needs to work with the processes himself and achieve experience and a close relationship to the process before he is able to make even the most simple sketches on parts produced by means of the process. The author believes that:

> *the designer must have some idea of what the part should look like, before he can consult an expert on the production method and obtain more detailed advice on shaping.*

The author thinks, therefore, that the designer must be able to sketch component solutions without help from the production engineer. In order for this to be possible, it is obvious that the designer must be aware of which form concepts each individual main process offers, and the aim is therefore to provide the designer with process information that makes it possible for him to make rough sketches of the component shape, and to ensure that he does not consider macro shapes that are impossible. The production engineer might later help him to design the part in detail in order to utilize all the capabilities of the process.

As a starting point, it must be assumed that it is possible to present process information in a way that enables the designer to make these form concept considerations on his own. To create a model for the information needed in sketching component solutions, a number of production methods were analyzed. Combined with experience gained from Cases 1 and 2, a model for the kind of information needed by the designer if he is to sketch solutions, is suggested here. This information could be split up into two groups:

- A process description
- Information on possible and impossible form concepts.

The process

The process description should give the designer an impression of the process. He must know how the process is carried out, since this will give him information on possible shapes that are difficult to describe in specific rules. For instance, it is obvious from the description of extrusion, that side holes are impossible to make. Another important point provided by this process description is the fact that it would be impossible to inform the designer about all possible forms of geometry in a part. Some examples can be presented, but the best way is through the information on how the process runs, which enables the designer to invent new possible shapes. The process could be shown as sketches, a video-tape, computer animation etc. The important thing is, that the designer is given an impression of how the process runs.

Form concepts

Information on possible and impossible form concepts is also needed by the designer. This information is difficult to separate from the information needed in the more detailed design for fabrication, but as a guideline for choosing what information he needs at this very first step, where he should sketch component solutions with different production methods, he needs to know about:

- Possible outer dimensions (length, height and width)
- Possible features
- Ratios between features and dimensions
- Limitations on possible features
- Impossible features

Dimensions

Possible outer dimensions (length, height and width) are some of the parameters that the designer (at least roughly) knows at a very early stage in the design phase. It is important that he knows about this information before he proceeds too far in generating solutions. The information should ensure that he does not sketch component solutions that are either too large or too small to be produced in the specific material by the specific production methods.

Possible features

Possible features should only be macro shape features and not micro shape features. It is important, for instance, for the designer to know if he can make holes and in what direction, whereas the tolerances of the holes are not relevant in the sketching of solutions.

Ratios

Ratios between features and dimensions. Frequently, it is not possible to give specific quantitative information on possible part dimensions, because the dimensions are interrelating and by raising one, one has to reduce another. Rules on the ratio between interrelated dimension have therefore to be specified.

Impossible features

Impossible features. The designer will often benefit from knowing which features are impossible to make with the given process. Many of these impossible features can be deduced directly from the process description of course, but not all. If the designer knows about impossible features, he will avoid sketching solutions impossible to produce. He will naturally generate designs that need to be improved in detail to fit the process limitations, but which, as an overall shape, are possible to produce. This also means that other adjoining components do not have to be changed on account of corrections to the sketched component, and this is extremely important, since it would be a great waste of time if other parts had to be changed because of the designer's lack of knowledge about a specific production method.

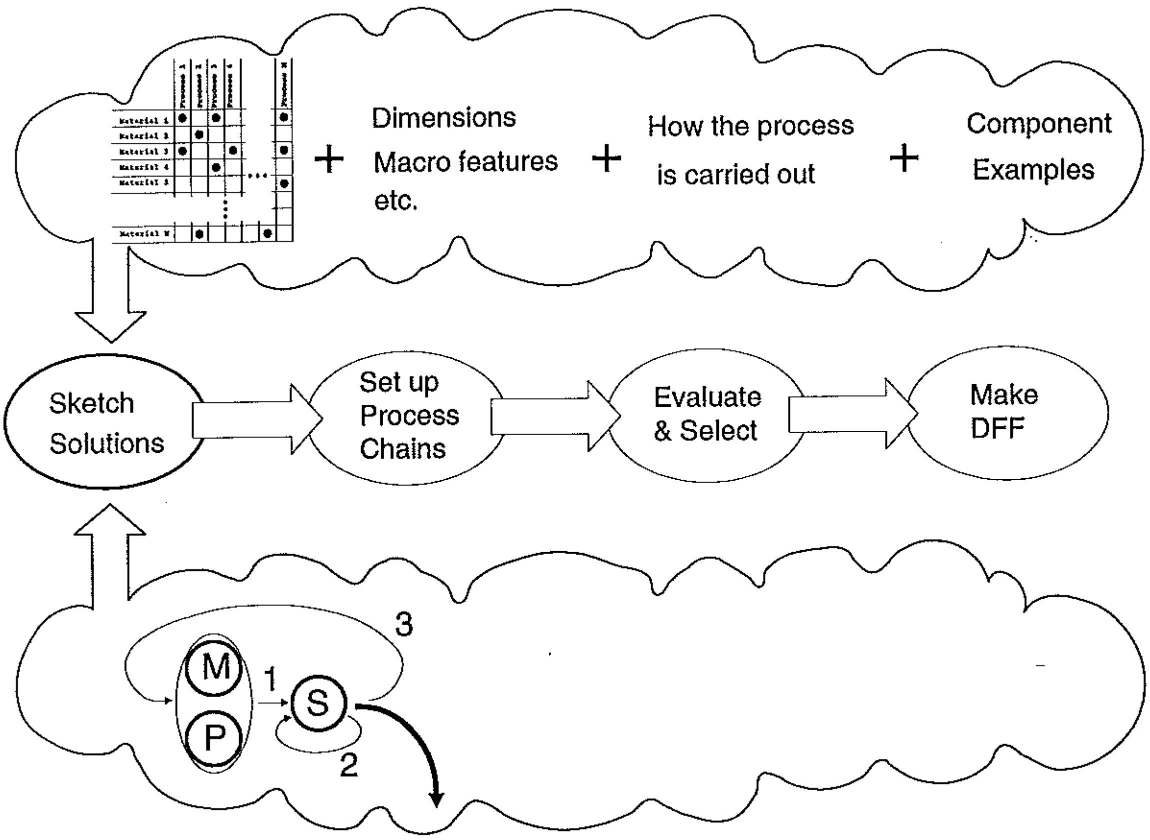

Figure 78 The procedure and the information needed to sketch solutions.

Component examples

Component examples. It is extremely difficult to make a complete list of possible and impossible features for a process. Presenting component examples on past designs is a way of inspiring the designer and of demonstrating to him the possibilities available with the specific material/process combination. For this purpose, pictures showing previous designs or drawings showing general shapes could probably be of great benefit here.

The information needed in the first step and the method to sketch solutions is shown in Figure 78. An example of process information for powder metallurgy is shown in Figure 79.

Powder methallurgy

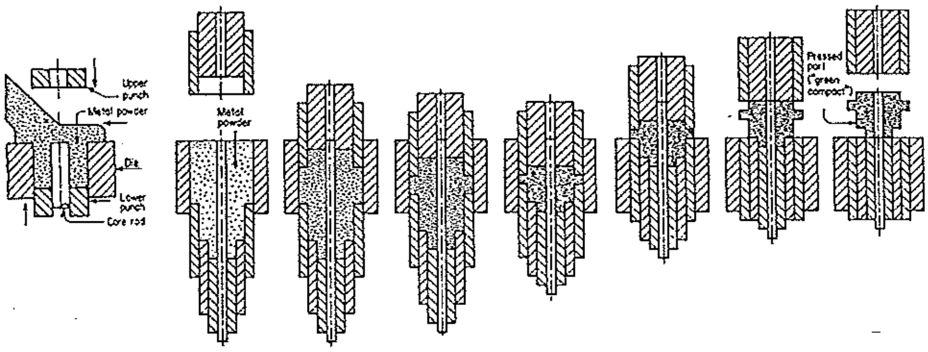

Figure A

The process

Powder-metal parts are formed by compresing metal powders with a press and die and subsequently sintering the piece thus formed. The mixed powder is accurately metered into suitable dies contained within an automatic high-speed compacting press.

The powder is molded to the required shape, at room temperature, by the application of high-tonnage compacting pressure. No binder or adhesive material is used in this operation.

Folowing compacture the "green compacts" are heat treated by the process known as sintering to induce optimum strength. Specialized sintering furnaces, utilizing accurately controlled atmospheric conditions to suit the particular alloy being produced, are used for this operation. For certain products, manufacture is now complete and the components are ready for use without further processing.

Should dimensions tolerances of extreme accuracy be required, the components can be subjected to repressing or calibrating operation.

Important process technical informations

- Powder must be filled into the mold in the shape of the finished component.
- Flow of powder perpendicular to the direction of pressing is not possible.

Main rules

Limits on dimensions:

- Maximum area 3.9 to 16000 mm² (varies for different materials)
- Maximum length 100 mm. (varies for different materials)

Ratio between features and dimensions

- Ratio between wall thickness and length < 18:1 (in special cases < 30:1)

Possible features

- Different wall thicknesses is no problem
- Holes parrallel to the punch movement direction is no problem (D>1.5mm).

Limits on features:

- Blind holes > Ø 6.3 mm
- Minimum wallthickness is 1.5 mm.

Impossible features

- Avoid drafts (except by recesses when they occur on the top side of a part)
- No undercuts, cross holes and threads
- Holes at right angles to the direction of pressing cannot be achieved.

Figure 79 *An example of the information needed by the designer to consider powder methallurgy. Inspired by* BRALLA 86.

7.2.4 Questions which arose in the setting up of the process information model

While setting up the above process information model, several questions arose. These questions could not be easily answered. Below, these questions are listed, while a discussion of the answers to the questions is given.

1. Is it possible to set up a generally applicable definition of the concepts "sketching solution" and "design for fabrication" so that the relevant process information can be placed?

2. It is not possible to name all the possible and impossible features, so on the basis of which criteria are the relevant features to be selected?

3. How are the rules for the different materials best presented?

4. Can materials and processes be grouped, so that process/-material combinations within a group do not differ in component sketches.

5. Is the specified information sufficient to sketch solutions?

6. What is the most optimum way of presenting the information?

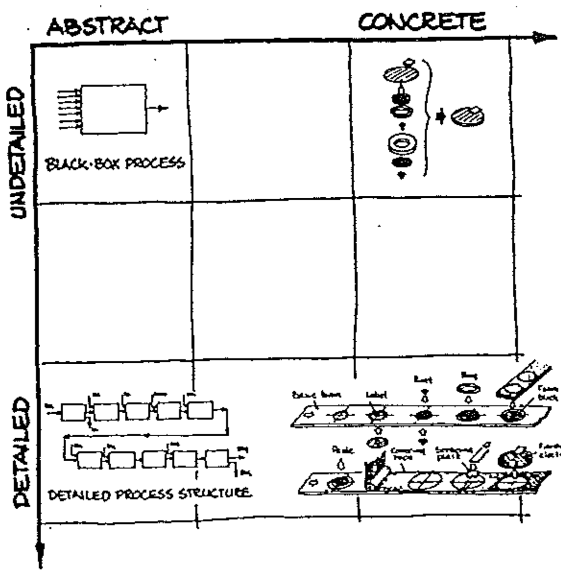

Figure 80 *A two-dimensional plane of design models.* BUUR 90.

Question # 1

In order to be able to differentiate between the process information activity of sketching solutions and the more detailed activity demanded by DFF, it is necessary to make clear limitations and definitions of the two activities. The question is whether it is at all possible. The division between concrete and detailed sketched by BUUR 90, which is shown in Figure 80 is characteristic of the way in which the problem presents itself here, since the component solutions must of course be made concrete, but not too detailed in the sketching activity.

The question is, which process information the designer must have, in order to make the component solutions concrete without going into more than the most necessary detail. The author can not come up with a generally applicable and sharply-limited division between the sketching and design for fabrication activities.

The problem in both this and in several of the following questions actually provides good arguments for the fact that the designer must have component examples which are able to provide him with inspiration. It is quite simply not possible to divide the process information into sharply-limited categories, but component examples will give the designer an insight into the process capabilities.

Question # 2
It is possible to state a number of possible and impossible features, but it is Utopian to believe that all possible/impossible features can be named and described. There is also a choice attached to which features are relevant to describe, but on the basis of which criteria should this choice be made? A couple of possible features are: those features which can not be deducted from the process description, those features of which the designers have no previous experience.

Question # 3
There are different ways in which the information coupled to different materials for one production method could be presented to the designer:

- Every rule is related to the material produced and is presented for the material to which it is related.
- All rules are related to a production method and are presented as being so, but a graph shows the comparative importance of the rule for the specific material.

It is not possible to use one of these information types as a general model. In some cases, the first one is the best and in other cases, the second one is the best. This is due to the fact that some types of information can be divided by degrees (good/bad), whereas others are absolute (possible/impossible).

Examples:

There is a great difference between the possible size ranges for aluminium and steel by extrusion. This information can not be presented as a graph but must be presented as absolute information: size range for extruded aluminium is A mm and for steel is B mm.

In extrusion, the making of holes in asymmetric parts should be avoided. Whereas this is very important for less extrudable materials, it is not so difficult for materials with high extrudability, and therefore the rule can be expressed by adding the importance of the rule for each material.

Question # 4
In order to be able to systematically sketch solutions for each individual process/material combination, it will be an advantage for the designer if the processes and materials can be grouped into categories with common characteristics, so that component sketches of combinations from the same category are not separated. Examples of processes which are closely related are: die casting and pressure die casting and possibly other forms of casting. Materials which can not be separated are, for example, zinc and aluminium (this at least applies for pressure die casting). At the sketching stage, extruded aluminium and extruded plastics can not be separated either (even though the processes, from a technical point of view, differ greatly). It ought to be possible, therefore, to divide process and material combinations into groups with rules etc set up for the individual groups.

Question # 5
The question of whether the sketched process information model contains sufficient information to enable any designer, without any previous knowledge of the subject, to sketch component solutions with the given process, can not be decided until the model is tested. Such a test has not been carried out in the course of this work, but should it be implemented, this could be done by means of video-taping, where novices within a certain process are provided with the information described and on the

basis of this, are set to sketch solutions. A possible "before" and "after" situation can be created by allowing the novice to sketch solutions without having been given the information.

Question # 6
The information on production processes needed by the designer can be presented through several different media.

The process

To show the designer how the processes are carried out, it might be a good idea to use "strip cartoons", video film sequences, computer animation or computer simulation. What is important, is that the designer obtains a visualization of the process, which gives him an impression of what shapes are possible and which are not possible. Moreover, it is important that he gets information on all steps of the process (for injection moulding: plastification, injection, packing, cooling and ejection), because each of these steps makes demands as to the shape of the component.

Features

The information on possible and impossible shapes could also be presented in another way but by means of text. One could suggest several ways, each with advantages and disadvantages, and therefore the best solution could be a combination of some of these different ways. One could suggest the following: One drawing showing all possible features, one showing impossible features and one showing possible but cost-increasing features.

Past designs

Examples of previous designs where a specific production method has been used provide also several possibilities: on video or in pictures (book or computer). Physical effects, such as a "museum" with components produced by a specific production method. This information has two purposes: to give inspiration and to secure producibility.

7.2.5 How the activity of sketching solutions fits in with the individual substeps in P&B.

The four steps in P&B which are connected with sketching solutions are:

- Developing preliminary layouts and form designs for the embodiment-determining main function carriers
- Selecting suitable preliminary layouts
- Developing preliminary layouts and form designs for the remaining main function carriers

- Searching for solutions to auxiliary functions

In the concept, embodiment-determining main function carriers, P&B mean here both the structure of single components (component shapes) and the structure of the entire product (general arrangement). It is obvious that for the single components and their structure, there is a close relationship with production processes. The question is, however, whether it is possible to map out a connection between product structure and production processes or the production system as such. PETERSEN 93 presents a model which shows that there is a connection between the product structure and the production layout (see chapter 3), so it would appear reasonable that it is possible to establish a connection between product structure and the assembly system (layout), but the author is of the opinion that a connection between the product structure and the production processes is not to be found.
The author's argument is:

> *that there is only a connection between the product's structure and the production processes/production system via the single components.*

ANDREASEN ET AL 88 state that the structuring of products can be tackled in several ways:

General principles
- To integrate
- To differentiate

General construction forms
- A frame
- Stacked construction
- Compound-construction
- Base component
- Modules

Product range considerations
- Building blocks
- Standardise

Structural considerations
- Avoid hard tolerance demands on the elements
- Avoid hard surface demands on the elements

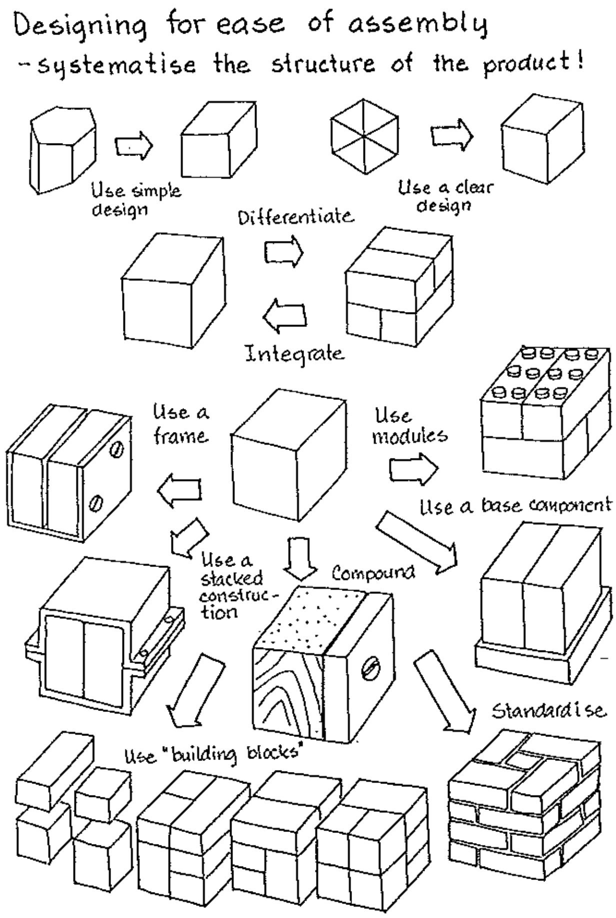

Figure 81 *Structuring principles for design.* ANDREASEN ET AL 88.

See, in addition, Figure 81, which illustrates this.

The question is whether these ways of structuring the product can be related to certain definite production processes or definite groups of production processes.

To integrate

It goes without saying that some processes more than others allow the possibility of integrating different components into one. Processes which can give complicated three-dimensional components, such as injection moulding and pressure die casting give greater opportunities for integration than processes which can only give single components, such as extrusion. But it depends, of course, on the given situation whether specific production can be seen as being integrated or differentiated.

Compound

Integration also includes the construction form compound-construction, in which the integration occurs by assembling different materials to form a permanent structure. Here it is possible, in addition to the traditional assembly processes (welding, gluing etc) to list several production processes which can combine several different materials. Such processes are, for example: outsert moulding, insert moulding, sandwich moulding and many others.

Link to processes

With regard to the other structuring principles, the author maintains that only construction forms which are characterized by single components (frame, base component) can be directly related to production processes. It is difficult to see any connection between, for example, stacked constructiont, modules, building blocks, standardised structure and production processes. For frame and base component, however, it is obviously possible to list a number of production processes which should be systematically considered. These production processes can again, on the basis of the actual product, be divided into relevant and irrelevant production processes. For instance, there is a great difference between the possibilities available for producing a basic component for a bicycle and for a walkman.Figure 82 shows examples of possible production processes with certain

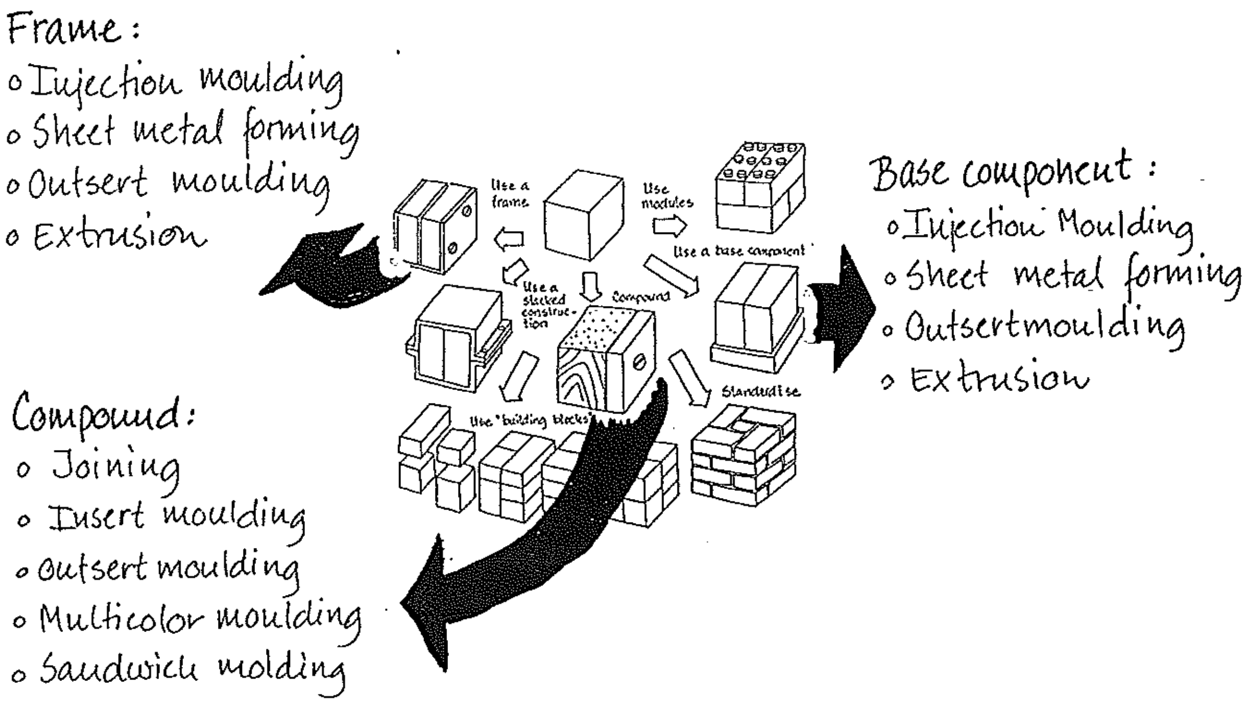

Figure 82 Examples of possible production processes with certain definite product structures

definite product structures. Notice that the named production processes can only be connected with the component which characterizes the structure and in no way can be related to other components in the product.

7.3 The second step: Setting up process chains

As far as the first sketching process is concerned, it is the designer who has the best insight into the demands placed on the component and it consequently natural that it should be he who does the first sketches. With the drawing up of the process chains it is another matter. When the process chains are to be

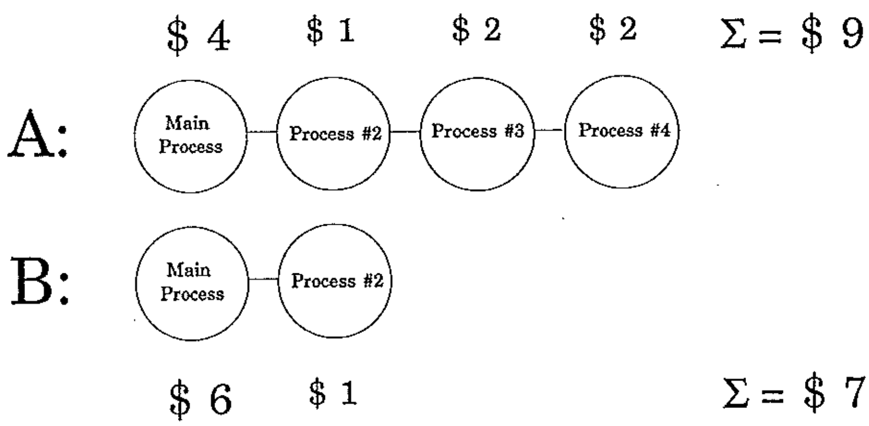

Figure 83 *All the processes in the chain and not only the main process have an influence on the cost.*

drawn up, the starting point is, of course, a given sketch of the main shape and suggestions as to which processes the component shall undergo are based upon the starting condition and the desired concluding condition. A natural question is: "Why not allow the process planner to plan the process chain when the component goes into production?" The answer to this question is that it is important that the designer considers process chains before selecting the final solution for the main shape since:

- The costs of producing the part will change by the pre and post processes and consequently the solution that seemed the cheapest when considering only the main process might not be the cheapest when the whole process chain is considered, see Figure 83.

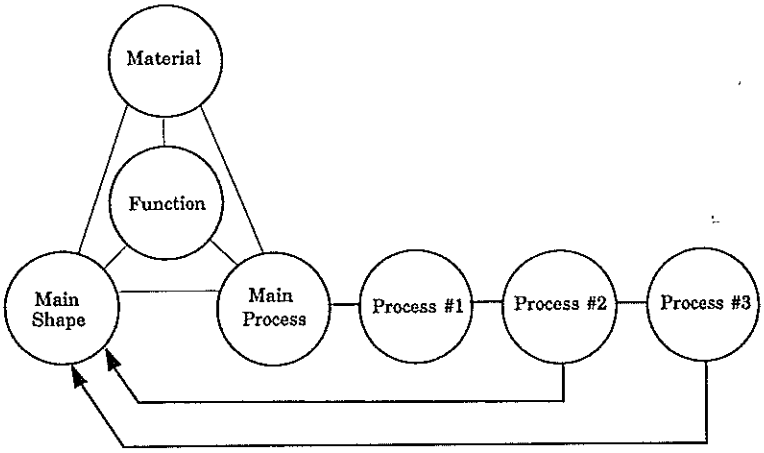

Figure 84 *The post-processes influences the main shape.*

- The post processes often involve demands on the main shape fabricated by the main process and these must, of course, be taken into account before the main shape is finished, see Figure 84.

The designer must therefore at least know which process chains the component must undergo before he chooses the component solution and thereby the main process, but it is not necessarily he personally, who should draw up the process chain. The following assertions about process chains can be set up:

- *Process chains only occur when one process alone cannot deliver the desired properties of the part or when it is in some way more appropriate.*

- *The desired properties are coupled to the function of the part, and the process chain arises as a result of either material limitations or geometrical limitations.*

- *Material limitations are characteristics such as e.g. strength and hardness (usually to be combined with a new material or a hardening etc. which gives the characteristics of the material)*

- *Geometrical limitations are characteristics such as surface roughness, and geometrical and dimensional tolerances.*

- *Net shape processes are preferable and other processes such as machining and surface treatment are only used when net* *shape processes are either too expensive or incapable of delivering the desired properties of the part.*

In order to build up process chains, it must be established for each individual feature (functional surface) of the component whether the given main process and material combination can deliver the desired properties. If not, then which processes/materials can do so? If there is a gap between the output from the main process and the possible input for the process which is capable of delivering the desired properties, extra processes must be build in between them. Consequently, there are three questions which should be answered in order to build the process chain:

- Which properties do I need from each functional surface on the part ? (What do I want ?)
- What can the given main process and main material deliver? (What have I got)
- If there is a gap between these two, how (by which production methods and which materials) can this gap be closed ? (How can I get what I want ?)

7.3.1 Information needed to set up process chains
To answer these questions, the designer needs information on the properties different process/material combinations can deliver. The properties which the process chain must deliver can be divided into material and geometrical properties:

Material-rooted properties

- Hardness
- Colour
- Gloss
- Strength
- Durability
- Resistance to corrosion
- Heat constancy
- Elasticity
- Weight
- Thermal conductivity
- Electrical conductivity
- Magnetic properties
- Permeability

Geometrical properties

- Geometrical tolerances (shape, straightness, roundness, profile form, planeness, cylindricity, surface form), direction (parallelism, perpendicularity, correctness of angle), position (position, concentricity, symmetry) and cast (circular cast, total cast)
- Dimensional tolerances
- Roughness

In order to determine whether a process chain is necessary, and in this case, which processes to be included in the chain, the designer must know the output of the main process and the possible input and output of the properties named above for each individual process.

If, for example, a component must have a certain gloss, the designer must first determine whether the output for the main process/material combination (A) is sufficient. If it is not, the designer must find a process (B), and possibly a material, which can deliver this gloss? If the output from the main process (A) does not correspond to the necessary input from (B), extra processes must be built in between.

The necessary information can be set up in two matrices, which for diverse process/material combinations show possible input and possible output respectively for the above listed parameters.

The post-processes in the chain set up demands for the output from the earlier processes in the chain. For instance, would a drilling process demand specific fixturing surfaces made by the macro shape creating process (e.g. die casting). Consequently, when the designer has a suggested process chain for a part, he has to go back and see what should be fulfilled by the earlier processes to make the post-processes (and post-operations) cheaper, easier, more secure etc. This is part of the P&B step *check and refine the overall layout*. It is very important that the designer is able to visualize how the part should run through the single steps of the process chain and that he understands the importance of building in the properties in the part that make production run smoothly. He must visualize how the part meets every system in the manufacturing process and must ensure that the part is prepared in the best possible way to meet the system.

7.4 The third step: Evaluation and selection

After having set up suggestions for solutions containing both main processes and process chains, the designer must evaluate the solutions against each other and select the best alternative. This is a complicated task, partly because it can be difficult to predict the consequences of a choice at this early stage, when only a few parameters are known, and partly because it can be difficult to obtain an overview of the selection criteria, which ought to be taken into account in the evaluation and finally because it can be difficult to weigh these criteria in relation to each other, since they have different units. Figure 85 shows a review of different authors' proposals to the criteria which ought to be included in the selection of production processes.

Process Selection Criteria \ References	Jansson et al 90	Niebel 66	Ishii et al 90a	Leuau et al 92	Value Control D	Sigurjónsson 90	Tjalve 83	Jepsen 78
Material	X	X	X	X	X	X	X	X
Part shape	X	X	X		X	X	X	X
Part size	X	X	X	X	X	X	X	
Part weight			X					
Tolerances	X		X	X	X	X	X	X
Surface finish			X		X	X	X	X
Basic shape complexity	X			X	X			
Part & Feature variety	X							
Standard parts	X							
Strength	X							
Production quantity	X	X	X	X	X	X	X	
Production rate			X	X		X		
Part count	X							
Material wastage	X				X			
Tool life	X							
Cycle time	X			X				X
Extra operations	X							
Different bugs	X							
Cost of manufacture		X		X		X		X
Time to market			X			X		X
Machine parameters	X							
Complexity of subsystems	X							
Tooling					X			
Strategy				X				X
Pre & Post processes				X				
Quality control				X				
Environment				X				X
Establishment				X				X
Advantages/Disadvantages				X				
Labor					X			
Shape of input material							X	
Number of necessary processes							X	
Number & Type of Machines							X	X

Figure 85 *Different authors' suggestions on which criteria to use by the selection of production methods.*

As can be seen, a great number of these parameters are not accessible for the designer at the stage when only a sketch of the components exists (including tool life and machine parameters).

The dilemma lies in the fact that the designer, (in order to avoid unnecessary time consumption on detailing) is obliged to select at this early stage, when the consequences of his choice are difficult to foresee. It is quite a task, then, to find methods which, on the basis of the few known parameters (dimensions, main shape, surface quality, tolerances, material, process chain, production volume) can establish the values of these selection criteria and thereby foresee the consequences of a certain choice.

Andreasen believes that there exist a few universal virtues, which should be used in the evaluation of solutions, namely: flexibility, efficiency, economy, time, risk, environment and quality. On the one hand, it is difficult to measure these values, since what is it they measure, and on the other, it is difficult to weigh them in relation to each other, since some are quantitative and others qualitative. Ultimately, the designer is frequently obliged to make a subjective evaluation.

The task of assisting the designer can be formulated as follows:

> *On the basis of parameters known at the sketching stage, (dimensions, main shape, material, production chain, production volume) to be capable of establishing the values of the individual universal virtues, so that the sketched solution proposals can be compared.*

It is outside the framework of this work to set up a general model for how criteria can be set up and weighed in relation to each other and how the production processes ought to be selected. This work is limited to investigating the universal advantage of cost; to describing and discussing the methods of cost calculation available today for production processes and to setting up a concept for a cost calculation method which can be utilized at this early stage, when only a sketch of the component and knowledge of process chains are available. Reference is made here to Appendix A, which contains an article written by the author and Torben Lenau, in which such a concept is described.

7.5 Summary

This chapter presents a method of consideration and selection of production processes at the embodiment design level. It is concluded that the designer must have sufficient process knowledge to be capable, at least, of sketching component solutions with the relevant production processes. A procedure which will make the designer consider all relevant production processes is suggested and a model for the process information necessary for this is presented. The question of whether it is at all possible to set up a general process information model is discussed. It is concluded that the designer needs to have knowledge of the way the process works and of the possible forms offered by the process. The question of whether the information on possible and impossible features can be exhaustively presented to the designer is still open. But the author tends to take the position that a major step along the way has been taken just by presenting a number of component solutions, which the designer can run through and from which he can take the versions which are possible.

CONSIDERATIONS ON THE PLANNING AND CLARIFICATION OF THE TASK LEVEL

8

This chapter presents a proposal for the considerations to be implemented at the planning and clarification of the task stage and what should be described in the criterion-related specification in order that the designer knows the guidelines available in the consideration and selection of production processes at the embodiment design level.

Seen from the process selection point of view, the purpose of this first step in Pahl and Beitz's methodology is to set up that part of the criterion-related specification, which influences the selection of processes. The criterion-related specification serves the purpose of assisting the designer in working towards the right objectives and in arriving at the right selection. When the designer must select a production process at the embodiment design level, it is important that he, on the basis of the criterion-related specification, can decipher directly or indirectly, the possible processes from among which he can make his final selection.

It is not the intention here to provide a complete list of the points a criterion-related specification ought to contain but rather to give suggestions as what a criterion-related specification could contain in order to facilitate the designer's selection of production processes at the embodiment design level, and to describe some methods of collecting the information necessary to complete a criterion-related specification. It is important that here the decisions which can assist the designer in his later selection of production processes are as adequate as possible, while it is naturally also essential that the designer's creative opportunities in the synthesis phase are not limited more than absolutely necessary. On the other hand, it ought to be evident to the designer which processes he is able to select between. If the management has, for example, decided that a certain sub-supplier is to be used, or that a certain department must be better utilized, then the possible production processes available to the sub-supplier or department can just as well be listed and described for the designer.

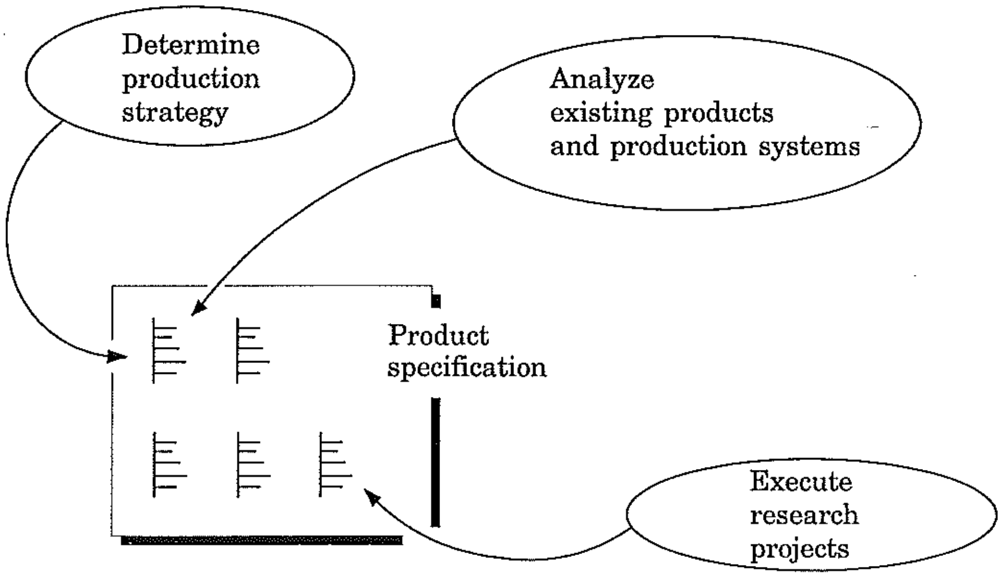

Figure 86 *There are several different activities which can form the basis of the specification.*

8.1 Basis for the fulfilment of the criterion-related specification

As can be seen in Figure 86, the author believes that there are several different activities which can form the basis of this part of the criterion-related specification, which will influence the selection of production processes later in the product development project. These include clarification of the company's production strategy, the designer's knowledge as to processes, concurrent research projects as well as analyses of existing products and production systems.

Production strategy
It is important that the management has decided which direction production is to take. The strategy applies both to decisions on a high level, such as the degree of automation and flexibility, but also decisions on single processes which in the long term are those on which the company will concentrate its resources. Of equal importance to the establishment of a strategy is naturally the fact that it should be clarified for the designer, so that he has the opportunity to select the production processes which are appropriate to this production strategy.

The starting point for the establishment of a strategy concerning the selection of production processes is a mapping of the different processes utilized in the company's products at the present time, and the amount of internal know-how available to the designers/production engineers as well as external know-how at the regular sub-suppliers An examination of the production processes utilized by competitors can also be good input. Awareness of which production processes not utilized in the products, along with an evaluation of potential of these processes in connection with the company's products forms the basis for deciding which production processes on which resources should be concentrated. Some of these can be immediately rejected, while others must be first tested for efficiency in connection with certain design solutions in the product range.

Research projects
In a given product development situation, the selection of some production processes can mean a considerable technological transition for the company. These great technological changes (e.g. to embark upon the production of pumps in plastics/metal by insert moulding instead of aluminium by pressure die casting) can be too tall an order in a development project, since uncertainty as to the efficiency of the solution can involve great risks for the company. It is consequently frequently not possible to implement such a transition in a development project, where a deadline for the product's entry onto the market is a decisive factor as regards the project. These technological changes must therefore be examined in parallel research projects, which can be exploited when the idea has been successfully developed and tested.

In order to be able to do this, the management must select production processes/materials, which in the long term will be able to result in a technological transition for the product, or can in some other way provide benefit to the company and the product. These processes and materials must be sought out and examined for their possibilities of providing new constructive solutions in the product range, whereupon they are adjusted to the desired purpose and are then tested for efficiency in the specific cases.

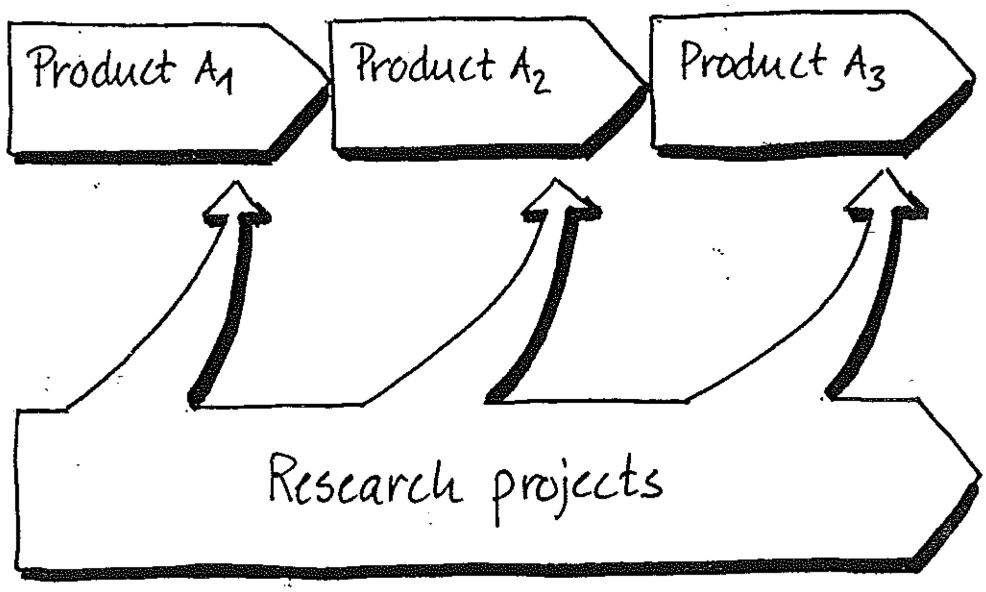

***Figure* 87** *The individual development projects should be provided with input on the usability of processes and materials from research projects.*

The individual development projects are thereby provided with input on the usability of processes and materials from these research projects, input which has not previously been utilized in the product or for a particular purpose in the product, see Figure 87.

Analyses of existing products and production systems

It is only in the minority of cases of product development that an entirely new product is concerned. Frequently, a similar product is already in existence and the desire is to further develop and renew this product. It could, for example, be the company's own product, but could also be a similar product from a competitor. If this should be the case and a product is already in existence, it will give great benefits to learn from the defects in the product so that these are not repeated in the new version, and it would be a good idea to take the existing product as a starting point before the new product is developed. Several angles of entry can be selected, including analyses of the product and production and an analysis of competitors' products.

Product and production analyses. One can obtain a good idea of where the product and production system are not optimum through the product and production analyses, and through this one can clearly understand the problems to be avoided in a new version of the product. Production problems are often due to the fact that the product has not been constructed in the optimum fashion in relation to the production system. It is obvious that such information should be collected and exploited in the development of new products.An analysis of production can refer

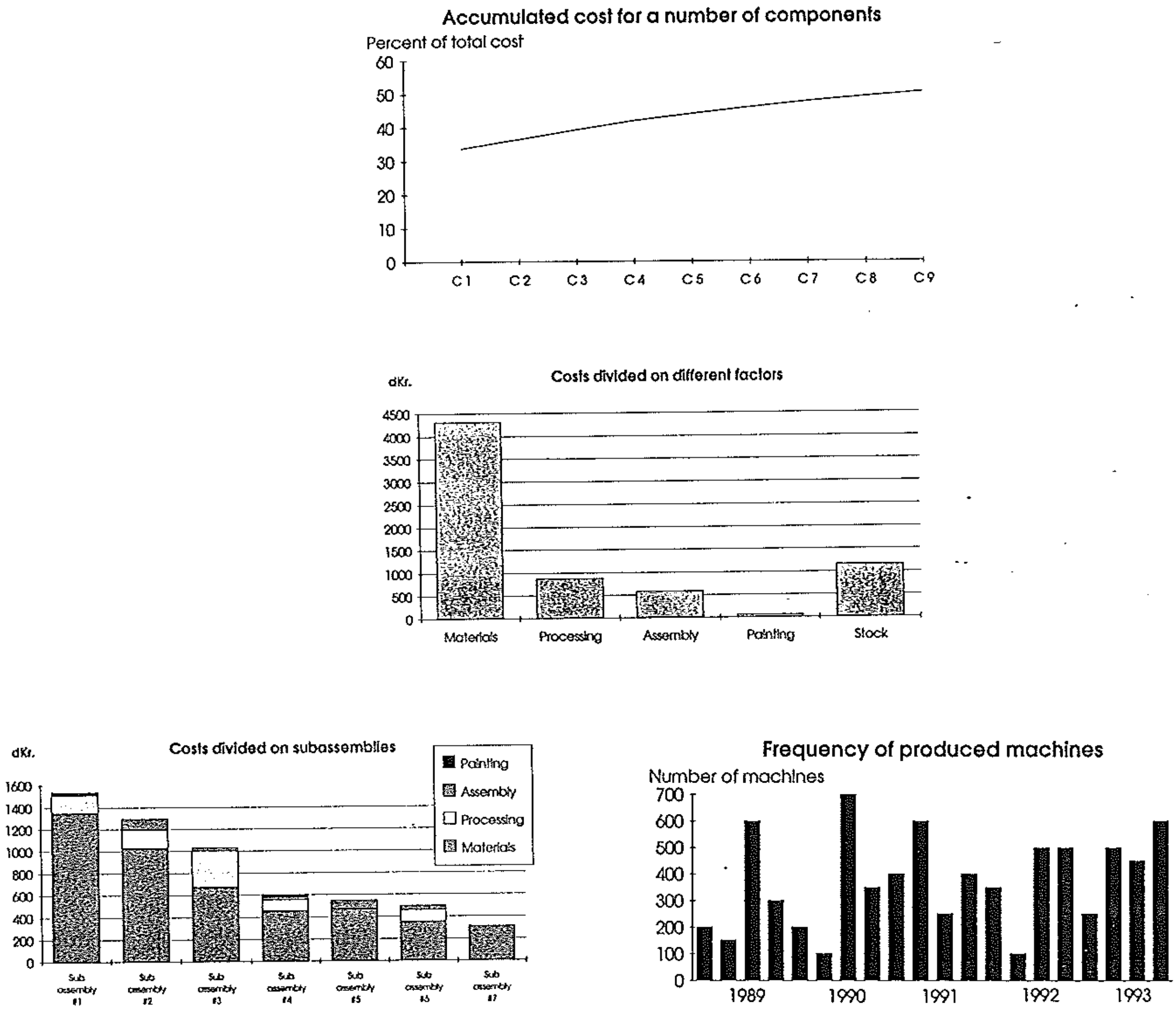

Figure 88 Examples of diagrams which can help to clarify cost profiles for an existing product.

to many different factors, and of these, it will usually be cost which is the most important. In order to facilitate the selection of process for the new product, it is naturally worth knowing how much the individual production of each component amounts to, as well as the cost price of producing and assembling the individual components and system parts, which solve specific functions in the product. But also other types of information, such as e.g., the indirect costs of having the components in stock etc can be extremely useful, since they can point out the fact that new production processes ought to be considered. Figure 88 shows examples of diagrams which can help to clarify cost profiles for an existing product. The diagrams do not each give a direct statement of which production processes which ought to be considered in connection with the new product, but collectively they can be a good tool to give a hint of where new production processes ought to be considered.

Analysis of competitors' products. Before a product development process is initiated, it can often be a good idea to carry out an analysis of competitors' products, where similar products from competitors are purchased and analyzed. Through this, good input for new constructive and production technological solutions can be achieved, just as it is possible to follow trends within production methods, possibly expressed in the production processes' share in percentage in the product.

When carrying out an analysis of a competitor's product, it is important to be aware of the fact that the product has come from

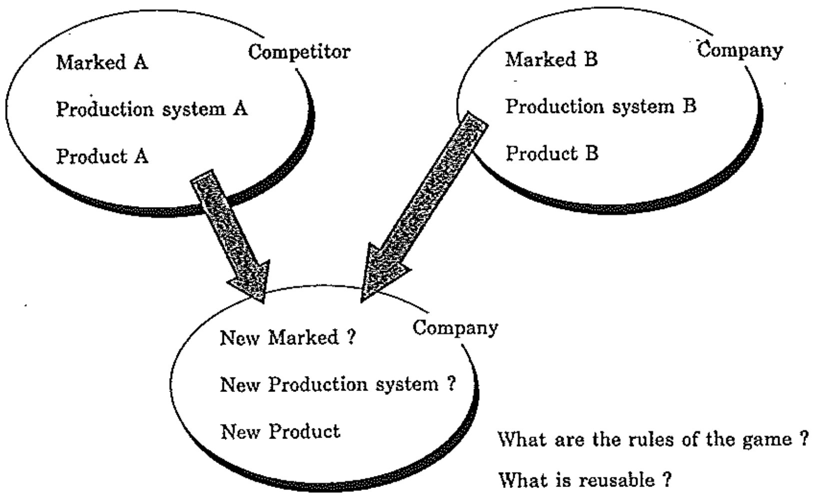

Figure 89 *The product has come from a company which has possibly a different production system and market share than that it is possible to create at the company doing the analysis.*

a company which has possibly a different production system and market share than that it is possible to create at the company doing the analysis, see Figure 89. The competitor's product comes from a certain specific company (A), with a certain specific production system and a certain specific market. Certain definite rules of the game apply, and not necessarily the same ones as in the system in which the new product is to be fitted into. Consequently, constructive and production technological solutions from company A, which on the face of things seem to be sound and usable, can turn out to be unrealistic in company B. For instance, there can be some "smart" constructive solutions, which are only achievable through the utilization of quite specific production processes, but these production processes require major investments. If, for example, the sales figures for company B's new product are far lower than those of company A, or if company A has the process internally in the company, which is not the case for company B, then the situation of utilizing this production process is quite different for company A than for company B. Consequently, it is not always certain that a solution such as that in the competitor's product, which initially appears to be good idea, is actually a good solution in the case of company B.

The conclusion is that, in the case of analyses of competitors' products, one should be careful of taking over smart production technological solutions without considering the consequences of transferring solutions from one production system to another.

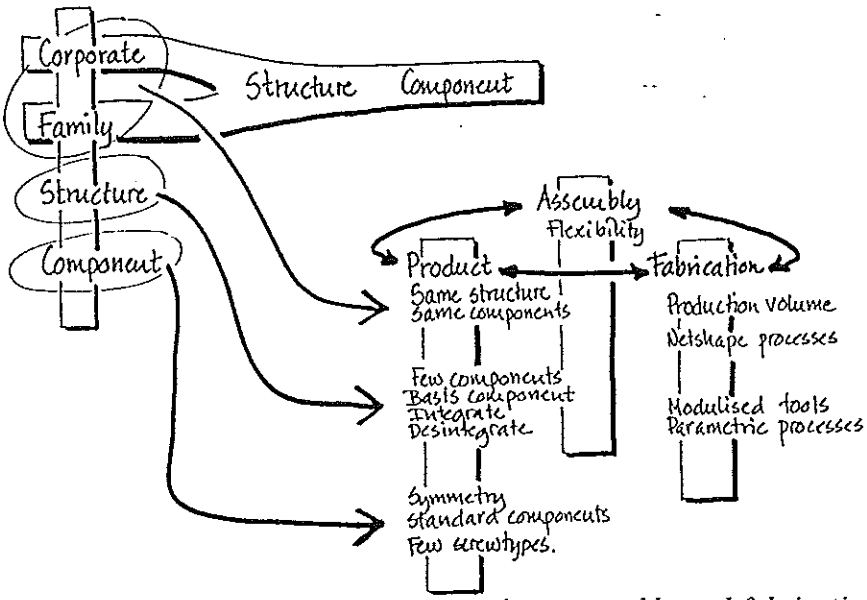

Figure 90 The connection between product, assembly and fabrication on different levels.

8.2 Considerations running across the company's products

In P&B methodology, only a method for the development of a specific product is dealt with. By establishing common features across the company's products and the individual variants within a product family, the possibility of more optimum solutions in both the product and the production system is created. Common features can be established at several levels. FABRICIUS 92 describes four levels:

- Corporate level
- Family level
- Structural level
- Component level

Corporate level

Family level

Corporate level is the relation between the different types of products produced by the company, whereas family level is the relation between the variants in a product family. Common features between the company's different products and variants within a product family can be established at both the structural and component level, see Figure 90, which also shows that common features in the products have an influence on assembly and fabrication. The fact that the products have the same structure has the greatest influence on the assembly system, while the same components have great influence on which production process can best pay. The fact that the same components are utilized in different products will result in a greater unit volume and consequently a greater degree of profitability for processes which require major investments.

Extra functionality

One way of achieving identical components in different products is to exploit the possibilities of the netshape processes to create extra functional surfaces "free of charge", such as, when the component is used in a product (a variant) one set of functional surfaces is utilized, and when the component is included in another product (another variant) or elsewhere in the same product, other functional surfaces are utilized. It is obvious that the greatest effect is obtained if the extra functional surfaces are free of charge, and this makes demands on the selection of process. Figure 91 shows an example from a vacuum cleaner.

Vary the number

Other opportunities for achieving the same components in different products is to vary the number of the same component A, so that, for instance, in one variant of the product there is one example of component A, while in a larger variant there are perhaps four examples of component A.

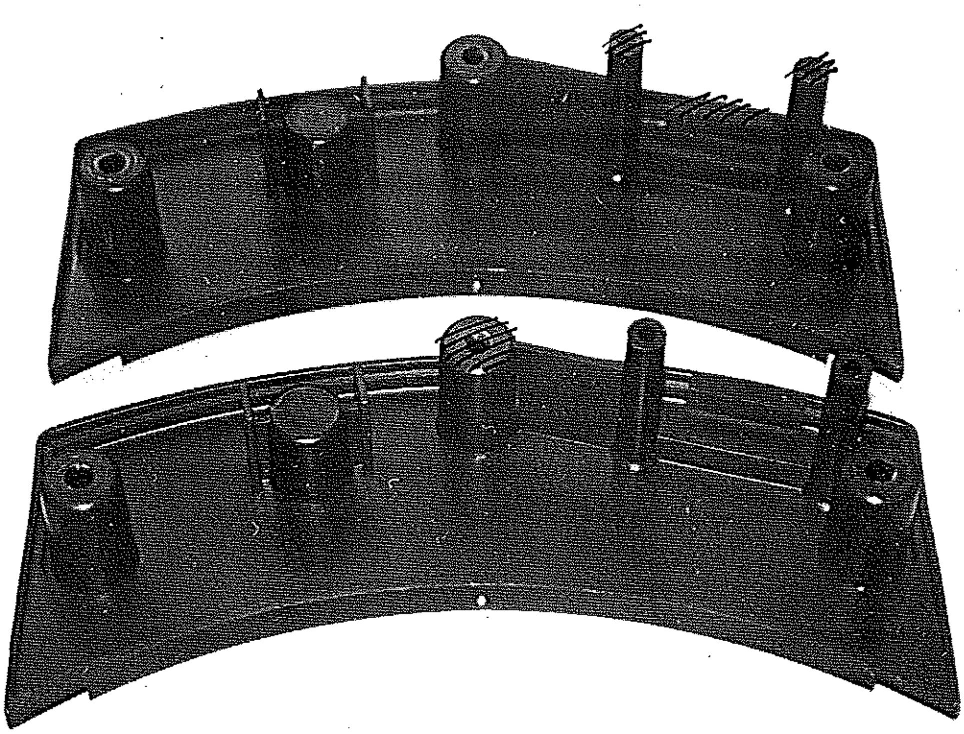

Figure 91 *The component is used twice in the same product but different functional surfaces (hatched) are utilised.*

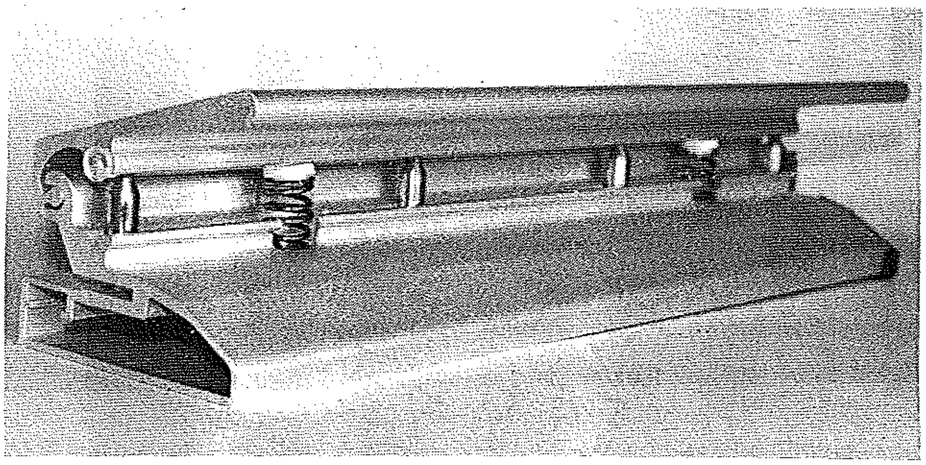

Figure 92 *The hole punching machine can be produced for two and four holes simply by varying the length of the extruded profile and the number of stampers.*

Parametric processes

Variants can also be achieved in a more profitable way by exploiting the possibilities of some processes to create different forms of a component "free of charge". For example, parametric components can be achieved by powder methallurgy and extrusion, in which the height and depth respectively can be varied without extra costs. One example of this is the hole punching machine in Figure 92. The handle and base are made of extruded aluminium. The figure shows a variant of the hole puncher with four holes. In order to achieve a variant with two holes, the two extruded components are simply sawn off in half the length, only two holes are drilled and the number of stampers is halved from four to two.

Moduralized tools

Other processes (for example, die casting) offer the opportunity of producing modularized tools which can be used to create different components by a single change of one module in the

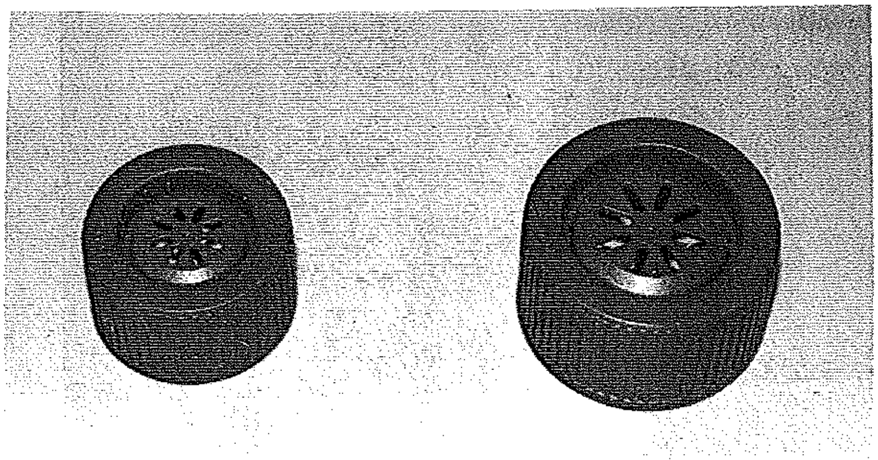

***Figure* 93** *The change from one size of the screw cap to another occurs by means of the exchange of the core and the matrix in the tool.*

tool. An example of this is the two screw caps shown in Figure 93, where the change from one size to another occurs by meansof the exchange of the core and the matrix in the tool. Similarly, the holes in the caps could be left out by utilizing a third matrix.

Structural level is the physical relation between subsystems and parts of a product. Just as for corporate and family level, it is possible, within the framework of a single product, to take advantage of identical components and modularized and parametricized processes. The structure of the product depends on the selection of production process and vice versa, since different processes will provide different possibilities for integrating and disintegrating components.

Component level is the design and specification of the components. Considerations of single components, e.g. cost considerations as already described in the previous section, occur at this level.

8.3 Setting up a criterion-related specification

A good basis for the setting up of that part of the criterion-related specification which influences the selection of process can be achieved through the activities described. A criterion-related specification can include information at different levels of abstraction. A statement at a high level could be, for instance:

- Productivity with low unit costs
- High degree of flexibility
- Short turn-around time
- Short reorganization times
- Rapid and reliable commissioning of new products
- "Green" production
- Low investments
- Establishing production in specific countries

A statement at a low level could be:

- Employing a specific sub-supplier
- .. a specific department
- .. a specific process
- .. a specific machine

High level

With a statement at a high level, it is not immediately possible for the designer to see which concrete processes he has available to select between. Here, he is obliged to evaluate the different production processes against each other in the concrete situation.

Low level

With the statement at a low level, it is immediately possible to see which processes are possible for selection. The lowest level of all is naturally when eligible and ineligible processes are directly named in the specification.

8.4 Summary

In this chapter a number of activities, which ought to be carried out early in the design phase, in order to clarify which production processes the designer of the project ought to consider and select between, are described. It is stated that the management ought to establish a production strategy, which points out the production processes on which the company will concentrate its resources in the future. Tools to determine such processes are described and comprise, for instance, a clarification of internal and external know-how on processes as well as analyses of competitors' products, where process trends are established, possibly measured in the processes' percentagewise share in the products.

Furthermore, there is a description of how solutions and the selection of production processes ought to be considered across the company's product range, since this provides the opportunity of increasing unit volume and thereby of taking advantage of processes which would otherwise only be taken into account in the case of a high volume of sales of the product. The exploitation of different function surfaces in the same component is a decided possibility here, in order to increase unit volume by processes in which the expansion in complexity of the component is free of charge, e.g., by die casting.

The restrictions and liberties inherent in the possibilities for the selection of production processes ought to be described in the criterion-related specification for the product, so that these are known to the designer of the development project.

CONCLUSION

9

This thesis is the final report on the research work: *Creating the basis for process selection in the design stage*. The work focused on two main aspects, namely:

- *to investigate how the selection of production methods is carried out today, and additionally what is needed by the designer to consider more relevant production methods, as well as how he is to make the selection in a more optimum way.*

- *to develope "a better way", which means to develop a systematic procedure for considering and selecting production methods, and to develop an information model describing the production method information needed by the designer in the early design phases.*

The first aspect

The first aspect was handled by means of empirical investigations in two cases, one where the author participated in a product development project and another where students were video-taped solving a design problem. This part of the work was concluded with the general impression that designers consider and select the production methods that they and the company are familiar with, and that a systematic consideration of new and relevant production methods provides the possibility of new and better solutions.

The second aspect

The second aspect was handled as a theoretical work combined with the teaching of students in *Design for Manufacture* projects. During the literature study it was concluded that the process selection procedures described in the literature were not based on a design methodology and that all authors treat process selection on the embodiment design level. In contrast, this work has been focused on developing a model that fits all the levels in the design methodology described by PAHL & BEITZ 86.

A systematic method

The production method has a close interreletion with the shape, function and material of the component and therefore the production methods must be considered at the stage where the component takes its primary form. A systematic method for doing this is suggested. This method takes its starting point in a process/material matrix, where the possible process/material combinations can be found. The method can be used slavishly by the designer every time he designs a component, but this is naturally not a realistic situation.

A frame of mind

The most important thing is that the designer, by being aware of this method is in a frame of mind, that will automatically make him consider alternative production methods when the situation allows him to do so. As a consequnce, he will consider different layouts of the function carriers and, while doing so, also take different production methods into consideration.

Process chains

It is argued in the report that whole process chains and not only main processes must be considered by the designer in the design phase. Often designers consider only the main process together with the main shape and leave the post process considerations to the production engineer in the production planning activity later in the sequence. This is not an optimum situation, since:

- The costs of producing the part will change by the pre and post processes and consequently the solution that seemed the cheapest when considering only the main process, might not be the cheapest when the whole process chain is considered.
- The post processes often involve demands on the main shape fabricated by the main process and these must, of course, be taken into account before the main shape is finished.

The designer must therefore at least know which process chains the component must undergo before he chooses the component solution and thereby the main process, but he need not personally draw up the process chain.

An information model

A process information model was set up, where information about the performance of the process and possible and impossible features should be presented. Today, after writing this thesis, the author believes that it could be enough simply to present the process performance and a number of component examples. From this information, the designer will probably be able to deduce the possibilities by the production method.

Levels of interest

In the report it is argued that the detail design phase is of no interest, seen from a process selection point of view, since the process should already have been selected at this stage. And it is likewise argued that in general there is no connection between the principle structure of the product and the production methods. This connection can only be found through single components (and their structure) and is therefore only valid in specific cases, where the structure of the product is characterized by one component, such as a base part or a frame, and for these specific cases, the connection is only valid for that specific component.

The planning and clarification of the task level is considered a very important step seen from a process selection point of view. Three years ago, the author had the impression that the problem was to develope a systematic procedure for considerating production methods, and that such a method would be of great benefit, since new production methods could provide new solutions.

A high risk

During the research work, however, the author has changed his view on this and today believes that the risk of selecting a new production method often is too high, and thus it is at least just as important that somebody in the company sets up guidelines for the designer indicating which production methods he should concentrate his efforts on.

Strategy and research

The investigation of a new production method is often impossible in a product development project because there is a deadline for the product to be introduced on the market. Therefore somebody in the company ought to work out a strategy for the production methods which could benefit the company in the next ten or twenty years and subsequenrly parallel to the product development project, investigate and test these production methods and their possibilities for use in specific product solutions.

It was the intention to set up a checklist for process selection-related parameters in the product specification. During the work, the author found it more important to describe what could be done by the company itself to set up its own parameters related to its specific products, and therefore some ideas have been presented in Chapter 8.

Contributions

- a procedure for systematic considerations of production methods that fits the design methodology described by PAHL & BEITZ 86.
- a process information model that fits the designer´s need when sketching component solutions.
- some ideas on how to set up process chains in the design phase.
- verification of video-taping as a tool for investigating how designers consider and select production methods, and a script for how to carry out the studies and analyze the results.
- recognition of the fact that the selection of new production methods is often impossible in a product development

project, and that the company therefor has to run parallel projects, where production methods are investigated for their use in specific product solutions.

Further work
For future research projects in the field of process selection the author suggests that the following is investigated:

- how should a company decide which production methods are relevant for them - in the short as well as in the long term.

- how can small and medium sized companies introduce new and, for them, unknown production methods and at the same time ensure that the risk is at an acceptable level.

A number of questions arose during the work with the systematic procedure (see Chapter 7). They have not all been conclusively answered and therefore some of them should be followed up in future work:

- We need a more clear differentiation between *the sketch solution* and *the design for fabrication*, or at least an investigation into what the more specific differences are.
- An investigation into the grouping of materials and processes into logical segments, where the sketching of component solutions does not differ within the group.
- A deeper investigation into what the information actually needed by the designer when sketching component solutions, and how this information should be presented to him.

Comments on the research work
When the author began this study, not much work had been carried out on problem of process selection at the design stage. The author has worked quite alone on the problem and the most difficult task has actually been to reduce the problem down to a treatable level.

The author has the feeling that it would have been easier to reach good results if several people had been working together on the project, since the best way to achieve results in this kind of research work is through discussions with colleagues. Unfortunately, discussions have been in short supply. It is the author´s hope that this experience will be used in the future, because it will surely help future Ph.D students in the field to minimize their periods of frustration.

This thesis can be regarded as a kind of pioneer work in the field of process selection in design and it is the author´s hope that it can and will be used as a springboard for other researchers in this field - there is still a long way to go !

BIBLIOGRAPHY

References are marked with a ●

Ahluwalia & Ping 90 Process Planning in concurrent engineering environment, S.A.R. Ahluwalia, J.Ping, Proc. 1990 Int Ind Eng.Publ. by Inst of Idustrial Engineering, Atlanta, Norcross, GA, USA, p 535-540

Allen & Alting 86 Manufacturing Processes D.K.Allen, L.Alting CAM software Research Laboratory, Brigham Young University, Utah, 1986 ●

Allen & Swift 90 Manufacturing process selection and costing A.J.Allen, K.G.Swift Journal of Engineering Manufacture, Vol 204, 1990 ●

Allen et al 90a. Development Of a Product Manufacturing Analysis And Costing System, Int. Allen, A J; Bielby, M S and Swift, K G.Forum on Product Design for Manufacture & Assembly, Newport Rhode Island, may, 1990. ●

Allen et al 90b, Manufacturing Process selection and costing,Allen, A J and Swift, K G. Proc. Instn. Mech. Engrs. Vol 204, 1990, pp. 143-148. ●

Allen et al 91. Process Selection and Component Costing System in Support of Product Design, Allen, A J; Swift, K G and Hird, G A.Autotech 91, NEC, Birmingham, UK. ●

Alting 78a Grundlæggende mekanisk teknologi Leo Alting 414 sider Akademisk Forlag 1978

Alting 78b A systematic theory of manufacturing L.Alting Environment and Planning B, 1978, volume 5, pages 131-156 ●

Alting 92a Industriel produktion i det 21. århundrede L.Alting Institute of Manufacturing Engineering Technical University of Denmark, DK-2800 Lyngby

Alting 92b The Change in Manufacturing Environment L.Alting CIRP seminar, Tecnical University of Denmark, June 92

Alting et al 79 Procesvalg-systematiske metoder (Process selection-systematic methods) L.Alting, E.L.Jepsen, J.Jørgensen, G.Jakobsen The Technical University of Denmark, AMT, 1979, (AMT 79.59-A), 94 pages. ●

Andreasen & Ahm 88 Flexible Assembly Systems M. M. Andreasen, T. Ahm Springer-Verlag, Berlin, 1988 ●

Andreasen & Hein 87 Integrated Product Development M.M.Andreasen & L.Hein IFS (Publications) Ltd, UK, 1987, 205 p ●

Andreasen 80 Syntesemetoder på systemgrundlag M.M.Andreasen Instituttet for maskinkonstruktion, Lunds Tekniske Højskole, 1980, 398 p. ●

Andreasen 90 The need for further developments in the modelling field M.M.Andreasen ICED 90, 7 pages.

Andreasen 91a Design for Production M.M.Andreasen Proceedings of ICED 91, Heurista Zürich, 1991 ●

Andreasen 91Fænomen-model for samspillet konstruktion/produktion, M.M.Andreasen, Institute for Engineering Design , DtH 1991. ●

Andreasen 92a Domæneteori(Domain theory) M.M.Andreasen Institute for engineering design, Techniical University of Denmark, IK. no. 92-107B, 1992, 18 pages ●

Andreasen 92b Designing on a "Designers Workbench" (DWB) M.M.Andreasen 9.WDK Workshop, Rigi, March 1992 ●

Andreasen et al 82 Montageteknik - Montagerigtig Konstruktion, Jernets Arbejdsgiverforening, København 1982

Andreasen et al 88 Design for Assembly M.M. Andreasen, S. Kähler, T. Lund, K.G.Swift Springer-Verlag, Berlin, 1988 ●

Asimow 62 Introduction to design M.Asimow Prentice Hall, USA, 1962, 135 p.

Asmussen En god historie K.Asmussen Grafisk litteratur, DK, chapter 10

Bahler et al 90 Constraint Networks for Concurrent Engineering D.Bahler, J.Bowen, P.O'Grady, R.E.Young Issues in Design/Manufacture Integration 1990 The Winter Anual Meeting of ASME, Dallas, Texas, USA November 25-30, 1990, pp 59-67

Berns 80 Denkmodell für methodisches und wirtschaftliches Konstruiren und Gestalten H.Berns Konstruktion 32 (1980) H.1, pp 13-18

Bolz 63 Production Processes - The Producibility Handbook R.W.Bolz Industrial Press Inc, New York, 1963, 924 p. ●

Bibliography

Boothroyd & Dewhurst 89 Product Design for Assembly G.Boothroyd, P.Dewhurst Boothroyd Dewhurst, Inc, USA, 1989 ●

Boothroyd & Dewhurst. Design for Manufacture and Assembly software packet.Boothroyd, G and Dewhurst, P. ●

Boothroyd & Radovanovic 89. Estimating the Cost of Machined Components During the Conceptual design of a Product. Boothroyd, G and Radovanovic, P, Annals of the CIRP vol. 38/1/1989, pp. 157-160. ●

Boothroyd & Reynolds. Approximate Cost Estimates for Typical Turned Parts. Boothroyd, G and Reynolds, C.Journal of Manufacturing Systems vol. 8/No. 3, University of Rhode Island, Kingston, pp. 185-193. ●

Boothroyd 87 Design for Assembly - The Key to Design for Manufacture G.Boothroyd The Int. J. of Advanced Manufacturing Technology, 2(3), 1987 pp 3-11 ●

Boothroyd 88. Estimate costs at an early stage.Boothroyd, G. American Machinist, august 1988, pp. 54-57. ●

Boothroyd et al 94, Product design for manufacture and assembly, G. Boothroyd, P.Dewhurst, W.Knight, Marcel Dekker, Inc., New York, 1994. ●

Bourne et al ? Tolerance-free designs for manufacturing D.Bourne, D.Navinchandra, R.Ramaswamy ? pp 47-69

Brachtendorf 89 Konzeption eines Informationssystems für die fertigungsgerechte Konstruktion T. Brachtendorf Fortschritt-Berichte VDI, Dissertation Reihe 1: Konstruktionstechnik/Maschinenelemente Nr. 176 VDI Verlag, Düsseldorf, 1989, 218 pages.

Bradburn & Stauffer 91 A comparison of knowledge elicitation methods B.Bradburn, L.A.Stauffer International Conference on Engineering Design ICED 91, Zürich, August 1991

Bralla 86 Handbook of Product Design for Manufacturing - A Practical Guide to Low-Cost Production J.G.Bralla Mcgraw-Hill Book Company, 1986, 1120 p. ●

Buur 90 A Theoretical Approach to Mechatronics Design J.Buur Ph.D. Thesis Institute for Engineering Design, Technical University of Denmark, 2800 Lyngby, 1990, 126p. ●

Catania 91 Form-features for Mechanical Design and Manufacturing G.Catania Journal of Engineering Design, Vol. 2, No. 1, 1991, pp 21-43

Christensen 92 Livscyklusvurdering H.W.Christensen UMIP F2, Institute of Manufacturing Technical University of Denmark, DK-2800 Lyngby

Christensen 93 De nye produktionsstrategier og koncepter - Hvilken vej viser de ?, John Christensen, Procesteknisk Institut, Danmarks Tekniske Højskole 1993, 15 pages. ●

Constantine & Hardt 90 Manufacturing Process Simulation for Product Design: Plate Bending. E.J.Constantine, D.E.Hardt Issues in Design/Manufacture Integration 1990 The Winter Anual Meeting of ASME, Dallas, Texas, USA November 25-30, 1990, pp 25-30

Corbett et al 91 Design for Manufacture - Strategies, Principles and Techniques. J.Corbett, M.Dooner, J.Meleka, C Pym Addison-Wesley Publishing Company Inc., 1991, 357 p.

Cross et al 91 Research in design thinking. N.Cross, K.Dorst, N.Roozenburg Proccedings of workshopmeeting held at the Faculty of Idustrial Design Engineering Delft University of Technology, the Netherlands, may 1991

Cutcosky et al 89 Extending concurrent product and proces design toward earlier design stages M.R.Cutcosky, D.R.Brown, J.M.Tanenbaum Proceedings of the Concurrent Product and Process Design Symposium ASME Winther Annual meeting, December 1989, San Francisco, CA, pp 65-73 ●

D'Cruz 92 Optimum efficiency A.D'Cruz Manufacturing Breakthrough March/April 1992, Vol. 1, No.2, pp 95-99

Datsko 78 Production engineering considerations in product design J.Datsko International Journal of Production Research, 16, pp 215-220

Degarmo et al 88 Materials and processes in Manufacturing E.P.Degarmo, J.T.Black, R.A.Kohser Macmillan Publishing Company, NewYork 1988, 1172 p ●

Delbressine & van der Wolf 90 Integrating Design and Manufacturing F.L.M Delbressine, A.C.H van der Wolf Annals of the CIRP vol. 39/1/1990, pp 149-152

Dewhurst & Blum 89. Supporting Analasys for the Economic Assessment of Diecasting in Product Design.Dewhurst, P and Blum, C.Annals of the CIRP vol. 38/1/1989, pp. 161-164.

Dewhurst & Boothroyd. Early Cost Estimating in Product design.Dewhurst, P and Boothroyd, G. Journal of Manufacturing Systems vol. 7/No. 3, pp. 183-191.

DS 90 Introduktion til ISO-standarden STEP Dansk Standardiseringsråd København 1990

Ehrlenspiel & Dylla 91 Wirksamkeit von Konstruktionsstrategien K.Ehrlenspiel, N.Dylla International Conference on Engineering Design ICED 91, Zürich, August 1991 ●

Ehrlenspiel 80 Möglichkeiten zum Senken der Produktkosten - Erkenntnisse aus einer Auswertung von Wertanalysen E. Ehrlenspiel Konstruktion 32 (1980), Nr. 5, S. 173-178

ESPRIT II 90 Integrated Modelling of Products and Processes using Advanced Computer Technologies ESPRIT II - CIM III.1.3.1, project-#2165, 1990

Fabricius 92 En 7-trins fremgangsmåde for skabelse af produktionsvenlige produkter, EUREKA, Instituttet for Produktudvikling, 1992. ●

Ferreirinha 85, Herstellkostenberechnung von Machinteilen in der Entwurfsphase mit dem HKB Program. Ferreirinha, P, Proceeding of ICED 1985, pp. 461-467. ●

Ferreirinha 90. Rechnerunterstützte Vorkalkulation im Machinenbau für Konstrukteure und Arbeitsvorbereiter mit "HKB". Ferreirinha, P. Proceeding of ICED 1990, pp. 1346-1353. ●

Garner & Mccallion ? The Purposeful Design Model: An Architecture for the Effective Integration of Work Roles in a Design Situation A.J.Garner, H.Mccallion, New Zealand

Gu et al 89 FDDL: A feature based design description language P.H.Gu, H.A.Elmaraghy, L.Hamid Design Theory and Methodology - DTM '89, DE.Vol.17 1990, pp 53-63

Halevi & Weil ? Algorithmic systems versus expert systems for capp - application to automatic producing of holes G.Halevi, R.Weill ?

Hasselriis & Olesen 92 Brug af virksomhedscases (The use of field studies in companies) M.Hasselriis, J.Olesen Slides from IPS Research Seminar, Fuglsø, Denmark, October 1992, 3 pages

Haudrum & Alting 93 Structured Methods for Process Selection in the Stage of Design, J.Haudrum and L. Alting, Proceedings of ICCIM'93, Singapore, September 6-10, 1993.

Haudrum & Lenau 94, See Lenau & Haudrum 94.

Haudrum & Mortensen 93. Ten Studies of how Process Selection is carried out in the Stage of Design - A Pilot Project (In Danish), Haudrum, J and Mortensen, N H.report, Institute of Manufacturing Engineering, Tecnical University of Denmark, PI 93.07-A/AP 93.20, june 1993, 140 s. ●

Haudrum 92a Case 1 - En rapport fra deltagelsen i et produktudviklingsforløb på K.E.W. (Case 1 - A report from the particpation in the product development in K.E.W.) J. Haudrum Internal report, maj 1992, 30 pages

Haudrum 92b Establishing the basis for the optimal selection of manufacturing processes in the early stages of design. J. Haudrum The sixth IPS Research seminar, Fuglsø, Denmark, march 1992, 103-118

Haudrum 92c Role-playing used for studying how Process Selection is carried out in Product Design J. Haudrum The seventh IPS Research seminar, Fuglsø, Denmark, october 1992 , 97-112

Haudrum 93a Process Selection Methods in the Stage of Design - State of the Art, J. Haudrum, Literature survey, Institute of Manufacturing Engineering, June 93, PI 93.02-B,AP 93-04, 57 p.

Haudrum 93b How to incorporate Production Method Information into the Embodiment Design, J. Haudrum, 4. symposium "Fertigungsgerechtes Konstruieren", 14./15. October 1993, Egloffstein, Germany, 11 p.

Hoffman 87 The problem of extracting the knowledge of experts from the perspective of experimental Psychology Hoffman, R.R AI Magazine 8(2): 53-67, 1987 ●

Hubka 82 Principles of Engineering Design V.Hubka Butterworth & Co (Publishers) Ltd, 1982, 75 pages ●

Hubka et al 88 Practical Studies in Systematic Design V.Hubka, M.M.Andreasen, W.E.Eder Butterworths, 1988, 138 p. ●

Ishii & Miller 90 Design for Net Shape Manufacturing K.Ishii, R.A.Miller PED v 47, ASME, New York, NY, USA, 1990, p 53-64 ●

Ishii & Nekkanti 89 Compability representation of knowledge about net shape manufacturing K.Ishii, R.Nekkanti Proc. of the ASME Design Theory and Methodology Conference 1989 ●

Ishii et al 89 Compatibility-based Design for Injection Molding K.Ishii, L.Hornberger, M.Liou Proceedings of the Concurrent Product and Process Design Symposium ASME Winther Annual Meeting, December 1989, San Francisco, CA. pp. 153-160

Ishii et al 90/91 HyperQ/Process: An Expert System for Manufacturing Process Selection K.Ishii, S.Krizan,C.H.Lee, R.A.Miller Engineering Research Center, Yhe Ohio State University, USA, 16 pages ●

Ishii et al 90 Methods for Process Selection in Design K.Ishii, C.H.Lee, R.A.Miller Design Theory and Methodology - DTM '90 ASME Annual Winther Meeting, Chicago, Illinois, 1990 ●

Jakobsen 89 The interrelation between product shape, material and production method K. Jakobsen ICED, Harroegate, august 1989, p. 775-784. ●

Jansson et al 90 Generalized Measures of Mnufacturability D.G.Jansson, S.R.Shankar, F.S.K.Polisetty Design Theory and Methodology, DE-Vol 27, ASME 1990

Jara-Almonte et al 90 A Design Environment for rapid Prototyping C.C.Jara-Almonte, A.Bagchi, A.A.Ogale, R.L.Dooley Issues in Design/Manufacture Integration 1990 The Winter Anual Meeting of ASME, Dallas, Texas, USA November 25-30, 1990, pp 31-36

Jepsen 78 b Valg af industrielle fremstillingsmetoder E.L.Jepsen Ph.D. Thesis, AMT, Technical University of Denmark, 1978, 110 pages. ●

Jepsen 78a Udvikling af en hensigtsmæssig strategi for procesvalg E.L.Jepsen AMT-Publikationsnummer AP.78.10-A AMT,Technical University of Denmark 1978, 145 p. ●

Jørgensen 91 Scientific working paradigms Poster IPS seminar, Fuglsø, january 1991, 1 page.

Kalpakjian 89 Manufacturing Engineering and Technology S.Kalpakjian Addison Wesley, USA 1989, 1194 p ●

Kambhampati & Cutcosky 90 An Approach toward incremental and interactive planning for concurrent product and process design S.Kambhampati, M.Cutcosky Issues in Design/Manufacture Integration 1990 The Winter Anual Meeting of ASME, Dallas, Texas, USA November 25-30, 1990, pp 37-41

Kristensen & Andreasen 92. Features describing products and processes, Proceedings of the sixth IPS Research Seminar, Fuglsø, Denmark, 23-25 March, 1992, pp199-136.

Kristensen & Kofoed 91 Danfossundersøgelse - diskussionsoplæg 2 Leslie Kristensen, Lise Kofoed #9/12, 8 sider Laboratoriet for Almen procesteknik, PI, DtH, 1991

Kristensen & Petersen 91 Angrebsvinkler ved videnindsamling og videnstrukturering Leslie Kristensen, Wilhelm Petersen #9/9, 10 sider Laboratoriet for Almen procesteknik, PI, DtH, 1991

Kristensen 90 Proceskæder Leslie Brandt Kristensen #9/1, 10 sider 1990 ●

Kristensen et al 91a Danfossundersøgelse - diskussionsoplæg 1 Leslie Kristensen, Wilhelm Petersen,Lise Kofoed #9/11, 4 sider Laboratoriet for Almen procesteknik, PI, DtH, 1991

Kuffner & Ullman 90 The information request of mechanical design engineers T.A.Kuffner, D.G.Ullman Design Theory and Methodology - DTM '90 ASME, DE v.27, New York, USA, 1990, pp 167-174 ●

Lenau & Alting 91 Models of manufacturing processes for design information systems Torben Lenau, Leo Alting #9/10, 10 sider Laboratoriet for Almen procesteknik, PI, DtH, 1991 ●

Lenau & Alting 92. Models of manufacturing processes for design information systems,Lenau, T. Manufacturing Systems, Vol 21, no.2. 1992, pp. 129-135. ●

Lenau & Kristensen 92 MADED - An Information System for Manufacturing Processes T.Lenau, L.Kristensen Proceedings of IPS Research Seminar, Fuglsø 5-7 October, 1992 ●

Lenau & Kristensen 93 MADED - An Information System for Manufacturing Processes T.Lenau, L.Kristensen Proposed paper for ICED 93, The Hague, 1993, 4 pages. ●

Lenau & Mu 93. Features in integrated modelling of products and their production. T.Lenau, L.Mu, Int. J. Computer Integrated Manufacturing, 1993, Vol.6, NOS. 1 & 2, pp 65-73.

Lenau 92 Procesplanlæggerens nye opgaver T.Lenau Procesteknisk Instistut, DTH, Bygning 425, 2800 Lyngby, 7 p

Lenau et al 90 Sammenhængen mellem konstruktion og produktionsteknisk forberedelse Torben Lenau, Leslie Kristensen, Morten Als Pedersen, Wilhelm Pedersen, Mogens Myrup Andreasen #9/4, 18 sider Laboratoriet for Almen procesteknik, PI, DtH, 1990

Lenau et al 91 Interface between process planning and engineering design components. T.Lenau, W.Petersen, L.Kristensen, J.Haudrum. Proceedings of the fifth IPS Research Seminar, Fuglsø, Denmark, October 1991, pp135-162.

Lenau et al 92 Beskrivelse af processerne pulverpresning, trykstøbning, ekstrudering og stansning (Description of the processes powder metallurgy, pressure die casting, extrusion and punching) H.Borstrøm, N.H.Mortensen, L.Kristensen, W.Petersen, T.Lenau Intern rapport, no. 9.27, sept 1992

Lovrich & Tucker 86 Computer-Aided Selection of Polymeric Materials and Manufacturing Processes M.L.Lovrich, C.L.Tucker III Annual Technical Conference - Society of Plastics Engineers 44 th. Published by Soc. of Plast. Eng., Brookfield Center, CT, USA, p 1388-1392 ●

Ludema et al 87 Manufacturing Engineering; Economics and Processes. K.C.Ludema, R.M.Caddel, A.G.Atkins Prentice Hall, 1987

Maloney et al 89 Compatibility-based Selection of Forging Machines and Processes L.M.Maloney, K.Ishii, R.A.Miller Proceedings of the Concurrent Product and Process Design Symposium ASME Winther Annual Meeting, December 1989, San Francisco, CA pp 161-167

Mason & Cox 89 MIS Experiments: A Pragmatic Perspective R.O.Mason, E. L. Cox A chapter in: The Information Systems Research Challenge: Experimental Research Methods I.Benbasat, J.I.Cash, J.F.Nunamaker Harvard Business School, Boston, Massachusetts, 1989.

Meerkamm Vorlesung: Fertigungsgerichtes Konstruieren - Bildteil (Compendium) H.Meerkamm Friedrich-Alexander-Universität, Erlangen Nürnberg

Miles 90 Design for Manufacture Techniques Help the Team Make Early Decisions B.Miles Journal of Engineering Design, Vol. 1, No 4, 1990, pp 365-371

Motensen & Andreasen 92 Structuring Product Data - based on the Chromosome model. N.H.Mortensen, M.M.Andreasen. Proceedings of the seventh IPS Research Seminar, Fuglsø, Denmark, october 1992

Nevins & Whitney 89 Concurrent Design of Products and Processes A strategy for the next generation in manufacturing J.L.Nevins, D.E.Whitney Mcgraw-Hill Publishing Company, USA, 1989, pp 537

Niebel 66 An Analytical Technique for the Selection of Manufacturing Operations B.W.Niebel The Journal of Industrial Engineering, Vol. 9, No. 11, pp 598-603 ●

Noble & Tanchoco 90 Concurrent design and economic justification in developing a product J.S.Noble, J.M.A.Tanchoco Int.J.Prod.Res 1990, Vol. 28, No. 7, pp 1225-1238

Noggle 85 Advantages and disadvantages of injevtion molding M.K.Noggle SPE PACTEC VIII, February, 1985, pp 158-165

O'Grady et al 91 An Advice system for concurrent engineering P.O'Grady, R.E.Young, A.Greef, L.Smith Int. J. Computer Integrated Manufacturing, 1991, Vol. 4, No. 2, pp 63-70

Oliver 90 A Knowledge-based System (KBS) for the support of early Manufacturing Involvelment (EMI) Activity G.D.Oliver Issues in Design/Manufacture Integration 1990 The Winter Anual Meeting of ASME, Dallas, Texas, USA November 25-30, 1990, pp 37-41

Pahl & Beitz 86 Konstruktionslehre G.Pahl, W.Beitz Handbuch für Studium und Praxis Springer-Verlag, Berlin, Heidelberg, New York, 1986, pp 590 ●

Pedersen & Alting 91 Life-Cycle Design of Products - An important Part of the CIM Philosophy M.A.Pedersen, L.Alting AUTOFACT '91, Chicago, Illinois, November, 1991 16 pages

Petersen & Kristensen 91 Procesvalgssystem/struktur og detaljer Wilhelm Petersen, Leslie Kristensen #9/8, 10 sider Laboratoriet for Almen procesteknik, PI, DtH, 1991

Petersen 92 A Common Language for Integrated Engineering Deisgn and Process Planning, Wilhelm E. Petersen, Ph.D-thesis, The Institute of Manufacturing Engineering, DTU, 1992.●

Petersen et al 91a Beskrivelse af parametre og skeletter Wilhelm Petersen, Leslie Kristensen, Torben Lenau #9/13, 9 sider Laboratoriet for Almen procesteknik, PI, DtH, 1991

Plastics World 90 Design Integrated Manufacturing Simultaneous Engineering Integrating Manufacturing and Design SME Dearborn Michigan, 1990

Quick et al 89 New frontiers in plastic moulding N.Quick, K.Stout Manufacturing Engineer, Volume 68, No. 9, October 1989

Rasmussen 89 A Model for the design of Computer integrated Manufacturing Systems - Identification of Information Requirements of Decision Makers J.Rasmussen International Journal of Industrial Ergonomics, 5 (1990) p 5-16

Rasmussen et al 90 Taxonomi for Cognitive Work Analyses Jens Rasmussen, Annelise Mark Pejtersen, Kjeld Schmidt Risø, September 1990, 154 pages

Rasmussen et al 91 Experimental Distributed Decision Making Scenarios in Manufacturing J.Rasmussen, B.Kaavé, O.Rindom Distributed Decision Making Scenarios: Working Draft, april 91, 22 Pages

Roberts ? Simultaneous engineering and DFM at Cadillac R.S.Roberts ?

Rouse 86 On the value of information in system design: A framework for understanding and aiding designers W.B.Rouse Information Processing and Management, 22, pp 217-228

Schmid 92 The Anthropocentric approach to computer integrated production systems and organisations F.Schmid Department of Manufacturing and Engineering Systems Brunell University, Uxbridge, Middlesex, UB8 3PH, UK. 9 p.

Schmidt & Carstensen 90 Arbejdsanalyse, Teori og praksis Kjeld Schmidt og Peter Carstensen Risø, DK, 1990, 139 pages ●

Schmitz & Desa ? The application of a design for producability methodology to complex stamped products J.M.Schmitz, S.Desa ?

SEAI 90 Design for Manufacturability/Assembly (CIP-LIB) SEAI Technical Publications P.O.Box 590 Madison, GA 30650

Sigurjónsson 92 A contribution to a theory for selecting production methods J.B.Sigurjónsson Ph.D. thesis Department of Machine Design, The Norwegian Institute of Technology, University of Trondheim, 1992 ●

Sigurjónsson 93 Identification and Verification of Production Methods in Component Design. J.B.Sigurjónsson Proceedings of ICED'93, August 17-19, 1993, The Hague, p 1065-1072. ●

Srinivasan & Allen 89 Partitioning and guided search: A generalized approach to problem solving in preliminary design S.Srinivasan, R.H.Allen Design Theory and Methodology - DTM '89, DE.Vol.17 1990, pp 37-43

Stauffer 87 An empirical study on the process of mechanical design, Ph.D Thesis, L.A.Stauffer, Origon State University, 1987

Stauffer et al 91 Eliciting and Analysing Subjective data about Engineering Design. L.A.Stauffer, M.Diteman, R.Hyde, Journal of Engineering Design, Vol. 2, No. 4, 1991, pp 351-366.

Stauffer & Ullman 88 A comparison of the results of emphirical studies into the mechanical design process L.A.-Stauffer, D.G.Ullman Design Studies, Vol No. 2, April 1988, pp 107-114 ●

Stoll 86 Design for manufacture: an overview H.W.Stoll A paper in the book: Design for Manufacture - Strategies, Principles and Techniques J.Corbett, M.Dooner, J.Meleka, C Pym Addison-Wesley Publishing Company Inc., 1991, 357 p. ●

Stoll 88 Design for Manufacture H. W. Stoll Manufacturing Engineering, Jan 1988, pp 68-73

Stomph-Blessing 91 The design process of a complex product: Slected results of an analysis L.T.M.Stomph-Blessing International Conference on Engineering Design ICED 91, Zürich, August 1991 ●

Stören 92 Vellykket Produktutvikling med Aluminium (slides) S.Stören Seminar TUD 18 sept 1992 Subramaniam 92 Representation of producibility constraints B.Subramaniam, K.Ulrich Design Theory and Methodology, DE-Vol. 42, ASME 1992

Suchman 91a The situated Structuring of Everyday Activity Lucy Suchman Cognitive Science Society, Chicago, 1991, 23 pages

Suchman 91b Technologies of Accountability: Of Lizards and Airplanes Lucy Suchman Cognitive Science Society, Chicago, 1991, 20 pages

Suh 84 Development of the Science Base for the Manufacturing Field through the axiomatic Approach N.P.Suh Robotics & Computer - Integrated manufacturing 1984, vol 1 no 314 pp. 397-415

Suh 88 Basic Concepts in Design for Producability N.P.Suh Annals of the CIRP, Vol. 37/2/1988, Keynote Papers, pp 559-567

Suh 90 The Principles of Design N.P.Suh Oxford University Press 1990, 401 p

Talukdar & Fenves ? Towards a framework for concurrrent design S.N.Talukdar, S.J.Fenves ?

Tang & Leifer 89 Observations from an Empirical Study of the Workspaced Ativity of Design Teams J.C.Tang, L.J.Leifer Design Theory and Methodology - DTM '89, DE.Vol.17 1990, pp 9-14

Tikerpuu & Ullman 88 General feature-based frame representation for describibg mechanical engineering design developed from empirical data J.Tikerpuu, D.G.Ullman Comput. Eng. 1988, San Francisco, CA, USA, 1988 Proceedings published by ASME, New York, NY, USA, p 245-253

Tjalve 83 Systematisk udformning af industriprodukter-værktøjer for konstruktøren (Systematic design of industrial products - tools for the designer) E.Tjalve Akademisk Forlag, København, DK, 1983, 233 pages. ●

Trigg et al 91 Open-Ended Interaction in Cooperative Prototyping: A video-based analysis R.Trigg, S.Bødker, K.Grønbæk Scandinavian Journal of Information Systems, August 1991, Volume 3 p 63-86

Ullman 89 A taxonomy of mechanical design D.G.Ullman Design Theory and Methodology - DTM '89, DE.Vol.17 1990, pp 23-36 ●

Ullman et al 90 The importance of drawing in the mechanical design process D.G.Ullman, S.Wood, D.Craig Comput. & Graphics, Vol 14, No. 2, 1990, pp 263-274

Value Control Design Guide 63. Value Analysis Incorporated, 426 Franklin Street, Schenectady, New York, 1963 ●

Wang ? Geometric algorithms and utilities for concurrent product and tooling design

Warnecke et al 86 Montagegerecht konstruieren H.J.Warnecke, R.Bässler, M.Richter VDI-Z 128 (1986), Nr. 15/16, pp 605-609

Weiying et al 89 Rules of constructing primitives for integration of design and manufacture D.Weiying, Z.Ji, Y.Jun Design Theory and Methodology - DTM '89, DE.Vol.17 1990, pp 73-80

Wierda 91 Linking Design, Process Planning and Cost Information by Feature-based Modelling L.S.Wierda Journal of Engineering Design, Vol. 2, No. 1, 1991, pp 3-19

Xerox 91 The Workplace Project: Designing for Diversity and Change Xerox Palo Alto Research Center, 1991, 24 pages.

Yokishawa 89 Design Philosophy: The State of The Art H.Yokishawa CIRP Key Note paper, 1989 ●

Yu et al 92 Computer Aided Design for Manufacturing Process Selection J.Yu, S.Krizan, K.Ishii Department of Mechanical Engineering, The Ohio State University, USA, 1992 ●

Zeidner & Hazony 92 Seamless Design to Manufacture (SDTM) L.Zeidner, Y.Hazony Journal of Manufacturing Systems, Volume 11/No.4, 1992 W.P.Wang, K.Y.Wang, J.M.Beck ?

Zenger 93. A cost based approach to the selection of materials and processes in product design, Zenger, D C.ICED'93, Thague, August 17-19, 1993, pp. 1136-1143. ●

Interesting but unread publications

Agranoff 85 Modern Plastic Enclypedia J.Agranoff Volume 61, No. 10A, McGraw-Hill, New York, 1984-85

Allen et al 85 Manufacturing processes, Manufacturing Consortium Dell Allen, Leo Alting Brigham Young University Prove, Utah, USA, 1985, 17 bind.

Barkan ? Competitive Product Design for Manufacturability P.Barkan, In preparation Macmillan Publishers

Beck 80 Plastic Product Design R.D.Beck Van Nostrand Reinhold Company, New York (1980)

Bishop 85, Huge gaps in designer's knowledge revealed, Eureka, October 1985.

Chen & Wallace 93 Manufacturing information for designers W-J. Chen, K.M.Wallace ICED 93

Dargie et al 82 Computer-aided Design System for Preliminary Material and Manufacturing Process Selection Journal of Mechanical Design, january 1982, vol 104, ASME, 1982

Delbressine ? On the integration of design and manufacturing F.L.M. Delbressine

Dixon et al 88 A proposed Taxonomy of Mechanical Design Problems J.R.Dixon, M.R.Duffey, K.I.Rohinton, K.L.Meunier, M.F.Orlup Proceedings of the 1988 International Computers in Engineering Conference San Francisco, 1988, pp 41-46

Ericsson 82 Protocol Analysis; verbal reports as data K.A.Ericsson, H.A.Simpson MIT Press, Cambridge, MA 1984
Eversheim 82 Organisation in der Produktionstechnik W.Eversheim Band 2: Konstruktion VDI-Verlag, Düsseldorf, 1982

Hubka 88 Theory of Technical Systems V.Hubka New York, Springer-Verlag 1988

Human Problem solving Prentice Hall Englewood Cliffs New Jersey, 1972

Jones 80 Design Methods J.C.Jones John Wiley and Sons, NY, 1980 Brown 80 Design and Manufacture of Plastic Parts R.L.E.Brown John Wiley & Sons, New York (1980)

Koller 79 Konstruktionsmethode für den Maschinen-, Geräte- und Appatebau R.Koller Springer-Verlag, Berlin, Heidelberg, New York, 1979

Kroll et al 88 A knowledge-Based Solution to the Design-for-Assembly Problem E.Kroll, E.Lenz, J.R.Wolberg Computer-Aided Production Engineering Conference, Ann Arbor, Michigan, 1988

Latour 86 Laboratory Life - The construction of scientific facts (1979) B. Latour, S. Woolgar Princeton, New Jersey 1986

Levis et al 77 Product Design Engineering Handbook S.Levis, J.H.Dubois Van Nostrand Reinhold Company, New York (1977)

Meerkamm 89b A Computer aided system for production design(om features) H.Meerkamm, K. Finkenwirth, U. Räse Proceed. of ICED 1989 Harrogate IMechE, London 1989

Meerkamm et al 89a Konstruktionssystem Fertigungsgerecht - ein Expertensystem für den Konstrukteur? VDI-Bericht Nr. 775 "Expertensysteme in Entwicklung und Konstruktion" s. 99-114, 1989

Mewes 72 Ein Informationssystem für die entwicklung und gestaltung von Produkten der Maschienenbauindustrie D.Mewes Dissertation, RWTH Aachen, 1972

Peters et al 90 Design: An integrated approach J.Peters, F.L.Krause, E.Agerman CIRP Annals vol. 39/1990, pp. 599-607

Pugh 74 Manufacturing cost information - The needs of the engineering designer S.Pugh Proceedings of the Information Systems for Designers Southhampton, Paper 12, pp 1-8

Rational analysis for a problematic world Problem structuring ... Jonathan Rosenhead

Rögnitz et al 59 Fertigungsgerechtes Konstruieren H.Rögnitz, G.Köhler B.G. Teubner-Verlag, Stuttgart, 1959

Shah 90 A framework for manufacturability evaluation in a feature based CAD system J.Shah, D.Hsiao, R.Robinson NSF Design and Manufacturing Conference, Tempe, Arizona, Jan. 1990

Steudel 82 Aufbau eines Informationssystems für Konstruktion und Arbeitsvorbereitung z M.Steudel VDI-Z 124 (1982), Nr. 19, pp 713-712

Systematic selection of Materials in Light Weight Design 4th Scand Symp Material Science Trondheim 1986

The elicitation and analysis of data of the mechanical design process. Proceedings of the NSF Design Theory and Methodology Conference Amherst, Conn, June 11-14 1989 Rosenhead ?

Ullman et al 87 Preliminary results of an experimental study of the mechanical design process D.G.Ullman, L.A.Stauffer, T.G.Dietterich NSF Workshop on Design Theory and Methdology, Oakland, CA, 1987
Ullman et al 87 Towards expert CAD D.G.Ullman, L.A.-Stauffer, T.G.Dietterich Computers in Mechanical Engineering 6(3) 1987

Waldron 87 A retrospective study of a complex mechanical system design K.J.Waldron, M.B.Waldron NSF Workshop on Design Theory and Methodology, Oakland, CA, 1987

THE PAPER:
COST EVALUATION OF ALTERNATIVE PRODUCTION METHODS

A

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Cost evaluation of alternative production methods

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Selecting the best of alternative production methods is becoming an increasingly important subject in developing competitive products. Different attempts are being made to supply designers and process planners with methods and tools which will help them to explore alternative production processes. A key issue is the evaluation of such alternative ways of producing proposed components. This paper will discuss this topic and present an overview of cost-calculation methods with an emphasis on the evaluation of components produced by different production methods. Furthermore, a practical method for evaluating alternative production methods is suggested.

Keywords: cost calculation; evaluation; product development

Introduction

The most important evaluation parameter for products is their cost. The product can have excellent properties but if the cost is too high, i.e. the profit is too low, there is no point in producing it. Cost estimation is therefore a very important subject which has been addressed from many different viewpoints. In this paper we will take a general look at previous work on cost-calculation methods that can be applied to the different stages of product development, and in particular we will focus on cost-calculation methods for an evaluation of production methods. Finally, we present a practical cost-estimation method to be used for selection among alternative production methods.

Classification of costing methods

In this paper we have found it appropriate to classify cost-estimation methods based on the stage of the product development at which it is used, as shown in *Table 1*. This is similar to the classification suggested by Ehrlenspiel and Hillebrand[1]. Esawi and Ashby[2] describe a slightly different method where the methods are classified based on their precision and the amount of required information as either macro-, meso- or micro-scaling methods. The proposed classification complies with the Pahl and Beitz design methodology[3].

At the very early product development stages where the development task is clarified and, for instance, an initial market investigation is carried out, rough estimation methods can suggest a cost level for the proposed product. Such methods can be based on a comparison of the product concept with similar products on the market (same product function, same technology or same material) or on a parametric function using parameters such as product weight, material type, technology contents, etc. The result is an indication of a market price for the intended product, and will therefore include both direct and indirect costs (overhead) as well as profit. The cost figure will, of course, be imprecise but can be valuable for decisions about whether to develop the product or not.

The next step in product development is the generation and evaluation of alternative product concepts. Here so-called functional costing methods can be used. For well-known functions such as bearings or linear actuators costs can be calculated based on a few input parameters.

Both for task clarification and the evaluation of product concepts the most common approach has been to consider the costs related to the development and manufacture of the product. But in an increasing number of cases it has become apparent that the customer takes into account the cost of buying, using and disposing of the product (e.g. the energy use and the CFC loss from a refrigerator). Therefore the whole life-cycle cost, which includes development, production, distribution, use and disposal, becomes the true evaluation criterion for the company. Life-cycle cost has been used for aircraft, military equipment and building construction for many years, but it is also becoming important for more low-cost appliances due to increasing energy costs and a more widespread environmental concern. For example, energy consumption is now an important sales factor for electrical devices.

At the embodiment design level costs are evaluated and compared for different materials and processing sequences. Designers often tend to use the few materials and processing sequences with which they are familiar, and methods that can show the value of considering and selecting other alternatives are therefore important.

At the detailed design level cost estimation is primarily targeted towards optimization of the design of single parts with respect to the production method chosen, and cost methods can therefore tell the designer in some cases how to change the design in order to achieve cost savings.

Re-use of existing cost information

Not all costs have to be calculated from scratch since a cost history may exist for previous products. This knowledge can be utilized for variant design and redesign of

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Table 1 Type of cost-estimation methods for different product development tasks

Product development task	Type of cost-estimation method
1. Clarification of the task and product planning	Comparison with existing products, life-cycle costing
2. Conceptual design, evaluation of alternative design concepts	Functional costing, relative costing, life-cycle costing
3. Embodiment design, process selection	Quick costing, relative costs, absolute costs
4. Detailed design, cost rationalization, design for fabrication	Cost structures, feature-based costing, design for cost, variant evaluation

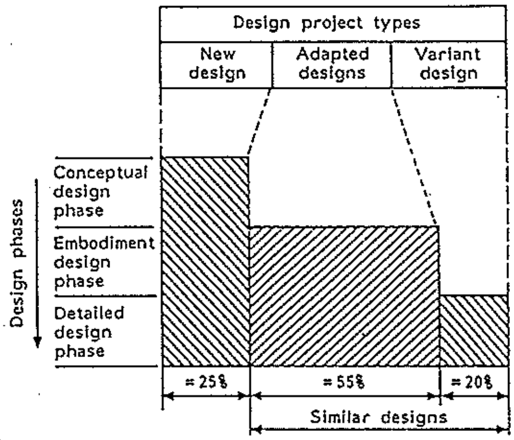

Figure 1 Twenty-five per cent of design work is concerned with new products[4]

products in conceptual design and the subsequent steps in product development. According to Diels[4] only 25% of product design projects are concerned with new products and 75% are either variant design or modifications of existing products (*Figure 1*). This means that cost figures for existing products can be a valuable information source in the majority of design cases.

Basic types of costs

In general, cost can be calculated as either absolute or relative. Both types are most often calculated by using a parametric function, i.e. a function where the cost depends on one or more descriptive parameters. This is called parametric costing and illustrates the principle that a mathematical function calculates a cost estimate based on (a few) important product characteristics.

An absolute cost figure is measured in cost units (e.g. pounds or dollars) in contrast to a relative cost figure which has no unit. Relative costing involves a calculation of a cost figure for an object relative to another known object, e.g. the cost of a gear wheel relative to another known gear wheel. Relative costs have the advantage that they tend to be independent of absolute cost levels and therefore of price development. This makes it easier to create lists of material cost or processing cost. A disadvantage for relative costs is that they cannot show whether the cost is low enough to manufacture and sell the product at a reasonable price. They only compare different solutions.

Methods used in initial design phases

This section is intended to give an overview of cost-estimation methods for early design phases in order to differentiate them from the methods for embodiment and detailed design phases. After a discussion of the life-cycle costing principle, costing methods for task clarification and conceptual design phases (which calculate subsets of the life-cycle cost) are described.

Life-cycle costing

This can be applied to both task clarification and conceptual design phases. Life-cycle cost depicts the principle that all costs related to the manufacture, distribution, use, maintenance and disposal of a single product are considered. Bush and Sheldon[5] describe the need for a methodology to be used by the designer when considering life-cycle cost. The requirements for such a framework include handling of not only the product but also of the total system of which the product is part, that the cost model is simple enough to understand but precise, that relationships between cost-consuming activities and design parameters can be handled and that the accuracy of the results should be apparent. Sheldon *et al.*[6] describe the type of cost to be included in life-cycle costing and illustrate the problems of allocating the overhead cost: adding 200–300% overhead can destroy any good cost estimate. The cost-estimation methods described in the following sections calculate only subsets of the life-cycle cost, e.g. production cost or total company cost.

Task clarification and product planning

At this stage it is decided among other things where the emphasis should be in product development work. In some cases, especially for redesign, it is possible to identify areas for the product which have the largest economic potential. A method for this purpose is the ABC method proposed by VDI[7] and Ehrlenspiel[8]. This is a general method for identifying cost-heavy elements in the product, and should be used for redesign of existing products. The result of using the ABC method is illustrated in *Figure 2*. This method must not be mistaken for the Activity Based Costing mentioned by Bush[5], which is an alternative method for overhead accounting. In the ABC method components and subsystems are divided into three groups, A, B and C, depending on their cost level, with objects in group A having the highest cost. The ABC method is used to prioritize efforts to improve product design and is reliable on access to cost information from previous products.

Another type of costing method for this design phase is the material cost share method described by Creese[9]. This is based on the observation that the material cost

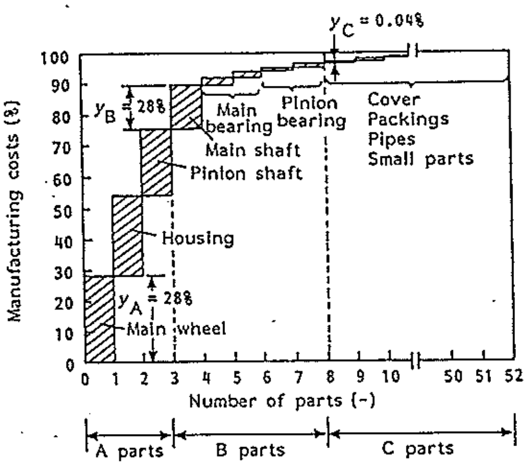

Figure 2 ABC analysis for identification of cost-heavy product elements[a]

share is fairly constant and significant for many groups of products, e.g. cars, machine tools, amplifiers, etc. Predicting the cost of a new product within one of these groups is done simply by estimating the material content and dividing its cost by the material cost share. Measuring tools, for instance, have a material cost share of 20% and a new measuring tool with an estimated material content of \$2 will therefore have an estimated cost of \$10.

Conceptual design
In this design phase cost estimation is related to more general product characteristics such as product functions (functional costing) or subsystems or to a few characteristic parameters (quick costing). Quick costing depicts rough estimation techniques based on parameters such as weight or volume. In some cases quick costing can also be used in the task-clarification phase. Functional costing is a method that estimates costs of parts or subsystems performing a certain function, e.g. gears for torque reduction. The advantage is that cost estimates can be calculated based on a few parameters which are known to the designer at a very early stage and that they are independent of the more specific selections of geometry and production methods. Functional costing can be used for three different purposes:

- Cost estimation directly from part specification (e.g. for quotations)
- Comparison of alternatives
- Detection of potential cost reduction areas (value analysis).

Fereirinha[10] reports a functional costing method developed for a Swiss machine tool producer which is claimed to serve all three purposes. The example given is the lubrication function for the slide on a milling machine, where a cost function can be created based on knowledge of the cost of slide lubrication for different milling machines. Cost calculation based on product functions is possible here because the company has knowledge of the relations between the functions and the cost, due to the fact that they produce variants of the same product. The cost calculated here is probably fairly precise but it is, however, specific to the company.

Ehrlenspiel[8] describes functional costing as a value analysis method to identify expensive areas of a product which is similar to the ABC analysis mentioned earlier. The method is illustrated by a mechanical gear and examples of functions mentioned are torque enlargement and torque guidance. Ehrlenspiel emphasizes that functional costing for this purpose can only be applied when the functional structure and the cost of the solutions are known, i.e. existing products with known cost structures.

French[11] gives a good overview of functional costing and notes that obtaining data for functional cost is difficult except where the product or the component is identical to the function. He describes simple examples of different types of functional costs, where e.g. cost based on product specification is illustrated with the estimation of the cost of a single-stage reduction gear as a function of the torque and the reduction ratio.

Li *et al.*[12] use three examples to illustrate functional costing: bearings, induction motors and linear actuators. Figures in pounds sterling are given. For all three examples the name of the function and the component used to perform the function are identical. It is concluded that functional costs found for the three examples are sufficiently accurate to be used for early estimates and comparisons.

Bradford and Culley[13] describe functional costs for power transmission systems as shown in *Figure 3*. These costs are probably best suited for comparison of alternatives, even though the absolute cost figures also make quotations possible. Esawi and Ashby[2] describe an improved and more precise cost-estimation method for functional costing which also includes considerations of cost levels for material, capital (equipment) and labour.

As can be seen, functional costing is only applicable to parts (or products) where a substantial amount of knowledge about cost exists and clear cost structures can be defined, e.g. standard components. It is also a requirement that the functions are well defined and that reliable data can be accessed. Many standard components are characterized by performing a single main function, and often the name of the component and the function are identical. Functional costing is suitable for use in the conceptual design phase to select among alternative concepts, to identify expensive elements and to calculate quotations, but functional costing is not suitable for evaluation of production methods.

Methods for embodiment and detailed design phases

Within these two design phases both process selection and design for fabrication (DFF) activities take place. Of the cost-calculation methods presented in the literature, some are suited for selection of production methods and others for DFF (or design for cost). When the designer

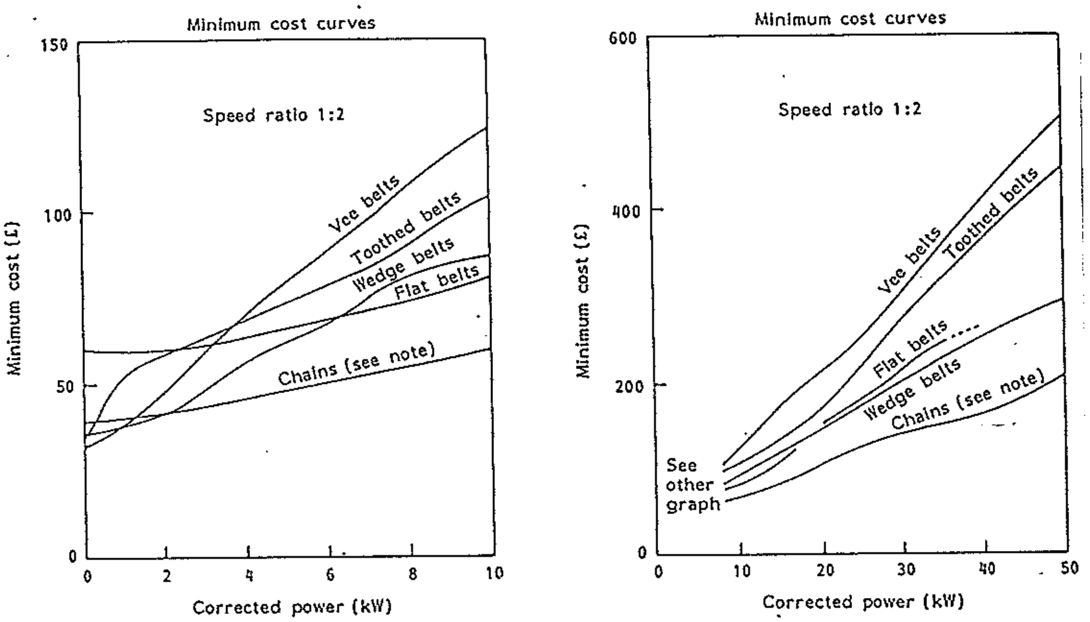

Figure 3 Functional cost curves for power-transmission systems[13]. Note: Chain costing does not include lubrication method: manual, drip feed or oil bath and sump

has selected a number of alternative possible production processes for further consideration, methods that can compare cost for more than one process are needed. In DFF the product design and the selected production equipment are tailored to each other. Costing methods can be used here to inform the designer of the economic consequences of changing the design of a single component, and perhaps to point out expensive areas. Such methods will always be specific to the production process for which they are developed. In a few cases costs calculated by DFF methods for different processes are comparable and can therefore be used to support process selection. The criteria are that absolute costs are calculated and that the input parameters can be used by a designer without a detailed production knowledge.

The question is how much information is necessary about the product/part before the designer is able to make a cost calculation and select a production method. It is obvious that the designer has to know the shape of the part. According to Jakobsen[14], there is a very close interrelation between shape, production method, material and function of a part and therefore these parameters have to be considered and selected simultaneously. Thus when alternative production methods are evaluated, the shape of the part has to be specified at this stage with some level of production relative to the manufacturing method. It is therefore clear that components with identical shapes cannot be evaluated for different production methods. Also, it is important that the different components compared through cost calculations have the same level of production for their respective manufacturing methods.

To avoid this, Haudrum *et al.*[15,16] suggest that the designer, on the basis of the given functions of the component, outlines a number of solutions consisting of material, production method and shape. With each of the relevant material/production method combinations in mind, a number of shapes are produced. This makes it more likely that the solutions outlined are in fact producible by the given production methods and that all solutions proposed for the different production methods have 'same' level of producibility. For example, the shapes of a die casting and an injection-moulded part may not be different at this level, whereas a turned part and an injection-moulded part certainly will be. Only primary processes should be considered when outlining, i.e. the processes that produces the main shapes. It is, however, necessary that the designer plans the whole sequence of production methods for each solution before the cost analysis. Otherwise a solution using an inexpensive main production method may be expensive when the whole production sequence is taken into consideration.

The literature reports 28 methods that calculate production cost for one or more processes. Based on available information, they have been classified as either specific to a single process (e.g. machining or forging) or as covering several processes. Furthermore, important input parameters and purpose are indicated for each method. This classification is shown in *Table 2* and reference numbers are indicated at the top of the table. Filled circles (•) indicate the purpose of the method as reported in the literature and open circles (○) the authors' suggestions for supplementary application areas.—

The following input parameters are shown in *Table 2*: part dimension (diameter/width, length, height, wall thickness), material type, part shape, surface quality,

Table 2 Purpose and input parameters for 28 costing methods

	Machining						Rolled profiles	Injection moulding						Powder metallurgy			Forgings	Sheet metal working		Die castings	Castings		Several production methods		
Reference no	23	24	25	26	27.1	22.1	27.2	28	29	30	22.2	31	32	33	22.3	34	34	36	22.4	22.5	27.3	37	38,39	40	41–43
Input parameters																									
Dimensions	●	●		●		●		●	●	●	●	●			●	●	●			●		●	●	●	●
Material		○		●		●	●					●	●		●	●	●		●	●		●	●	●	●
Shape	●	●		●		●	●	●	●	●	●	●	●			●	●					●	●	●	●
Surface quality	●			●				○	○	●	●									●			●		●
Tolerance	●			●				●	●	●	●				●					●			●		●
Volume				●							●	●			●	●	●			●		●		●	●
Area											●	●			●		●			●					
Prod. vol./batch size				●		●	●						●		●							●	●	●	●
Other parameters			●	●		●							●	●	●	●		●	●	●			●		
Not mentioned					●																●				
Purpose																									
Process selection				○								○	○			●						●		●	●
Quotations	●						●							○									○		
Variant evaluation				○				●	○				○				●								
Design for cost	●	●		●	●					●				●		●	●					●	○		
Process planning			●																				●		
Not mentioned						●					●	●			●			●	●	●	●				

tolerance level, part volume, cross-section area, production volume, other parameters and 'not mentioned', where no information has been available. The input parameters described in the table as *other parameters* are typically not known by the designer at the stage when the production method is selected, (e.g. number of teeth on the cutter and cooling ability). Two papers have not described the input parameters and are therefore marked *not mentioned*. The purposes of the cost-calculation methods are shown in the table as: process selection, quotations, variant evaluation, design for cost and process planning.

It is recognized by several authors that the selection of production methods in the early phases of design has to be made with the knowledge of very few and quite rough parameters. This characterizes the cost-calculation methods called *process selection*. The methods called *quotations* are suitable for calculating offers. Theoretically such methods can be used for selecting processes as well, but several of the input parameters are typically only known by production engineers. Methods capable of evaluating different component solutions (shapes) for the same production method are called *variant evaluation* methods. These are relative methods and can only be used for comparing two alternative solutions for the same process and component. The methods are therefore of little use when different production methods or different structures of the product are evaluated. The relative methods can only be used for the specific process for which they are developed. Furthermore, the production sequence problem are not addressed by these methods.

The purpose of the *design for cost* methods is to help the designer in selecting the most inexpensive solution for a given production method. One type of design for cost methods makes it possible to calculate the cost, change the component and then recalculate. Another type interactively tells the designer which features are expensive and which changes would improve the component cost. Methods dedicated to *process planning* focus on cost of the total production route, and include specific machines rather than groups of machines (processes). A detailed knowledge of production parameters is required.

Boothroyd and Dewhurst[17-21] are represented in the literature with several papers on cost calculation but since these papers describe only parts of their calculation methods, they are not mentioned here. Instead, we have chosen to describe their computer system, where all these calculation methods have been realized[22]. The system for cost calculation includes modules for five different production methods: sheet metalworking, injection moulding, die casting, powder metallurgy and machining.

As can be seen, many cost-estimation methods are developed specifically for a single production method. There are several reasons for this. An obvious one is that many methods are developed by experts within a specific production method. These experts naturally concentrate on their field of expertise. Another reason is that cost factors vary for different production methods. In the milling process, for instance, cost estimation is dependent on the number of different cutting tools which can be translated to the number of different form features. For injection moulding the number of side cores is more important than form features and the estimation algorithm will be different. For extrusion the distribution of wall thickness is essential and for powder compaction the important parameters are the existence of internal features and the number of steps. Factors that influence the production cost are therefore highly specific to individual production methods.

In the following each of the methods are briefly described, their purpose is outlined and, if possible, the input parameters are given.

Cost-calculation methods for machining

The method described by Spur and Kreisfeld[23] is developed for quotations and design to cost. It takes its starting point with the shape of a component and is divided into an envelope shape and local features. Additional parameters such as tolerance and surface quality are also needed. The authors claim that from a classification into 27 envelope shapes and eight local features it is possible to calculate the cost of simple rotational parts. The paper does not describe how the calculations are made, but mentions that the deviation from actual cost is about 10%.

Kreisfeld[24] describes two methods for cost calculation of rotational parts. One method is based on a static and the other on a dynamic classification of 'cost families'. The static method consists of 27 different group describing length/diameter ratio, outer shape and inner shape. The dynamic classification is valid in a computer, where the user selects the criteria used for this classification. According to the author, these methods offer very good results. Except for the 'cost family' classification, the paper does not clarify the algorithm behind the methods and the results.

Gopalakrishnan and Pathak[25] propose a computer system which, on the basis of features, will select the required process parameters for milling operations (process planning) and, with these parameters, calculate the cost. The inputs needed to run the program are very detailed (e.g. number of teeth on the cutter and number of resharpenings) and therefore the system is not useful for early cost estimates. The program is passive in the sense of design for cost, since it does not specify the expensive features on the part. Instead, the design has to be changed and the program executed again.

Ott and Hubka[26] describe a method for design to cost of turning, milling and drilling operations. On the basis of a number of parameters (number of machines, production volume, weight, material, volume, tolerances and shape in the sense of form features) values for different time parameters are given in a table. From these figures it is possible to calculate the total manufacturing time including material cost.

Ehrlenspiel and Rutz[27] present a cost-calculation system for rotational parts. The input parameters are not described. In addition to cost calculation the system also supports the user in the design for cost activity by suggesting changes to features that are too expensive to produce (e.g. 'A cylinder here instead of a cone would save 2.58 DM' or 'Doubling the production volume would save 3.49 DM').

The cost-calculation program of Boothroyd and Dewhurst[22] includes a *machining* module which makes it possible to produce two different calculations. One is a very rough cost estimate and the other is a more accurate analysis of the part. The rough estimate is made from the parameters shown in *Table 2* where the shape is chosen from a list of basic part shapes in the program. The more accurate calculation is made on more detailed inputs.

Cost-calculation methods for rolled profiles

Ehrlenspiel and Rutz[27] present a program for quotations on rolled profiles. The designer builds a profile from a set of standard profiles or standard features. From this input and information about material and batch size, the system is able to calculate the cost.

Cost-calculation methods for injection moulding

Poli and Fernandez[28] present a relative method to obtain the mould cost for injection-moulded parts. The method can be used to compare the tooling cost for two alternative variants. Through information on component size, number of internal undercuts, number and type of external undercuts, amount of cavity detail, parting plane complexity, surface finish, tolerance requirements, projected area and thickness of the mould base a six-digit code is obtained. Each digit of the code has a cost associated with it, and the total tooling cost can be determined based on formulas involving all digits.

In Rosen *et al.*[29] the same cost-calculation method as in the paper by Poli and Fernandez is described. The difference is that from a design feature representation (CAD) of the part, a computer system automatically derives a representation in terms of manufacturing features and evaluates the manufacturing representation for tooling cost. The method can be used for injection moulding and die casting.

Poli *et al.* [30] include both the tool cost-calculation method from reference 28 and a relative method for processing cost. The former can be used very early in the embodiment stage but the latter requires much more detailed information than may be available at so early a stage, e.g. questions such as 'Is the part easy/not easy to cool?' and 'Is the part difficult/not difficult to fill and eject?' The question is whether the tool cost has any value in the early stages if the processing cost cannot be calculated.

The *injection moulding* module in the Boothroyd and Dewhurst cost-calculation program requires (in addition to the parameters shown in *Table 2*) knowledge of the mould, e.g. if it is a two-plate or a three-plate mould, if it has a hot runner system, the parting line factor, the number of unscrewing devices, etc. which means that it is suited for detail design and not for early estimates.

Johansen[31] presents a method for calculating material cost and processing cost. This uses input parameters such as dimensions, volume, area and material. The tooling cost must be found through quotations from a tool maker and is not included in the method. Depending on the parameters that have to be specified for the tool maker, the method can be used for the selection of production methods. Johansen suggests that the user should present the result as a cost per part versus production volume curve.

Mileham *et al.*[32] describe a parametric cost-estimating method for injection moulding. The method is intended for use in the conceptual stage of design and can apparently be used for both process selection and design for fabrication activities. Cost data have been collected from industrial companies and, based on statistical analysis, significant cost drivers have been identified. These include weight, production volume, cycle time and machine size. Of these, only production volume is likely to be known by the designer and a number of rules describing input data conversion have therefore been developed. Using such converting rules weight can be estimated based on input of material type and rough shape and size. The method has been implemented in a computer system and an accuracy of 20% is reported for the ABS parts initially put into the system. However, it is not shown how the initial data were collected and it is therefore difficult to determine the method's accuracy. If the method is intended to be used for process selection then similar methods for other processes should first be developed.

Cost-calculation methods for powder metallurgy
Han *et al.*[33] present a method for spreadsheet-based estimation of P/M processed parts. It is claimed that the cost consists of four factors: equipment, material (including tools), energy and labour. The paper does not explain how these factors are obtained but it is obvious that it is for very detailed calculations since parameters such as sintering temperature and moulding pressure have to be specified.

The Boothroyd and Dewhurst program includes a module for calculating cost of powder metal parts. The user must possess a considerable amount of knowledge about processing, since parameters such as type of sintering furnace and the type of secondary processes and heat treatments have to be specified.

Knight[34] describes a procedure intended to be used at the early stages when alternative part configurations and processes are being considered. A number of different input parameters are needed but they all seem to be available at the very early stages of design. Evaluation of the method shows that the calculated results are quite close to the actual *tooling cost*, but, unfortunately, this evaluation does not include *material cost* and *processing cost*.

Cost-calculation methods for forging
Knight and Poli[35] present a method for relative cost estimation for forging. Through classification codes based on part shape, size and specific features that affect manufacturing difficulty, relative costs for various designs can be estimated. The method is very easily used in the early stages of the design process, but only for evaluating different forged parts. Using the method for process selection is not possible due to the relative costs, which cannot be compared with calculations made by other methods.

Cost-calculation methods for sheet metalworking
Haan[35] describes a system that can be used by designers to estimate the cost of stamped parts. No details are given on how the system works. Haan mentions some of the 18 input parameters required, and many of them seem to be parameters that are not available in the early stages of design (e.g. strip dimensions, feeding increment, the kind of stops used). Also, since the estimated die cost must also be specified, the system could not be of much use in the early stages.

The Boothroyd and Dewhurst program includes a module for sheetmetal working. Using the *sheet metalworking* module it seems that the designer must know a considerable amount about production methods. Many of the parameters that the designer has to specify are more likely known by a production engineer, e.g. length pitch, width pitch, number of different punches, stock form, number of hits, etc., and therefore the module is not suited for early cost estimates.

Cost-calculation methods for die castings
The cost-calculation program of Boothroyd and Dewhurst includes a module for die casting. This requires knowledge of almost the same parameters as the injection moulding module although some of the more mould-specific parameters are omitted. It requires some level of processing knowledge, e.g. number of holes to be trimmed, parting line factor, side cores, etc., but the parameters seem to be manageable for the designer even at the early stages.

Cost-calculation methods for castings
Ehrlenspiel and Rutz[27] describe a computer system intended to make rapid quotations. They do not mention what parameters are used as input, but they state that one needs 45 parameters of which only 15 are geometric, and that they have made another program with only 14 input parameters. They also want to couple the program with a CAD system. It seems to be necessary to specify very detailed designs in order to use the program.

Pacyna *et al.*[37] present a method for variant evaluation as well as process selection. The dimensions of the component are transformed into three form characteristics: compactness, relative length and relative wall thickness. A set of formulas based on these and other parameters such as material, number of cores and casting class factor are presented. The method is developed for castings but the authors claim that the concept is also suitable for forging, welding, plastic parts and powder metallurgy parts.

Cost-calculation methods including several production methods
Ferreirinha[35,39] describes how the HKB system can be used for cost calculation. Production methods included are turning, milling, casting, welding, forging, sheet metal forming and plastic parts. Inputs to the system are component parameters (shape, dimensions including tolerances, surface quality, heat treatments, quality features), raw material parameters (material, pre-processes, shape, maximum sizes, pretreatment) and production parameters (batch sizes, number of clampings). It is claimed in these papers that the method is suitable for the embodiment design phase, that it is unsuitable for the input parameters, that the system is developed for early estimates, and that it would be unable to support the designer in early calculations of alternative production methods.

Zenger[40] presents a system for a comparison of different production methods on the basis of cost. With a few inputs such as production volume, average batch size,

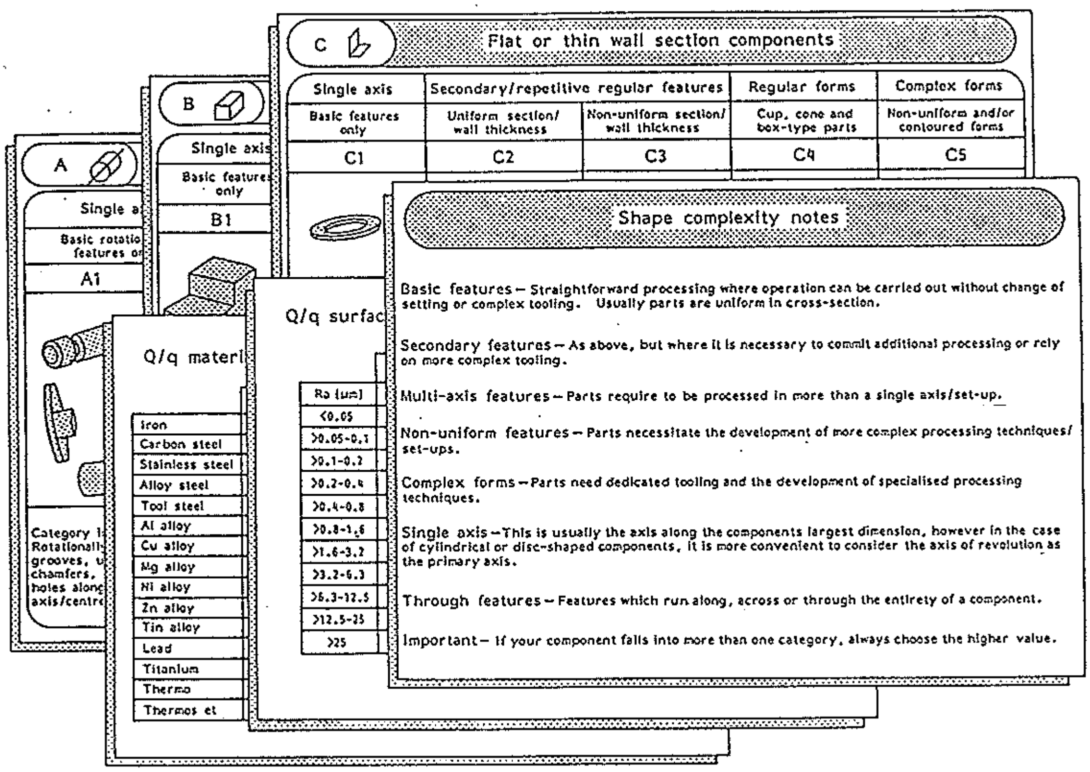

Figure 4 Input tables in the costing method from Hull University[41–43]

basic part dimensions, volume and simple geometric complexity values, the system is able to present comparable cost analyses for different combinations of materials and production methods for a given component and it is only possible to calculate combinations which are actually realistic. The system includes five different casting processes as well as machining, injection moulding and sheet metalworking. Material selection is made by general class such as aluminium, cast iron, copper, zinc, etc. The system is able to give different outputs to the designer: the cost is listed in order of least to most expensive combinations or a curve showing cost per part versus production volume for all combinations. It is not mentioned how near the analysis is to the actual production cost.

The program developed by Zenger is very close to the ideal concept for the designer. Zenger is aware that the designer has to consider whole sequences of production methods before selecting a solution, although this capability is not yet implemented in the system. The best part of the output is the curves showing cost per part versus production quantity for all investigated process/material combinations, since these curves make it possible for the designer to see the result of changing the production volume. It seems that all process/material combinations are calculated on the basis of the same component shape. Obviously this means that the shape does not have the same level of producibility for all combinations and therefore the calculations could be misleading.

Allen *et al.*[41–43] present a technique for evaluating processes in the early stages of design. The papers give an overview of the concept and show that the predicted costs lies very close (within 16%) to actual costs (for plastic moulded and pressed sheet components). It is not shown how the method is used, but private communication with Mr Allen has clarified the following. Calculations are based on material cost and cost of production methods, where the latter is determined using a basic processing cost and design-dependent relative cost coefficient. The basic cost derived from the production method, the production volume and the relative cost coefficient are derived from material-process suitability, shape complexity, tolerances, etc. *Figure 4* illustrates how material and shape complexity is selected. The user does not require detailed information on the different production methods used to produce a component. For example, when evaluating a design, the user has to select only the primary production method; any secondary production methods are automatically accounted for in the metrics. Thus the designer is simply made aware of the fact that it will be necessary to employ secondary processing for the design in its current form. The method seems to be very useful for designers in the selection of production methods.

Although Boothroyd and Dewhurst often claim that their cost-calculation methods are intended to be used at the early design stages, it seems that most of the modules included in the cost-calculation program require information about the production environment which is unavailable to the designer when production methods are selected. The machining and the die casting module are exceptions and seem to be suitable for this purpose.

Requirements for a cost-calculation method for selection of production methods

Only a few papers deal with the problem of selecting production methods in the design phase[26,31,32,34,37,40,41–43]. Some treat single and others several production methods. It seems that the methods/systems developed by Zenger and Allen *et al.* are close to the concept we have in mind. From our point of view the ideal concept for cost-calculation methods for selection among alternative production methods must fulfil the following criteria:

- It should be possible to *compare parts outlined for different material/production method combinations*, which means that input parameters in general should be one or more of the following: rough material, rough shape, rough dimension, production volume, tolerances and surface quality.
- *Sequences of production methods* and not only single production methods should be considered, since a component that seems to be cheapest when comparing the main processes could be more expensive when comparing entire processing sequences.
- Both *cost for the product and subassemblies* as well as cost for single parts should be available, which is necessary when components are integrated or disintegrated.
- *Replacement and renovation of tools* should be included. The number of components that can be produced by a tool (e.g. by injection moulding) is limited and therefore the investment in renewal of the tools must be included in the calculation.
- The method shuld be *trustworthy* and should make the *sensitivity to the different parameters visible* to the designer, e.g. it is essential that the designer can identify the most cost-effective solution if the production volume is increased or decreased.

Both Zenger and Allen *et al.* are concerned about the first two requirements, but it seems that they are not aware of the last three points. The next section will outline our ideas of a concept for a method/system to support the designer in cost calculation as a basis for selecting production methods.

A cost-estimation method for early process selection

Based on a review of the literature and on case studies in several industrial companies[44–46] we have identified the need for a fast cost-estimation technique which can be used to compare and rank different sequences of production methods. In the following a method that can be used for this purpose will be described. This is based on a previous method developed for the MADED system[47,48].

The method is based on the basic hypothesis described by Jepsen[49] that a sequence of production methods (a process chain) is used to produce a part, but process selection is made by first selecting the primary production method used to produce the main shape of the part and secondary processes hereafter. In the proposed method the entry point is therefore to select the primary production method, and in the example shown in *Figure 5* injection moulding has been chosen. For each production method a table describes typical parts in different sizes and with different geometrical complexity. An underlying hypothesis is that cost rises for increasing size and geometrical complexity. This hypothesis is based on the observation that a larger part contains more material and generally requires more expensive equipment. Increased geometrical complexity does, in general, mean a higher cost, e.g. why does the cost for turning increase with the number of form features or operations? Similarly, does the cost of injection moulding increase with the number of side cores and, to some extent, also with more complex geometry? The rows in *Figure 5* represent the size of the part and the columns the complexity. For each cell, i.e. each typical component, a cost curve can be displayed, a curve showing the cost per part as a function of production volume. Material type can be selected before choosing one of the typical components and will then influence the cost curve. Additional production methods can be selected similarly and thereby influence the cost curve. This makes the method capable of handling the total sequence of production methods required to produce the part.

Results are displayed as cost curves where the cost is shown as a function of production volume. Curves have a number of advantages compared with single results. When the cost algorithms work as a black box, where the input is a number of parameters and the output a single figure, the disadvantage is that the result appears more precise than it really is (the analogue/digital clock problem) and there is no indication of where the uncertainty lies. This is important since costs by nature are not very precise. Different companies have different costing policies and a company with free production capacity will probably give a better price. The curves solves this problem. Since it is difficult to make a precise reading from a curve the user will have a better understanding of the lack of precision. Furthermore the curves do have the advantage that a certain degree of sensitivity analysis is possible and the designer can investigate what happens if product volume is halved or if a more complex geometry is selected.

It is possible to choose several different typical parts for the same or for different production methods and to display the resulting cost curves in the same diagram, which makes it easy to compare the costs. Furthermore, it is possible to group parts together as products, which means that the cost curves are added together and give a picture of the cost for the total product as shown in *Figure 6*. The cost curves can be shown for single parts or

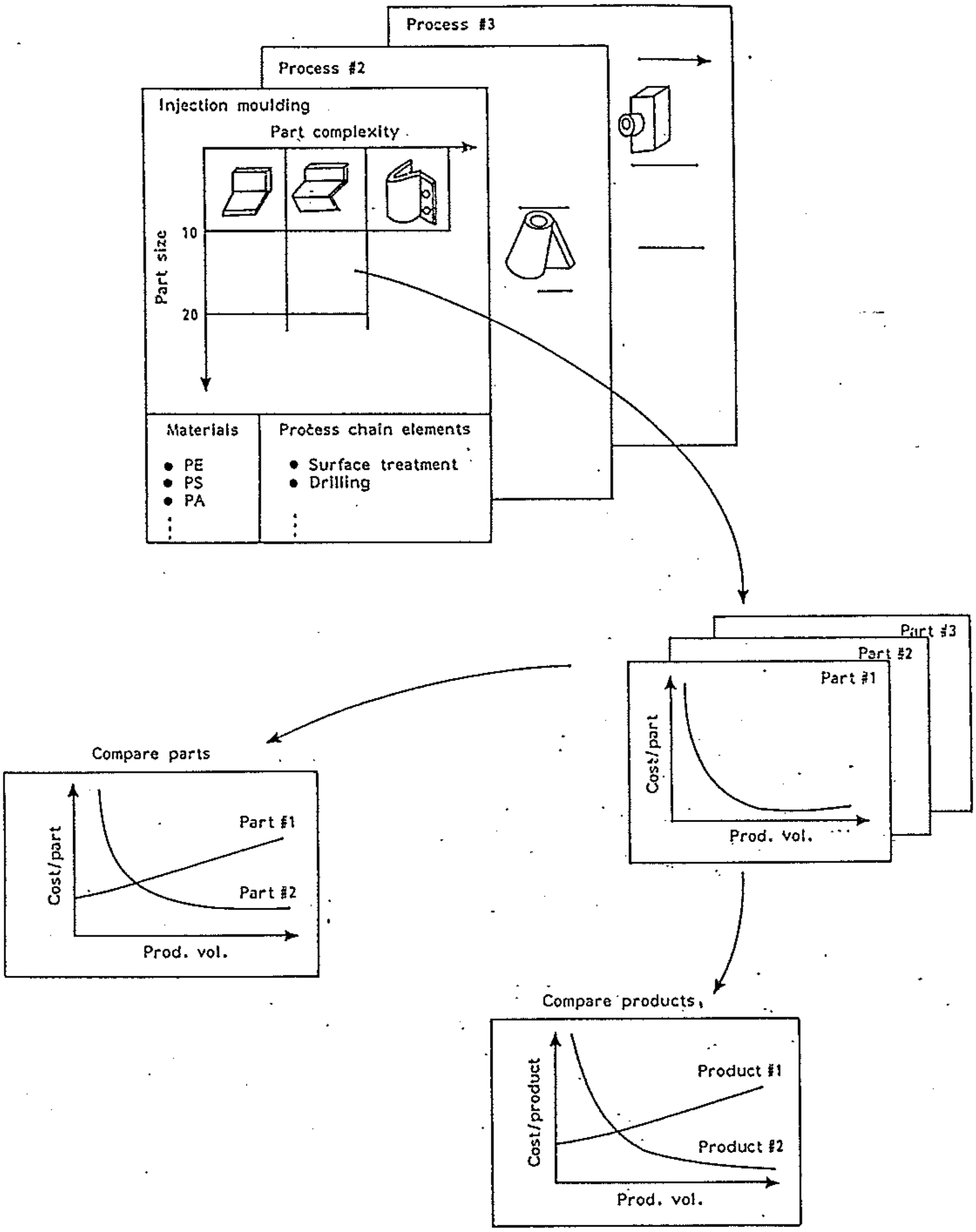

Figure 5 Entry tables and cost curves for the proposed cost-evaluation method.

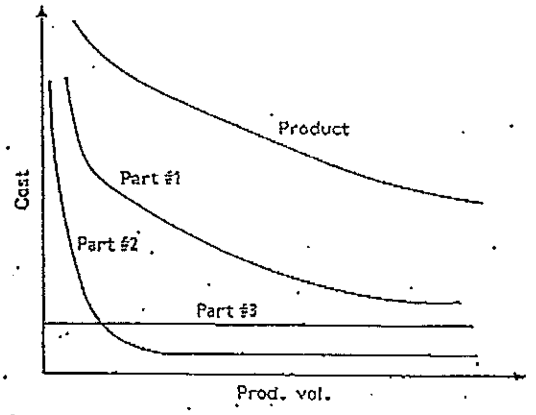

Figure 6 Cost curves for a product consisting of three parts

for whole products and can therefore be used to compare alternative production methods for a specific part or to compare alternative products, and thus ensure that cost savings for one part in a product are not made by sacrificing cost in another part. It is also possible to consider the fact that components look different when produced by different processes by comparing typical components from different tables.

Costs are calculated as the sum of tooling cost, total material cost and total production cost (labour ÷ machine cost). This sum is divided by the production volume. The cost curves not only represent the cost of the primary production methods but also include any additional production methods normally used, e.g. sawing before turning. Other additional production methods are selected from a list as described earlier.

Figure 7 shows an example of groups of geometric complexity for the powder compaction production method[5]. Parts belonging to Class 1 are the most inexpensive to produce and parts in Class 4 are the most expensive. In this case the tool becomes more expensive when more pistons are needed to perform compaction. In this way increased tooling cost can be handled fairly well except for one problem which occurs in moulding processes.

A problem in calculating the cost is that the tools have a limited life and that this life in some cases depends on the type of material. This can be handled by the proposed method since material cost is treated as a function of, for example, production volume. The resulting cost curve will then 'jump' each time the production volume reaches a multiple of the tool life as shown in *Figure 8*.

The proposed method complies with the requirements that were formulated in the previous section. It is possible to compare dissimilar parts produced by different production methods and the two resulting cost curves can be shown in the same diagram. Both single processes and sequences of production methods can be handled since secondary processes can be selected and will influence the resulting cost curve. Cost curves can be generated for several components which then can be combined into a single product curve as shown in *Figures 5* and *6*. This product curve contains only the sum of the cost of the components, not the cost of assembling them. Replacement and renovation of tools can be handled as shown in *Figure 8*. Using cost curves rather than cost numbers creates a sensitivity towards variations in production volume.

The method described in this section is developed only to a conceptual level, and much work remains before a prototype system appears. On the theoretical side it should be considered how indirect expenses should be included (e.g. the cost of the machine). On the practical side it should be decided how the considerable amount of information is collected and later maintained. Obviously this is very labour-intensive work which could be placed with the interested industrial organizations. These have an interest in knowing what their member companies can produce and especially how they differ from other types of production. The system will most naturally be a general system that can be used by many companies, but it will be desirable to make individual changes.

Conclusion

Different costing methods are being applied to different design stages. For the conceptual design stage functional costing and quick costing techniques are used for selecting among alternative concepts, to make quotations and to detect cost-reduction areas. In the embodiment and detailed design phases cost estimation is used for selecting among alternative production methods and to support cost optimization. Several costing methods for an evaluation of production methods are reported in the literature, but most of them are targeted to part optimization. Because of the detailed information about production method which is required in these methods they are not suited for early selection of production methods. Only two methods for this purpose were found and another four could be used at the same design level, but they had cost information only about a single production method. Based on previous industrial studies and on a review of the literature, requirements for costing methods to select production methods have been set up. A concept for this purpose is suggested. It is capable of handling sequences of production methods, different materials and single parts and products. It also allows tool life and maintenance to be included in the cost.

Acknowledgements

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References

1 Ehrlenspiel, K. and Hillebrand, A. *Konstruieren und Kalkulieren am Bildschirm*. VDI-Berichte No. 610.2, Düsseldorf, 1986
2 Esawi, A. and Ashby, M. F. Cost estimation techniques for the early stages of design. Internal report from Cambridge University Engineering Department, 1993
3 Pahl, G. and Beitz, W. *Engineering Design*, Springer-Verlag, Berlin, 1984
4 Dieks, H. Kostenwachstumsfunktionen – ein Hilfsmittel zur Kos-

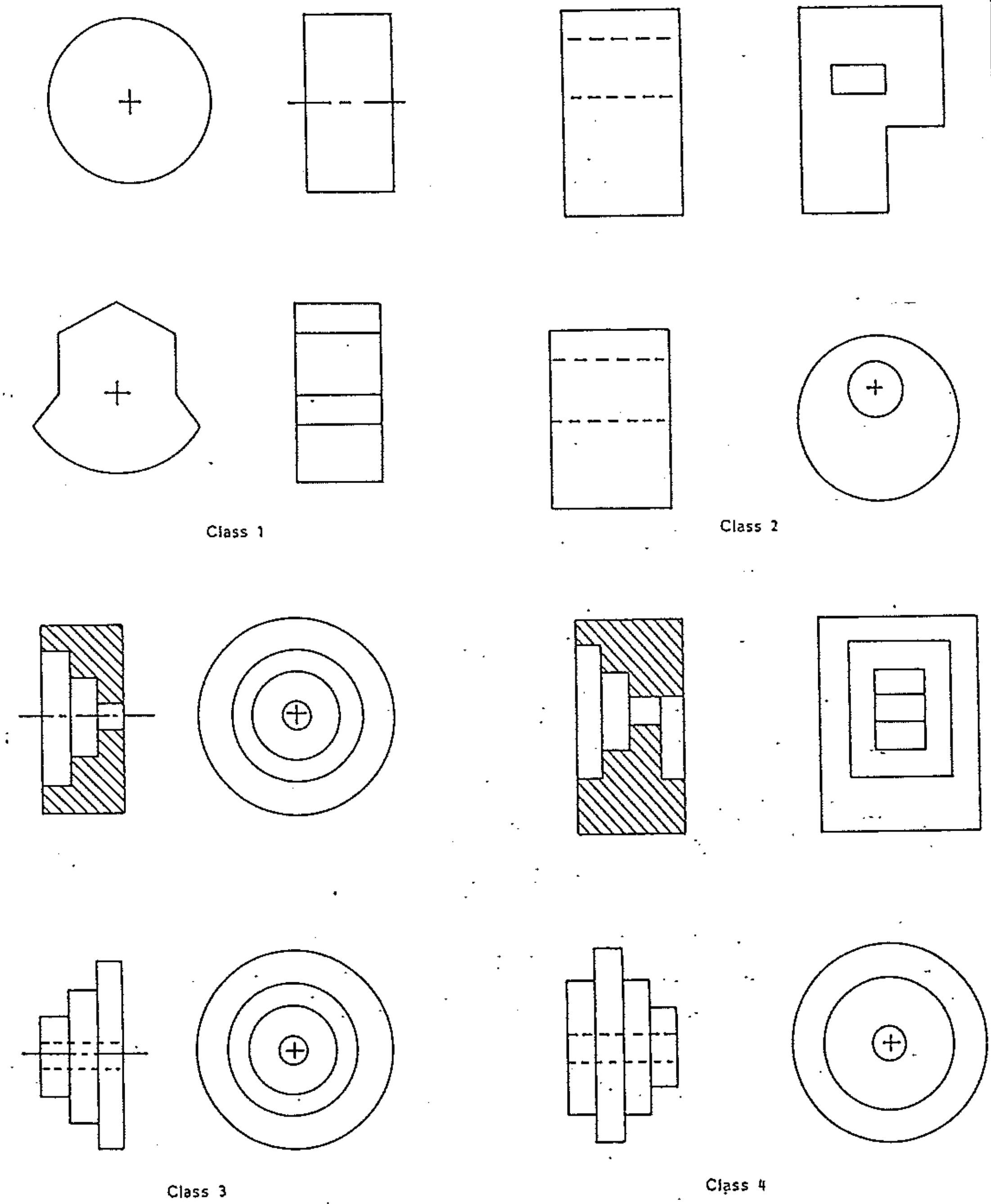

Figure 7 Geometric complexity classes for powder compaction[30]

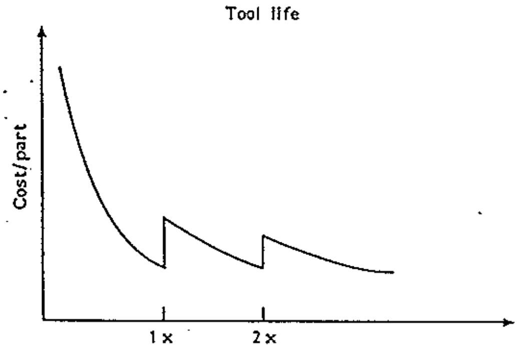

Figure 8 Cost curve which takes tool life into account

tenfrüerkennung im Konstruktionsprocess. *ICED'85*. Hamburg. August 1985. pp. 437–449

5 Bush. S. A. and Sheldon. D. F. Whose cost is it anyway? *ICED'93*. The Hague. pp. 1130–1135

6 Sheldon. D. F.. Perks. R.. Jackson. M.. Miles. B. L. and Holland. J. Designing for whole life costs at the concept stage. *Journal of Engineering Design* 1990. 1. No. 2. 131–145

7 VDI 2235. *Wirtschaftliche Entscheidungen beim konstruieren. Methoden und Hilfen.* October 1987

8 Ehrlenspiel. K. *Kostengünstig Konstruiren.* Springer-Verlag. Berlin. 1985

9 Creese. R. C.. Adithan M. and Pabla. B. S. *Estimating and Costing for the Metal Manufacturing Industries.* Marcel Dekker. New York. 1992

10 Ferreirinha. P. Kalkulationssystem fuer neuentwicklungen mit anwndung von funktionskosten. *ICED'83*. Copenhagen 1983. pp. 166–173.

11 French. M. J. Function costing: A potential aid to designers. *Journal of Engineering Design* 1990, 1 No. 1. 47–53

12 Li. M.. Stokes. C. A.. French. M. J. and Widden. M. B. Function-costing: Recent developments. *ICED'93*. The Hague. August 1993. pp 1123–1129

13 Bradford. D. T. and Culley. S. J. A strategy for costing at the concept stage of design. *ICED'89*. 1989. pp. 425–434

14 Jakobsen. K. The interrelation between product shape. material and production method. *ICED'89*. Harrogate. August 1989. pp. 775–784

15 Haudrum. J. and Atling. L. Structured methods for process selection in the stage of design. *Proceedings of ICCIM'93*. September 1993. Singapore. pp. 143–154

16 Haudrum. J. How to incorporate production method information into the embodiment design. 4. *Symposium Fertigungsgerichtes Konstruieren*. 14/15 October 1993. Egloffstein. Germany

17 Boothroyd. G. Estimate costs at an early stage. *American Machinist* 1988, August. 54–57

18 Boothroyd. G. and Reynolds. C. Approximate cost estimates for typical turned parts. *Journal of Manufacturing Systems* No. 3. University of Rhode Island, Kingston, 185–193

19 Boothroyd, G. and Radovanovic, P. Estimating the cost of machined components during the conceptual design of a product. *Annals of the CIRP*. 1989, 38, No. 1, 157–160

20 Dewhurst. P. and Boothroyd. G. Early cost estimating in product design. *Journal of Manufacturing Systems* 7, No. 3. 183–191

21 Dewhurst. P. and Blum, C. Supporting analysis for the economic assessment of diecasting in product design. *Annals of the CIRP* 1989, 38, 161–164

22 Boothroyd, G. and Dewhurst, P. *Design for Manufacture and Assembly* software package

23 Spur, G. and Kreisfeld, P. Hilfsmittel zur Kostenprognose abgespanter Einzelteile. *VDI-Berichte* 1982, No. 457. 91–102

24 Kreisfeld. P. Exakte Kostenprognose von Rotationsteilen durch Bildung von Kostenfamilien. *Industrie* 1986. 4.3, No. 18, 45–46

25 Gopalakrishnan. B. and Pathak. M. A. Machine parameter selection and cost estimation techniques: applications in concurrent engineering. *Manufacturing International, ASME* 1992. 249-256

26 Ott. H. and Hubka. V. Überschagige Herstellkostenberechnung für Maschinenteile in der Entwurfsphase. *ICED 1983*. Copenhagen. pp. 179–188

27 Ehrlenspiel. K. and Rutz. A. Drei Beispiele zur rechnerunsterstützten Kostenberechnung in Konstruktion and Arbeitsvorbereitung. *VDI-Berichte* 1983. No. 492. 89–104

28 Poli. C.. Escudero. J. and Fernandez. R. How part design affects injection-moulding tool costs. *Machine Design* 1988. November. 101–104

29 Rosen. D. W.. Dixon. J. R.. Poli. C. and Xin. D. Features and algorithms for tooling cost evaluation in injection moulding and die casting. *Computers In Engineering. ASME* 1992. 1. 45–52

30 Poli. C.. Kuo. S. M. and Graves. R. J. Design for injection moulding: a group-technology-based approach. *Journal of Engineering Design* 1992. 3. No. 4. 307–324

31 Johansen. O. Omkostningskalkulation for Sprojtestobte emner herunder beregning af cyklustid og valg af maskinstorrelse. Danmarks Tekniske Universitet. 1994. Publ. no PT.94.01.

32 Mileham. A. R.. Currie. G. C.. Miles. A. W. and Bradford. D. T. A parametric approach to cost estimating at the conceptual stage of design. *Journal of Engineering Design* 1993. 4. No. 2. 117–125

33 Han. Y. C.. Park. J. C.. Clark. J. P. and Field. F. R. Spreadsheet based cost estimation for the P/M fabrication process. *Proceedings of the 1988 International Powder Metallurgy Conference*. Vol. 21. pp. 723–733

34 Knight. W. A. Design for manufacture analysis: early estimates of tool costs for sintered parts. *Annals of the CIRP* 1991. 40. No. 1. 131–134

35 Knight. W. A. and Poli. C. A. Systematic approach to forging design. *Machine Design* 1985. January. 94–99

36 Haan. T. J. A. Cost estimating during the design process. *Proceedings of ICED 1983*. Vol. 1. pp. 174–178

37 Pacyna. H.. Hillebrand. A. and Rutz. A. Kostenfrüherkennung für Gussteile. *VDI-Berichte* 1982. No. 457. 103–114

38 Ferreirinha. P. Herstellkostenberechnung von Machinteilen in der Entwurfsphase mit dem HKB Program. *Proceedings of ICED 1985*, pp. 461–467

39 Ferreirinha. P. Rechnerunterstützte Vorkalkulation in Machinenbau für Konstrukteure und Arbeitsvorbereiter mit 'HKB'. *Proceedings of ICED 1990*. pp. 1346–1353

40 Zenger. D. C. A cost based approach to the selection of materials and processes in product design. *ICED'93*. The Hague. 17–19 August 1993. pp. 1136–1143

41 Allen. A. J. Swift. K. G. and Hird. G. A. Process selection and component costing system in support of product design. *Autotech 91*. NEC. Birmingham

42 Allen. A. J.. Bielby. M. S. and Swift. K. G. Development of a product manufacturing analysis and costing system. *Int. Forum on Product Design for Manufacture & Assembly*. Newport. Rhode Island. May. 1990

43 Allen. A. J. and Swift. K. G. Manufacturing process selection and costing. *Proc. Instn. Mech. Engrs* 1990. 204. 143–148

44 Haudrum. J. Role-playing used for studying how process selection is carried out in product design. *The Seventh IPS Research Seminar*, Fuglso, October 1992. 97–112

45 Haudrum. J. and Mortensen. N. H. Ten studies of how process selection is carried out in the stage of design – a pilot project (in Danish). Report. Institute of Manufacturing Engineering. Technical University of Denmark, PI 93.07-A/AP 93.20. June 1993

46 Lenau. T. Models of manufacturing processes for design information systems. *Manufacturing Systems* 1992. 21. No. 2. 129–135

47 Lenau. T. and Kristensen. L. MADED – an information system for manufacturing processes. *ICED'93*, The Hague, 17–19 August 1993. 1093–1096

48 Lenau, T. and Kristensen, L. MADED – An information system for manufacturing processes. *The Seventh IPS Research Seminar*. Fuglso, October 1992, 67–84

49 Jepsen, E. L. *Valg af industrielle fremstillingsmetoder*, PhD thesis. AMT, Danmarks Tekniske Hojskole, 1978

50 Tvenge, K. Vaerktojsprincipper – Pulverpresning. Danmarks Tekniske Højskole, AMT, 1981, AP.81.27

THE PAPER: STRUCTURED MEDTHODS FOR PROCESS SELECTION IN THE STAGE OF DESIGN

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Structured Methods for Process Selection in the Stage of Design

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ABSTRACT

This paper is devoted to a discussion of how production methods must be considered in the stage of design. It is argued that production should be considered from the very earliest step of the design phase. A new paradigm of process selection is argued, namely that the process selection must be seen as an integrated part of the selection of a component solution and that the process selection must be based on the entire process chain needed and not only on the main process. Some individual tools for supporting the designer in these process considerations at the different levels of the design stage are presented.

1 Introduction

1.1 Background

One of the essential key factors in designing a successful product is to incorporate the considerations for manufacturing early in the design process. The selected production methods not only influence the production factors: lead time; costs, flexibility, quality, environment and risk. The production methods also, through material, shape, etc., have an indirectly influence on many factors of the products life cycle such as material consumption and reusability. Thus it is not possible to make the right product without selecting the right production method, and therefore the selection of the most appropriate production method for the individual components is essential and a very important task. The selection of the most optimal production methods for a product is not a simple task though, since: The total number of production methods is huge and it is difficult for the designer to form a general view of the possibilities and constraints; the available process information is structured by production engineers for production engineers and not for designers; the close interrelation between production method, function, material and shape, Figure 1, makes it necessary to consider and select all factors simultaneously, which is difficult to handle; the production methods are related to individual components, but through the shape of these individual components the production method influences the structure of the product. However, the influence on the structure is not visible until the shape of the component is generated; further, the number of relevant process selection criteria is high and includes factors from all phases in the products life cycle and there is a lack of evaluation methods to support the designer in weighing these criteria.

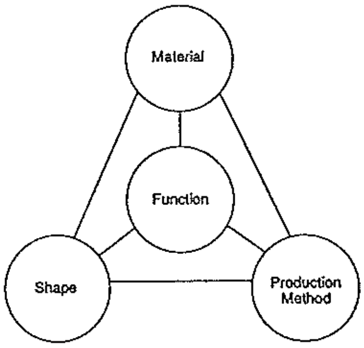

Figure 1 There is a close interrelation between function, material, shape and production method of a component[16].

Thus the process selection task is a very complex and difficult task and the two key-words to solve this problem are information and methodology. To select the most optimal production methods the designer needs the right information at the right time and he needs to make the considerations and selections of production methods the right way. The challenge is to present the manufacturing process information in a way that fits the work of the designer and to find a procedure that helps him to consider all relevant production methods and select the most optimal ones for the product he is designing.

This paper suggests how production methods should be considered and selected on the different levels of the design phase. It is shown why the process selection activity must be considered as an integrated activity at the very beginning of the design phase and that the designer has to understand the production methods as an inspiration source to create better solutions, as well as he has to consider alternative process chains (and not only single processes) before a solution is selected. A process chain for a component is for instance: pressure die casting, removal of burrs, and drilling of holes.

1.2 Related work
The designer has two fundamental different types of questions about production methods:

- What processes can fulfil my needs ? (e.g. what processes can give me a surface finish of 10-15 μm ?)

- What can a specific process provide? (e.g. What wall thickness is possible by injection molding ?)

In between these two questions the designer considers and selects the process, thus the information he needs before he selects the process is the answers to the first question, and the information he needs having considered and selected the process is the answers to the second question.

Books on manufacturing process information typically only answer the second question[1,2,3,4]. The structure of the books is process related and describes each process, and thus supports the designer with a structure that he needs after and not before the process selection.

Some researchers[6,7] have treated the problem of how to answer the first fundamental question: "What processes can fulfil my needs ?". Their object is to support the designer with the manufacturing process information he needs before selecting the process. Some try to solve the problem by developing computer systems that can assist the designer in his selection of production methods. Examples of such systems are MADED[7], CKB[11], DFPS[12,13] and MAPS[14]. Some researchers have tried to develop a procedure[8,9] or a theory[10] of how process selection should be carried out.

The mentioned authors treat process selection at the component level of design. Naturally the process is connected to a component, but the process selection will also affect and be affected by the structure of the product, and it is therefore important that process considerations are made on all levels of design and not only at the component level. The authors also treat process selection as if components are fabricated with only one process, but that is most often not the case. Components are usually fabricated with a chain of processes. Thus, process selection must be carried out by comparing entire process chains that can fulfil the component requirements.

Most of the procedures and the systems mentioned are not based on a design theory or methodology which could be the reason why they only treat components.

1.3 Objective of this work
As mentioned before the two key-words for solving the problems of process selection in the design phase are methodologies and information. The designer needs methodologies which can support him in selecting the most optimal production methods, and he needs a structure of the process information which fits his way of working. The objective of this work is to develop such methodologies and a process information structure.

Since designers have different ways of designing products, it is important to have some kind of general description of how designers should work, which can be used as a basis for the methods and process structure to be developed. The design methodology described by Pahl and Beitz[5] (P&B) is very useful for this purpose. In this design methodology the design process is divided into four main steps or levels: Product planning and clarification of the task, Conceptual design, Embodiment design and Detail design, see Figure 2.

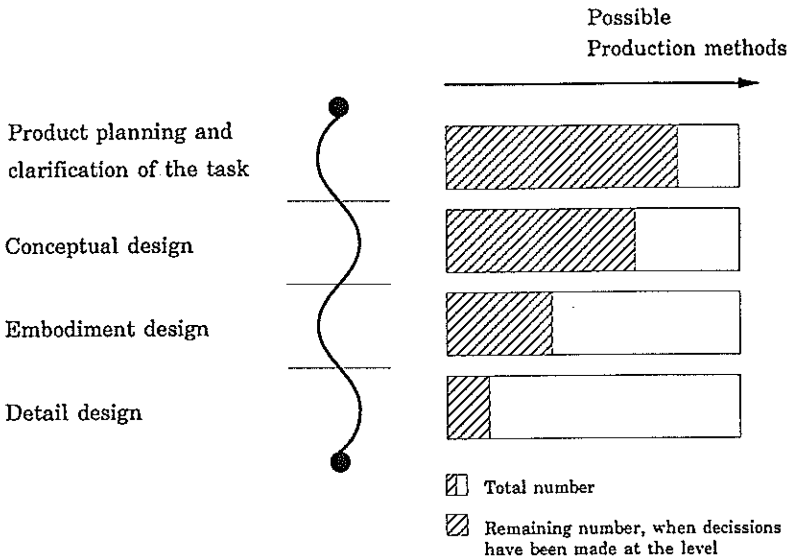

Figure 2 To the left the four levels of design are shown. The right side illustrates that the number of possible production methods is decreased with the decissions made at each level of the design phase.

On different levels of design the designer needs different methods and different kinds of information and the objective of this work is to develop a set of structured methods to be used at these four different levels of the design phase to support the designer in searching, considering, evaluating and selecting production methods and to develop a process information model including the information the designer needs on the different levels of design.

The number of possible production methods decreases along with the decisions made in all these levels, see Figure 2, and it is therefore very important that the decision makers are aware of the production considerations that should be made at all levels and not only at the level of embodiment design. Figure 3 shows a general model of the problem. As shown the idea is that the designer needs different methods to consider and select processes and different kind of information at the four levels of design. The methods might be of different types; at the higher level it could be checklists of questions about production technology that has to be asked, where as they on the lower levels could be more formalized, for instance into design tools with specified rules. The information is likewise different at the four levels and the arrows in Figure 3 illustrates that there must be a close interrelation between the methods and the information, since the methods must handle the information and the information must support the methods.

The structured methods are based on the statements : that the number of possible

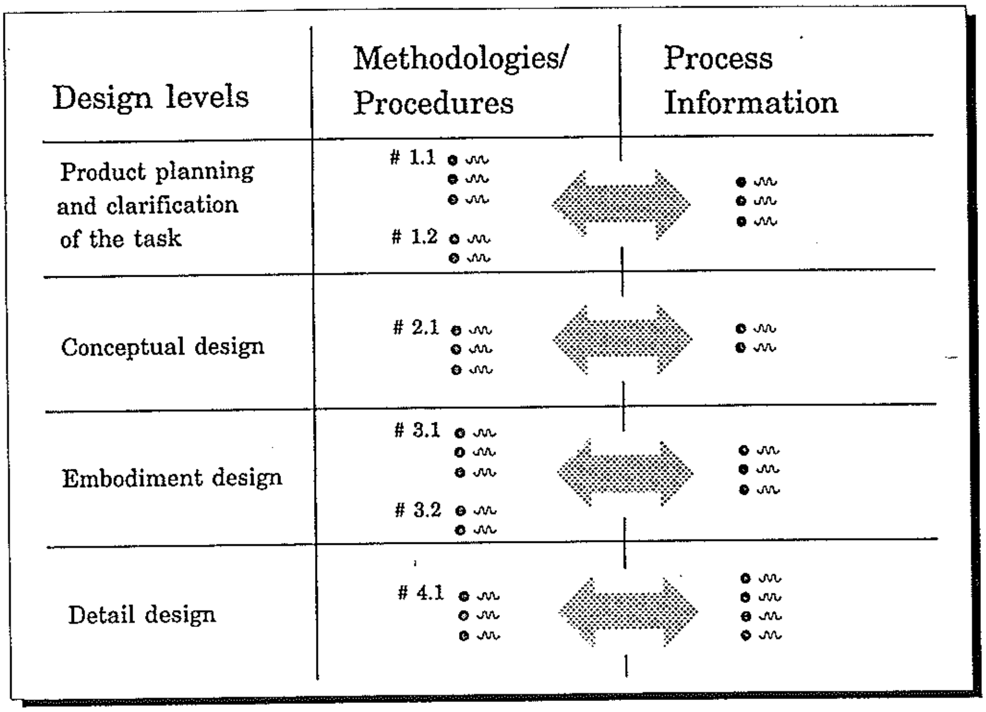

Figure 3 A general model of the objective illustrates that there must be developed tools and process information models for each level in the design phase.

processes decreases with the decisions made in the design phase, that processes influence and are influenced by the structure of the product, that there is a close interrelation between function, material, shape and processes, that the selection of production methods must be based on process chains and not single processes, and that the words process, process search, process considerations, process evaluation and process selection have different meanings on the different levels of design.

2 The four levels of design and some process selection tools.

This section gives a brief description of what is included at each of the four levels of design and some tools for process considerations and selection are presented.

2.1 Product planning and clarification of the task.
The first step in the design methodology is product planning and clarification of the task. In this step it must be clarified which need - which problem - the product should fulfil. The output from this phase is a description of the demands and properties the product must fulfil and posses.

Tool # 1.1
Usually the task is to develop a new generation of an already existing product. In this case it is important that "the old" product is analyzed before the design of a new generation begins. The production analysis must reveal where the production has difficulties in producing and assembling the components in the existing product, and what causes these problems. If there are problems with the old product it is obvious that these problems must be avoided in the new generation. A cost analysis of the production must be made to identify which process steps give unnecessary cost contribution. Tool # 1.1 must decribe how to carry out this production analysis.

Tool # 1.2
The company policy and strategy must be analyzed. Are there some production methods that should be avoided ? How is the make/buy policy ? Should the production/assembly lines from the old product be reused ? What is the attitude about new technology to well-known technology ? Should technologies in which the company has experience be preferred to investment of time and costs in introducing new technologies ? etc. Tool # 1.2 is a list of questions about production technology that must be answered before developing the new product.

Tool # 1.3
This analysis must end up in specifications describing the demands and properties of the product. The demands and properties that influence the process selection are beyond the already mentioned parameters for instance: Product envelope size and weight, time to market, production quantity, material wastage, establishment, etc. The specification is the guideline for the designer when designing the product and therefore the parameters must be sufficient and specified in a way that makes it possible for the designer to evaluate and select between the available production methods. Tool # 1.3 describes a list of parameters about production that must be specified in this specification.

2.2 Conceptual design
The conceptual design phase has several sub steps. The essential problem is identified through abstraction, subsequently the functions in the product are identified and divided into subfunctions for the product. Working principles for the functions are searched and these principles are combined to fulfil the overall function of the product. Suitable solutions are selected and developed into principle solution variants. Finally the solution variants are evaluated.

The question is at which steps production and production methods must be considered. It seems difficult to identify a connection between the product and the production before the working principles are developed. It is in this step that the product takes its first structure, and since the structure is influenced by the production methods, and visa versa, the production methods should be considered at this level of design. However, process considerations should only be made for main components in the product, and for instance important or critical subsystems or components. By considering production methods on this level, the designer could find inspiration to new structures that otherwise would not have occurred to him. The systematic considerations of relevant production methods could enable new structures of a main component and thereby enable a new concept. The concept must be build up around this main component that could be extruded or molded, etc. These different production methods will give different conceptual solutions since different ways of producing the main part in the product will give different structural possibilities. The structure of an extruded part is quite different from the structure of a molded part.

Tool # 2.1
If it is possible a main part or a frame in the product or subsystems must be identified. The main part in the product must be considered as produced in different concrete ways and in different materials. A concept is build up with the hypothetical question: "I wonder if it is possible to make the main part in extruded aluminum ?". Consequently the shape of the main component must be considered and then the subsystems/parts of the product must be arranged around this main part.

It is obvious that not all processes and materials should be considered for the main part. It would be nonsense (in this phase of design) to consider both pressure die casted aluminum and pressure die casted zinc, since they would on this level give exactly the same solutions. However, it might be a good idea, a.o., to consider injection molding, pressure die casting and extrusion because the possibilities of plastics versus metal and extrusion versus molding are quite different.

Thus the question is what combinations of materials and processes should be considered on this level of design ? The answer to this question is naturally to a great extent depending on the type of product (a frame in a car is produced quite differently than a frame in a camera), but it might be possible to give some sort of guidelines for which processes and materials should be considered, depending on different parameters like for instance the product size and the production quantity.

2.3 Embodiment design
The embodiment design step is the step where the working principles are worked through from a technical and economical point of view. It is in this step the materials and processes for each component are selected and the components are given shape. From a process selection point of view this is a very interesting step of the design methodology.

As mentioned before there is a close interrelation between function, material, production method and shape. This interrelation means that if one factor is selected the possibility of selecting the other factors freely is decreased. The combinations of these four factors are representing the total number of possible solutions, and if the possibility of selecting some of the factors is decreased, the remaining number of solutions is decreased, see Figure 4. This means that selecting process and material very early, which is most often what designers do, will depreciate the odds for creating the best component and product. Thus it is very important that the designer considers a sufficient amount of possible combinations of processes, materials, functions and shapes before making the final selection of a solution. The conclusion on this must be that the designer has to consider, evaluate, and select solutions and not the four factors as individual parameters.

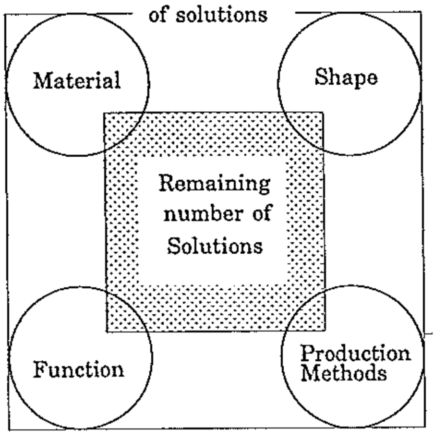

Figure 4 The interrelation between the shown factors means that if one factor is selected the possibilities of selecting the other factors is decreased.

Another argument for this conclusion is that life cycle criteria like material wastage, reusability, recycling etc. cannot directly be coupled to the process itself, but has to be coupled to the solution - the mentioned combinations of the four factors. How should one be able to tell how much the material wastage is for a process if not knowing the shape of the component ? How should one be able to tell the processes effect on reusability and recycling if not knowing about the material combinations in the component ? And what about cycle times, flexibility, quality etc. could these factors be evaluated by only considering the process and not the component as a whole ? Of course not, and therefore the designer must consider, evaluate and select solutions and not the four factors as individual parameters.

It is very important to realize that components often have to be fabricated by more than one production method, since one process alone cannot give the component the desired properties. Therefore the component is often fabricated by a chain of processes. The processes can be divided into the following groups of processes:

- The main processes, which are the processes creating the main shape of the components.
- The pre and post processes, which give the components the required local or global properties which the main process is not able to fulfil.

One could say that the main process creates the material connection between the functional surfaces - and if the required properties of the functional surfaces cannot be satisfied by the main process a process chain is necessary. Which processes could be placed in the different groups depends on the specific situation (component size, component complexity, production rate etc.) but typical main processes are netshape and near netshape processes like injection molding, casting, forging etc.

Often designers select the production method having considered only the costs of the main process. This is a big mistake, since the pre and post processes must be included in the evaluation - alternative process chains, and not only single processes, must be compared before the selection.

There are two statements that should be taken into consideration before suggesting a procedure for process selection at the level of embodiment design:

- Processes must not be selected as individual parameters, but must be seen as an integrated part of a solution. Therefore solutions and not processes must be generated, evaluated and selected.

- Components are most often fabricated with chains of processes and not single processes, and therefore solutions with the entire process chains should be generated, evaluated, and selected.

Naturally it is not possible to consider different materials, different processes, different functions and different shapes at the same time and therefore the procedure must be, that three parameters are kept unchanged while the fourth parameter is changed. And now the question arises in which order this should be done. Naturally there will be situations where one of the factors is given, and then the problem is less complex. For instance the shape is given by toothpicks and propellers, and the process and the material are given in companies specialized in for instance injection molding. But when none of the factors are given the task of component design is complex and for solving this problem the following procedure is suggested:

Tool # 3.1
In the second step of the design methodology it was selected which functions should be included in the product, consequently the functions are given. However, it is not given which components should carry these functions, so the first step is to make a preliminary suggestion. Now the functions of each component are given, and the next step is to keep two of the remaining three factors unchanged while the third one is changed. Since the number of different shapes is infinite and the number of processes and materials and the number of possible material/process combinations is finite, the logical answer is to keep the processes and materials unchanged and change the shape.

A matrix showing the possible process/material combinations is consulted, Figure 5. Based upon the decisions made on the earlier steps, the processes and materials not suitable at this point, are deleted. For the remaining combinations one or more shapes are suggested. At this point it is very important that the designer has not chosen a shape; he must consider every process/material combinations and think of the processes as an inspiration source but on conditions given by the process/material combinations. This exercise is only done for the main processes.

For each solution the process chain is considered. The final properties for each solution are considered, and if the main process does not fulfil these properties a process chain is a reality. When the process chains have been set up for each solution, the solutions can be evaluated and the best one chosen.

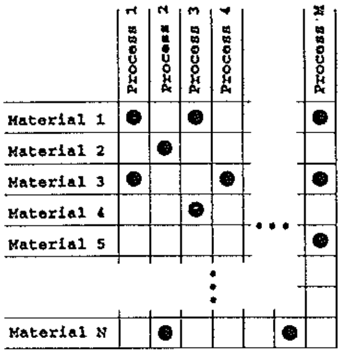

Figure 5 The matrix showing possible process/material combinations.

An example is shown in Figure 6, where the task is to design a component that can be used to open beer bottles. The function is therefore given and the process/material matrix is consulted. Of different reasons some of the combinations are deleted. For the remaining combinations: punching/steel, extrusion/aluminum and insert-molding/thermo plastics some suggestions are made. As one can see there are six different solutions and these solutions have different properties and costs. The consideration of process/material combinations inspires the designer to consider solutions that would not have occurred to him, if he had just been thinking of the shape, and it ensures that he does not waste his time on shapes that are impossible or expensive to make.

Solution number two has the properties that the weight and the costs are low and it is small and handy and could be used as a key-ring. These properties are coupled to the solution and neither shape, material nor production method as individual parameters, thus it would not have been possible to select these parameters individually and get the same solution.

2.4 Detail design

The detailed design is where the final specifications for the components are determined. The final solution has been selected in the embodiment phase and now the designer has to select the specific alloy and make the detailed shapes of the components. In this detailing he has to be very aware of making the right shape for the selected production methods. In this phase he is detailing for fabrication.

3 Further work

In the paper some tools at some of the design levels have been suggested. These tools are mostly concerning the activity process considerations, and are still on a impracticable level. The further work will be to develop these tools to a workable level. Some of the questions to be answered are: How should the production analysis be carried out ?, What questions must the checklists include ?, What

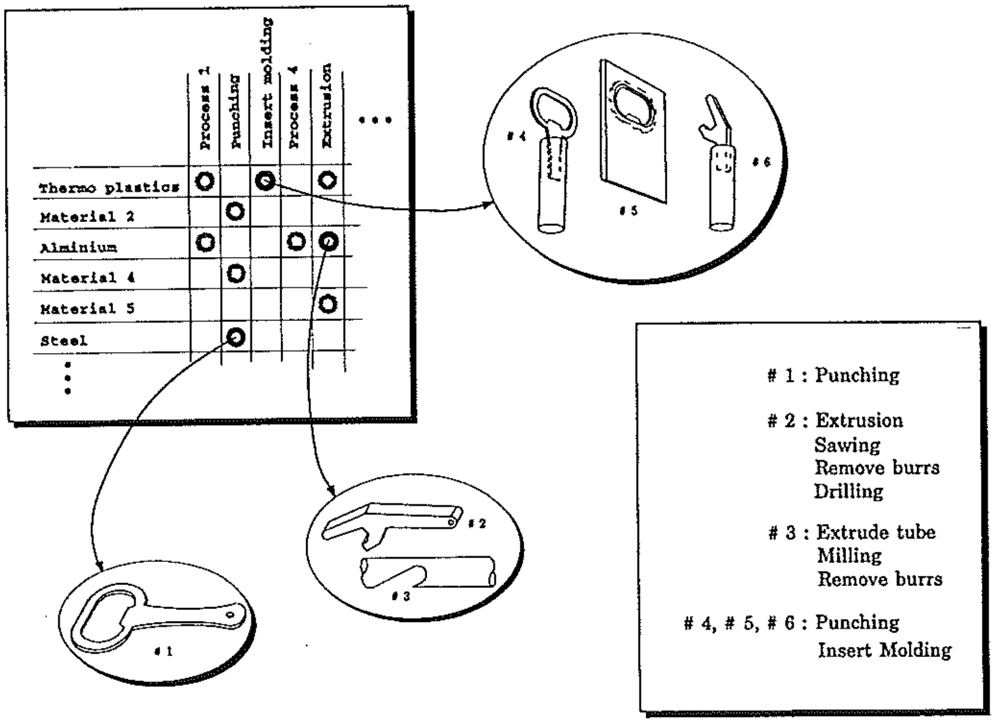

Figure 6 An example of how the P/M matrix is used. The process material combination left when unsuitable combinations have been deleted, are used as inspiration for different solutions, and the process chains are described.

processes and material should be considered at the conceptual level ? To what extend should materials and processes be described in process/material matrix ?. Furthermore other methods for searching, evaluating and selecting production methods at the four levels of design will be developed, where central questions are: What process selection criteria must be considered ?, How is it possible to weight these criteria against each other ? How can process chains consisting of different types of processes be compared ? Together with these tools a process information model that supports the designers work at all four levels and could be used in the tools will be developed as well.

4 Conclusions

The paper has pointed out, that the possible production methods for the individual components in a product are affected by decisions made early as well as late in the design stage. Therefore it is very important that decision makers in the whole design stage are aware of what consequences their decisions have on the production. It is argued that process considerations should be done on all levels of design, and that the designer should use the processes as an inspiration source for creating component solutions. It is also argued that processes cannot be regarded as individual parameters, but has to be seen as an integrated part of a component solution, and that the process selection in the design phase must be made on the basis of a component solution described with the whole process chain to produce the component and not only the main process. Furthermore some tools to support the designer in process considerations on all levels of product development are presented.

5 Acknowledgements

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6 References

1. R.W.Bolz, *Production Processes - The Producibility Handbook*,Industrial Press Inc, New York, 1963, 924 p.
2. E.P.Degarmo, J.T.Black, R.A.Kohser, *Materials and processes in Manufacturing*, Macmillan Publishing Company, NewYork 1988, 1172 p
3. D.K.Allen, L.Alting, *Manufacturing Processes*, CAM software Research Laboratory, Brigham Young University, Utah, 1986
4. S.Kalpakjian, *Manufacturing Engineering and Technology*, Addison Wesley, USA 1989, 1194 p
5. G.Pahl, W.Beitz, *Konstruktionslehre*, Handbuch für Studium und Praxis Springer-Verlag, Berlin, Heidelberg, New York, 1986, pp 590
6. J.G.Bralla, *Handbook of Product Design for Manufacturing - A Practical Guide to Low-Cost Production*, Mcgraw-Hill Book Company, 1986, 1120 p.
7. T. Lenau and L. Kristensen, *MADED - An Information System for Manufacturing Processes*, proposed paper for ICED 93, The Hague, 1993, 4 pages.
8. E.L.Jepsen, *Valg af industrielle fremstillingsmetoder (Selection of manufacturing methods)*, Ph.D. Thesis, AMT, Technical University of Denmark, 1978, 110 pages.
9. Value Analysis-Incorporated, Value Control Design Guide, 426 Franklin Street, Schenectady, New York, 1963
10. J.B.Sigurjónsson, *A contribution to a theory for selecting production methods*, Ph.D. thesis, Department of Machine Design, The Norwegian Institute of Technology, University of Trondheim, 1992
11. K. Ishii and R. Nekkanti, *Compatibility representation of knowledge about net shape manufacturing*, Proceedings of the ASME Design Theory and Methodology Conference 1989.
12. K.Ishii, S.Krizan, C.H.Lee, R.A.Miller, *HyperQ/Process: An Expert System for Manufacturing Process Selection*, Engineering Research Center, The Ohio State University, USA, 16 pages
13. J.Yu, S.Krizan, K.Ishii, *Computer Aided Design for Manufacturing Process Selection*, Department of Mechanical Engineering, The Ohio State University, USA, 1992
14. M.L.Lovrich, C.L.Tucker III, *Computer-Aided Selection of Polymeric Materials and Manufacturing Processes*, Annual Technical Conference - Society of Plastics Engineers 44 th., Published by Soc. of Plast. Eng., Brookfield Center, CT, USA, p 1388-1392
15. K. Jakobsen, *The interrelation between product shape, material and production method*, ICED, Harroegate, august 1989, p. 775-784.

THE PROCEDURE FOLLOWED IN THE LITERATURE STUDY

C

The procedure of how the literature study was carried out is described in this appendix, as well as the experience attained by carrying out the described procedure.

The author find, that there is two good reasons to describe the procedure of how literature was found and treated: *Firstly* to give the reader a possibility to judge if the subject is suitably well invetigated. There is always a risk that not all papers or all books in the field has been found and read. By making it visible to the reader *how* the study was carried out, it is possible for him to judge if the search for relevant publications was systematic enough to secure that the field is covered to a reasonable level by the presented literature. *Secondly* there is a possibility that some readers could learn something or at least get some good ideas of how a literature study should (or should not) be carried out in relation to a Ph.D. study, since the author of this report has seen no procedure described elsewhere. The procedure of searching literature was carried out as follows:

Firstly the following keywords were selected:
- Design
- Production
- Design for Manufacture
- Process selection
- Process sequence
- Design for production
- Known relevant authors names

and with these keywords the PC-ROM and the ALIS system at the National Technological Library of Denmark (DTB) was consulted. The PC-ROM contains about 600.000 technical papers published within the last five years. The ALIS system is a data-base containing the books and dissertations which are stated in DTB and published after 1968.
The keywords described were early in the project expected to pay result in the literature search. Later in the project other keywords have shown to be essential. Examples are: DFM, DFF, Production Method, Design for Manufacture, Design for Manufacturing, Concurrent Engineering, Simultaneous Engineering, Integrating Design and Manufacture, and Integrated Product Development. Including the domain of empirical studies the list would be even longer. Only english key-words have been

used; this is of course decreasing the possibility of finding publications from countries like Germany, France, Japan, etc., but one must assume that important results will be published in english, and that english key-words should be sufficient to find relevant publications.

Secondly the following journals were skimmed:
- Manufacturing Engineering 1990 and 1991 (excl. no 12)
- The Int. J of advanced manufacturing tehcnology (1988-1991)
- Manufacturing Engineer (1989-1991)

In the beginning of the project, it was assumed that papers about process selection would be published in journals concerning manufacturing and production and therefore these journals were consulted. The benefit of this consultation was poor since it showed out that this field is covered more in journals and proceedings concerning design, design for manufacture and other related subjects. For researchers working in the field of process selection it must be recommended to read the following journals and proceedings since it is notoriously worthwhile:

- Journal of Design and Manufacturing
- Proceedings of ICED.
- Journal of Concurrent Engineering
- Journal of Engineering Design
- Issues in Design/Manufacture Integration.
- Proceedings of the Concurrent Product and Process Design Syposium.
- Proceedings of Design Theory and Methodology.

The last three are proceedings of the ASME Winter Annual Meeting conferences.

Thirdly while reading the already found articles and books the references in these were investegated, and the interesting ones were ordered at the library. This method has a kind of domino effect since every paper found references one or more interesting papers, and thus one could keep on finding new interesting references. One has to stop somewhere and therefore the reader will find, that the bibliography of this thesis includes a section called *Interesting but unread publications*. The section contains the publications found interesting, but for some reason were not found. The section is included in the list while these publications could be a comfort to new researchers in the field. This method is of great value and has to be strongly recommended, since this is one of the best ways to find interesting publications.

Fourthly some publications were mentioned by collegues who knew about the field. It is worthwile telling collegues in what field one works. Often collegues in related fields find publications of interest for others. If the researchers are aware of what subjects their collegues treat, many interesting papers, that would not have been found, rise to the surface.

Fifthly relevant authors were directly contacted to get publications they had written before and after the one/ones possessed. The contact with relevant researchers is of great value, since this is the way to get papers that are newly written and to be published in the future. With the time to market for papers in mind, one can guess that in this way one will get the paper half a year, or even more, before it will be published. Since the duration of a Ph.D. study is 2½ years, it is a long time to wait half a year or more to get a paper that has already been written !

EMPIRICAL METHODS

D

One of the tasks in the project is to uncover how process selection is carried out in companies today. To do this it is obvious that one needs to carry out field studies. The different empirical methods described in literature are discussed in this section. According to STAUFFER & ULLMAN 88, STOMPH-BLESSING 91, SCHMIDT & CARSTENSEN 90, and HOFFMAN 87 there are the following empirical methods for data collection: Unstructured interview, structured interview, questionnaires, document analysis, direct observations of real life and set ups, dictionary, protocol analysis, dialog analysis, participation, thinking aloud protocols (audio/video taping), the method of familiar tasks, limited-information tasks, constraint processing tasks, the method of tough cases. These methods are described and compared in order to select what methods should be used for the field studies in this work. The methods are divided into retrospective and concurrent methods. Retrospective methods are "looking back" and collecting data about the past, whereas concurrent methods are used to collect data about contemporary happenings.

B.1 Retrospective methods

Unstructured interview.

In the unstructured interview the interviewer asks more or less spontaneous questions. The method is often used when the problem of the investigation is not known precisely. The analyst has to formulate his hypotheses in forehand and present them to the expert during the interview. The intention is that the expert must either confirm, deny, or qualify the interviewer's statement. Often the hypotheses has to be modified or even scrapt because they are definitely wrong. The analyst has to be open minded for following new interesting aspects that he had not been thinking of from the beginning. The interview is like a conversation, where the interviewer must go into details about answers that are strange, remarkable, unexpected or interesting to him. For this purpose the question "why ?" is essential, and he has to be very carefull that he does not make his own conclusions by guessing, but instead he has to keep on asking until he is sure that he knows precisely what *the interviewee thinks* about the subject. SCHMIDT & CARSTENSEN 90, HOFFMAN 87

Structured interview.

The structured interview presupposes a well defined formulation of the problem. The questions are created in advance and the interviewer has a list of questions he has to ask. Side leaps should be avoided, and therefore he can not follow interesting subjects like in the unstructured interview. The interviewer has to make him self strictly qlear what he wants to know, before he is making the interview. SCHMIDT & CARSTENSEN 90, HOFFMAN 87

Questionnaires.
A questionnaire is in principal like the structured interview although the questions are put in writing. Since the "interviewer" has no change to enlarge on the questions, if they are difficult to understand, the questions must be understandable and unambiguous. A questionnaire is of great vallue if one wants to get a general overview of how a bigger number of persons thinks about a subject. The way the questions are formulated is essential to the result of the survey. The two extrem ways to put the questions are as multipal choice or as questions where the questionned person in his own words freely can put together his answers. The formulation should be considered with care, and the type of questions should be selected with the purpose in mind. SCHMIDT & CARSTENSEN 90

Document analysis.
In document analysis documents like; minutes, product and process documentation, company strategies, drawings, press cuttings, etc. The documents can be divided into documents produced before and during the product, the former can be difficult to trace whereas the latter more easy. Documents can contain valuable information about the system to be analysed. SCHMIDT & CARSTENSEN 90, STOMPH-BLESSING 91.

B.2 Concurrent methods

The concurrent methods can be subdivided into two sub-groups: the real life situations and the scenarios. In the real life situations the researcher analysis the real world whereas in the scenarios the real world is imitated in a somehow restricted way.

Direct observations of real life situations.
In this method the scientist follows a working situation by being present concurrently while it takes place. "The fly on the wall" is difficult to obtain because the observed person(s) would be aware that they are observed. Unless of course they are watched through a hidden camera, but this gives some ethical problems. One way to make observations is to follow the engineer like a trailer through one or more "typical" days, and observe what activities he carries out during a working day. SCHMIDT & CARSTENSEN 90, STOMPH-BLESSING 91.

Participation.
In participation the scientist should learn for himself what it is like to be in the studied situation. For instance the scientist works as a designer in the company, and thereby he gets information about how decisions are made. Both the decisions he has to make himself and decisions made by others around him. The challenge for the scientist is to be accepted as a member of the system he is studying. The other persons in the system have to look upon him as "one of their own", and this is a very difficult task. STOMPH-BLESSING 91 used participation in her analysis. She experienced that participation was more a burden than a help, because it forces the researcher to focus on one topic, thus loosing the overall view and reducing the time to observe. This is also the authors experience.

Dictionary.
By this method the designer is told to write a dictionary every day showing what activities and decisions he has carried out/made during the day. It is of course very time comsuming for the designer to write down in detail what activities he carries out during a day, and therefore a dictionary is only a realistic technique if a simple scheme can be created. The scheme must consist of only a minor number of well defined categories. In a modified version of the dictionary, called time-writing, the project members write down the hours they spend on a specific activity. It can be discussed if the dictionary method belongs to the concurrent or the retrospective methods, may be it is something in between. SCHMIDT & CARSTENSEN 90, STOMPH-BLESSING 91

Direct observation of scenarios.
The method of familiar tasks described by HOFFMAN 87 is an observation method. In this specific method, the expert solves the kind of tasks they are typically engaged in. *The limited information task* described by HOFFMAN 87 is also an observation method. By this method the amount or kind of information that is available to the expert is somehow restricted. The limited-information task is especially useful for revealing an expert's strategies since the incompleteness of the information affords the formulation of hypotheses, strategic thinking and the use of heurestics. *Constrained-processing tasks* described by HOFFMAN 87 is like limited-information task a method that involves tinkering with the familiar tasks. This could be done by limiting the amount of time to solve the problem, or by asking the expert specific questions rather than to require the full analysis that is conducted during the familiar task. In *The tough case method* the problem to solve should be a difficult one, since this will uncover subtle and refined aspects of the expert's reasoning. HOFFMAN 87 says that in the later phases in the study, when some of the expert's knowledge and methods have already been described, one could use the method of tough cases.

Thinking aloud protocols have the purpose to analyse the cognitive decisions, the subject uses in realistic decision making situations. The subject is given a problem to solve and he is told to speak out loud during the session. Compared to interviews this method has the advantage that it goes beyond what experts can explicitly tell you when asked how they solve a specific problem. The session can be audio or video taped. SCHMIDT & CARSTENSEN 90, STOMPH-BLESSING 91. *Dialog analysis* is actually the same as *thinking aloud protocols*, whith the only difference that in dialog analysis there are two or more subjects. This method has the purpose of analysing the cooperative decision making going on between persons in a group, e.g. a product development group. Dialog analysis could also be used in real life situations (observation of a meeting). SCHMIDT & CARSTENSEN 90, STOMPH-BLESSING 91. *Role-playing* is like thinking aloud protocols and dialog analysis, but with the difference that the subjects are playing a role; they are not acting as themself in the situation. For instance a designer could play the role of a manufacturing engineer and thereby get insight in his job; thus understand his situation better and increase the mutual comprehension.

B.3 Concluding remarks and selecting the most suitable methods for this work.

As it can be seen above, there are several different methods that could be used to make empirical work analyses. *The concurrent methods* (role-playing, participation, observation etc.) have the advantage that the researcher follows the activities while happening but with a risk of disturbing and jamming the activities he is studying. *The retrospective methods* (interviews, questionnaires etc.) have the advantage that the activities to be studied happened without disturbance but in return for this, the picture is not a true picture, since the interviewed persons may have forgotten or does not know exactly what happened; why he did what he did.

The empirical methods are presented by the authors as different *methods* or *tasks*, but they are not in the same dimension. They can be mixed and one could for instance carry out a scenario where the subjects are acting them self or another person. The subjects could be told to speak aloud or not. There could be one or more persons. The problem to solve could be a familar task or a tough problem. The scenario could be carried out as a constrained-processing or/and a limited-information task. The scenario could be recorded, using audio or video taping or the information could be stored as written notes by the researcher or as pure memory. The heading of these so called methods and tasks is scenarios and the methods and tasks are *parameters* the researcher can put together as he pleases, to get the composite scenario that fulfil his claims in the most optimal way.

HOFFMAN 87 and SCHMIDT & CARSTENSEN 90 speaks about extracting the knowledge of an *expert* and they mention many of the methods described above. But it is difficult to find an expert in process selection, since he is a non-existing person. The designers select process allright, it is even possible to find designers who have selected processes several times in their carrier, but to find a designer one could call an expert in process selection is probably impossible. Thus the only possibility is to ask several designers and try to find out how they are doing and trough these informations, together with theory and common sence, puzzle a picture that shows how process selection should be done.

One problem by using the observation method in this field, is that designers do not have "typical" days. Using the method on a cleaning lady, a busdriver or a mechanic obviously would be possible since they are doing the same routine every day and perhaps even several times per day. But to find out how a designer makes process selection one would probably have to be the designers shadow for several days, or even several weeks, and in this time he is probably only using some few minutes on relevant subjects.

Allthough the task of this project is rather to develop a methodology than an application program or an information system, the kind of analyses used in this project must belong to operational analyses and according to SCHMIDT & CARSTENSEN 90 the suitable methods are: structuret interviews, documentaric analysis, questionnairs, dictionary, protocol analysis, and dialog analysis.

The ideal procedure for selecting the most suitable method would be: to define the problem, to find the most suitable method for this problem and to find a company that fits the problem and where the method could be used.

In this case the company was selected before the author was started on his Ph.D. work, and there was an agreement that the author should participate on a project in the company. Unfortunately the task of participating the project was not clear from the beginning, but was formulated as "find out how the activities in design and production could be integrated" instead of the more specific task "how is production methods selected in the design phase" and unfortunately the project had already gone into the production realization phase, before the author even started on the project, and therefore 95% of the production methods had already been selected. Nevertheless it was decided that the author should participate on the project in the company and beside the participation do some unstructured interviews of the designers on the project. It was necessary to make unstructured interviews since the task was to loose to be questioned in structured interviews or by questionnaires.

If the task had been specified from the beginning it would have been clear, that the best solution would have been to participate another project where production methods had not been selected yet, or to drop the participation and instead to interview the designers on the project.

In addition to these field studies where participation and interviews were carried out it was decided to do some video-tapings of students solving a design problem. This was ment as a pilot-project to develope the design problem as well as the method before the method was used with professional engineering designers as subjects.