G. Pahl
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K.H. Grote
Ken Wallace · Luciënne Blessing
Translators and Editors

Engineering Design

A Systematic Approach

Third Edition

Springer

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Preface

Sadly, just one year after the publication of the fourth German edition in 1997, my co-author Wolfgang Beitz died after a short but severe illness. His many outstanding contributions to engineering design, including his contribution to this book, were honoured in a memorial colloquium held in Berlin. It would have made me very happy if he had been able to see the continuing success of our book, including its translation into Portuguese. Our collaboration was a perfect one—always fruitful, always beneficial. I am deeply grateful to him.

The book, “Pahl/Beitz—Konstruktionslehre”, has now been translated into eight languages and recognised as an international reference text. For reasons of continuity, our publisher Springer wanted to publish a fifth German edition of the book. To assist with this task two former students of Wolfgang Beitz became involved: Professor Dr.-Ing. Jörg Feldhusen and Professor Dr.-Ing. Karl-Heinrich Grote, both of whom have continually promoted and expanded his ideas. Professor Feldhusen worked for many years as a senior designer in the automotive industry and is now at RWTH Aachen University, succeeding Professor Dr.-Ing. R. Koller. Professor Grote has considerable experience of teaching design and running projects as a Professor in the USA, and is now at the Otto-von-Guericke University in Magdeburg. He succeeded Professor Beitz as the Editor of the Dubbel Handbook for Mechanical Engineering.

Gerhard Pahl
Darmstadt

Authors' Forewords

Sixth German Edition

The fifth German edition, which was published in March 2003, was so well received that just a year later a sixth German edition was required. The opportunity was taken to add some new developments to the chapter on size ranges and modular products.

The authors would like to reiterate their thanks to all those involved in both editions.

G. Pahl, J. Feldhusen and K.-H. Grote
Darmstadt, Aachen and Magdeburg, April 2004

Fifth German Edition

For the fifth German edition we have retained the well-established pattern of the previous editions, but updated it with new material. Because of its widespread use, the basics of electronic data processing*, including CAD, have been moved into the chapter on fundamentals. The chapter on the product development process has been expanded and strengthened by adding new perspectives. As a result, Chapters 1–4 now fully represent the necessary basic knowledge, including cognitive aspects, needed to underpin a systematic approach to engineering design. Chapters 5–8 describe the application of this basic knowledge to product development from the task clarification phase, through conceptual design up to the final embodiment and detail design* phases, supported by many detailed examples. Chapter 9 describes some important generic solutions including composite structures*, mechatronics and adaptronics. Basic knowledge about machine elements is, as always, assumed. Chapter 10 covers, as in previous editions, the development of size ranges and modular products. The increasing importance of achieving high quality is reflected by additions to

* The starred topics do not appear in this third English edition and as a consequence some chapter numbers have changed—see Editors' Foreword.

Chapter 11. The important theme of estimating costs can be found, as before, in Chapter 12. Because the basics of data processing technology have now been included in the chapter on fundamentals, Chapter 13 focuses on general recommendations for designing with CAD*. Chapter 14 provides an overview of the recommended methods, and reports on experiences of using the approach in industrial practice. The book closes with a definition of terms* as they have been used in this book. The index supports a rapid search for specific themes.

In this way, the systematic approach to engineering design has been brought to a level that provides a basis for successful product development. Throughout, fundamentals have been emphasised and short-term trends avoided. The approach described also provides a sound basis for design education courses that help students move into design practice. The literature has been updated, offering those who are interested in more detail or in the historical background a rich source of information.

The authors have to thank many individuals. Frau Professor Dr.-Ing. L. Blessing, successor to Professor Wolfgang Beitz, kept the original figures and made them available to us. Professor Dr.-Ing. K. Landau, TU Darmstadt, helped us update the literature on design for ergonomics. Professors Dr.-Ing. B. Breuer, Dr.-Ing. H. Hanselka, Dr.-Ing. R. Isermann and Dr.-Ing. R. Nordmann, all from TU Darmstadt, contributed to the sections on mechatronics and adaptronics with suggestions, examples and figures. In this connection we also thank Dr.-Ing. M. Semsch for his contribution. Emeritus Professor Dr.-Ing. M. Flemming, ETH Zurich, greatly supported us with suggestions and figures on the themes of composite construction* and structronics. Last but not least, we thank all those hardworking assistants, such as Frau B. Frehse at the Institut für Maschinenkonstruktion-Konstruktionstechnik, Universität Magdeburg, who prepared and reworked the electronic transformation of the text and figures. Finally we warmly thank our publisher Springer, in particular Dr. Riedesel, Frau Hestermann-Beyerle, Frau Rossow and Herr Schoenefeldt for their continuous support and for the excellent printing of the text and figures.

G. Pahl, J. Feldhusen and K.-H. Grote
Darmstadt, Aachen and Magdeburg, June 2002

Fourth German Edition

The third edition of our book proved to be so popular that after a relatively short time a further edition was required. A reprint was not considered appropriate as several important new concepts and methods for the product development process had emerged, and these could not be ignored. Furthermore recently published findings needed to be taken into account.

The structure and content of the third edition forms the basis of the fourth edition. The topic of product planning has been extended through the integration of methods such as portfolio analysis and scenario planning. New sections have been introduced on effective organisation structures, on applying simultaneous engineering, on leadership and on team behaviour. The increasing importance of quality assurance has reinforced the need to adopt systematic engineering design as a primary measure. This should be extended through the application of secondary measures, such as Quality Function Deployment (QFD) using the House of Quality. Developments in the area of sustainability have led to modifications in the section on design for recycling. Because of its general technical and economic importance, a new section on design to minimise wear has been introduced. The method of target costing has been included in the chapter on design for minimum cost. Finally, the chapter on CAD required updating*.

The third edition, slightly abridged, has been translated into English, *Engineering Design: A Systematic Approach* (2nd Edition, Springer-Verlag, London), under the leadership of Ken Wallace, who was supported by Luciënne Blessing and Frank Bauert. We thank them warmly. A Japanese translation has also been published, and a translation into Korean is in progress. These translations significantly increase the international influence of *Konstruktionslehre*.

The employees of both our institutes have again supported our work on the fourth edition in their usual trusted and willing way. For their help we are deeply grateful. Our publishers have again to be thanked for the excellent advice we have received, as well as for their careful realisation of the book. Finally, we thank our wives for their continuous understanding, for without their support this book would never have been possible.

G. Pahl and W. Beitz
Darmstadt and Berlin, January 1997

Editors' Foreword

Background

The first German edition of *Konstruktionslehre* was published in 1977. The first English edition entitled *Engineering Design* was published in 1984 and was a full translation of the German text. Both the German and the English editions of the book rapidly became established as important references on systematic engineering design in industry, research and education. International interest in engineering design grew rapidly during the 1980s and many developments took place. To keep up-to-date with the changes, a second German edition was published in 1986. It was too soon after the publication of the first English edition to consider a second edition. However, since the translation was being extensively used to support engineering design teaching, a slightly abridged student edition entitled *Engineering Design – A Systematic Approach* was published in 1988.

When preparing the student edition, the opportunity was taken to review the translation and the contents of the first edition. No changes in terminology were thought necessary and the contents were the same as the first English edition except for the removal of two chapters.

The first chapter to be removed was the short chapter on detail design. It must be emphasised that this does not mean that detail design is considered unimportant or lacking in intellectual challenge. Quite the reverse is true. Detail design is far too broad and complex a subject to be covered in a general text. There are many excellent books covering the detail design of specific technical systems and machine elements. For these reasons, the German editions did not discuss technical aspects of detail design, but only dealt with the preparation of production documents and the numbering techniques required to keep track of them.

The second chapter to be removed dealt with computer support for design, including CAD. Again, this chapter was clearly not removed because the topic is unimportant. Computer support systems are used universally and develop rapidly. Many specialist texts are available.

In 1993 an updated and extended third German edition of *Konstruktionslehre* was published. It was considered timely to produce a second English edition to bring the translation into step with the latest thinking. The new layout of the German edition was incorporated, along with the important discussions of psychology and recycling. The new chapters on design for quality and design for minimum cost were included, but, for the reasons given above, the chapters on detail design and computer support were again omitted.

The third German edition also contained a new chapter that described selected standard solutions (machine elements, drives and controls) in line with the systematic approach and concepts presented in the book. This knowledge is covered comprehensively in the translation of the German *Dubbel* [*Dubbel Handbook for Mechanical Engineering*, Springer-Verlag, London, 1994]. This chapter was therefore also omitted.

There are now six German editions of Pahl/Beitz (4th 1997; 5th 2003; 6th 2005)—so it is timely to produce a third English edition. The structure has changed compared to the previous English edition and is described below.

Structure of the Third English Edition

Introduction—Chapter 1

The book starts with the historical background to modern systematic design thinking in Germany. The work of influential design researchers and practitioners is reviewed briefly.

Fundamentals—Chapter 2

This chapter discusses the fundamentals of technical systems and of the systematic approach, including cognitive aspects. The fundamentals of the use of computers to support product development were omitted for the reasons mentioned above.

Product Planning, Solution Finding and Evaluation—Chapter 3

In this chapter the flow of work during the process of planning is described, see Figure 3.2, along with general methods for finding and evaluating solutions that can be used not only for planning but also throughout the product development process. These methods are not linked to any specific design phase or type of product and include a range of intuitive and discursive methods.

Product Development Process—Chapter 4

This chapter presents the flow of work during the product development process and describes the main phases: Task Clarification; Conceptual Design; Embodiment Design; and Detail Design. The authors' overall model is shown in Figure 4.3. New to this edition is a discussion about the effective management and organisation of the design process.

Task Clarification—Chapter 5

This phase involves identifying and formulating the general and task-specific requirements and constraints, and setting up a requirements list (design specification). The steps of this phase are shown in Figure 5.1.

Conceptual Design—Chapter 6

This phase involves (see Figure 6.1):

- abstracting to find the essential problems
- establishing function structures
- searching for working principles
- combining working principles into working structures
- selecting a suitable working structure and firming it up into a principle solution (concept).

This chapter concludes with two detailed examples of applying the proposed methods to the design of a single-handed water mixing tap and an impulse-loading test rig.

Embodiment Design—Chapter 7

During this phase, designers start with the selected concept and work through the steps shown in Figure 7.1 to produce a definitive layout of the proposed technical product or system in accordance with technical and economic requirements.

About 40% of the book is devoted to this phase and the authors discuss the basic rules, principles and guidelines of embodiment design, followed by a comprehensive example of the embodiment design of the impulse-loading test rig introduced in Chapter 6.

The chapter on detail design has again been omitted, but a new Section 7.8 outlining the steps of this phase has been introduced (see Figure 7.164).

Mechanical Connections, Mechatronics and Adaptronics—Chapter 8

This chapter is new to the English series of Pahl/Beitz. Three classes of generic solutions are presented in a way that is consistent with the systematic approach presented in this book. Because of their overriding importance in mechanical design, mechanical connections are the first class to be discussed. Because of their growing importance, the other two classes are mechatronic and adaptronic systems.

The decision was taken to leave out drives, control systems and composite structures as these are covered extensively in the English literature.

Size Ranges and Modular Products—Chapter 9

This chapter presents methods for systematically developing size ranges and modular products to meet a wide range of requirements while at the same time reducing costs. In this edition the concepts of product architecture and platform construction are introduced.

Design for Quality—Chapter 10

The chapter on design for quality now includes a discussion of Quality Function Deployment (QFD).

Design for Minimum Cost—Chapter 11

This chapter now includes a section on Target Costing.

Summary—Chapter 12

The short final chapter provides a summary of the ideas covered in the book. Figures 12.1 and 12.2 provide a quick reference to the main steps in the design process and the appropriate working methods.

Every design must meet both task-specific and general requirements and constraints. To remind designers of these during all stages of the design process, a set of checklists is used throughout the book. An overview of these checklists is provided in Figure 12.3.

Translation Issues

The aim of the translation has been to render each section of the book comprehensible in its own right and to avoid specialist terminology. Terms are defined as they arise, rather than in a separate glossary, and their meanings should be clear from their usage. On occasions other authors have used slightly different terms, but it is hoped that no misunderstandings arise and that the translation is clear and consistent throughout.

Some terms, however, require special mention. The German methodology includes a standard concept introduced with the German prefix 'wirk'. Translators have used a number of different English terms to translate 'wirk', including 'active', 'working' and 'effective'. After careful consideration, we decided to continue to use 'working' as in the previous English edition, so, for example, 'wirkprinzip' becomes 'working principle', 'wirkort' become 'working location', 'wirkfläche' becomes 'working surface' and 'wirkbewegung' becomes 'working motion'. In

English 'working' does not immediately convey fully the correct German meaning. In German, the 'wirk' prefix is used to focus on the principles, locations and surfaces, etc. that ensure the desired physical effect takes place. So, for example, 'wirkort' (working location) is where the physical effect takes place using two or more 'wirkflächen' (working surfaces) and a 'wirkbewegung' (working motion). 'Wirkprinzip' brings these ideas together as the 'working principle'. For example 'clamping' is the working principle that can realise the friction effect by preventing certain working motions through an appropriate combination of suitable working surfaces (see Figure 2.12).

The term 'drawing' is used in this book to represent the output of either a traditional design approach, i.e. a physical drawing, or a modern computer-supported approach, i.e. a CAD model or drawing.

Of the four phases of the product design process, only the terminology used for the third, 'embodiment design', requires some explanation. Other translations, in a similar context, have used layout design, main design, scheme design or draft design. The input to this third phase is a design concept and the output is a technical description, often in the form of a scale drawing or CAD model. Depending on the particular company involved, this drawing is referred to as a general arrangement, a layout, a scheme, a draft, or a configuration, and it defines the arrangement and preliminary shapes of the components in a technical artefact. The term 'layout' is widely used and was selected for this book. The idea to introduce the term embodiment design came from French's book, *Engineering Design: The Conceptual Stage*, published in 1971. Embodiment design incorporates both layout design (the arrangement of components and their relative motions) and form design (the shapes and materials of individual components). The term 'form design' is widely used in the literature, and its meaning ranges from the overall form of a product in an industrial design context, to the more restricted form of individual components in an engineering context. This book tends towards the latter usage.

There are numerous references to DIN (Deutsche Industrie Normen) standards and VDI (Verein Deutscher Ingenieure) guidelines, a few of which have been translated into English. Examples are the DIN ISO standards and the translation of VDI 2221. In important cases, references to DIN standards and VDI guidelines have been retained in the English text, but elsewhere they have simply been listed along with the other references. In technical examples, DIN standards have been referred to without any attempt to find English equivalents.

The original text includes many references. Most of these are in German and therefore not of immediate interest to the majority of English readers. However, to have omitted them would have detracted from the authority of the book and its value as an important source of reference. The references have therefore been retained in full but grouped together at the end of the book, rather than at the end of each chapter as in the German text. An English bibliography has been added by the Editors, as well as an overview of the main engineering design conference series and journals.

It must be stressed that nothing was deleted that detracted from the main aim of the original German book, that is, to present a comprehensive, consistent and clear approach to systematic engineering design.

Acknowledgements

Donald Welbourn was responsible for encouraging the translation of the first English edition in the late 1970s, and he helped and supported the task in numerous ways. Many of the challenges that arose with the translation and terminology at the time were resolved with the help of Arnold Pomerans.

We first worked together on the translation of the second English edition, and Frank Bauert assisted us with the new figures. Nicholas Pinfield from Springer provided encouragement and support throughout.

For the third English edition, we worked jointly on the overall task of translation and editing.

John Clarkson helped with the compilation of the English bibliography. Anthony Doyle and Nicolas Wilson from Springer contributed enormously to the overall production of the book and their help and patience are gratefully acknowledged. Sorina Moosdorf from LE-TEX in Germany was responsible for the detailed task of typesetting the book. She and her colleagues did an excellent job.

Finally, and most sincerely, we must thank Professor Pahl, Professor Feldhusen and Professor Grote for trusting us with the translation of the book.

As with the previous two editions, it is hoped that this translation faithfully conveys the ideas of *Pahl/Beitz – Konstruktionslehre* while adopting an English style.

Ken Wallace and Luciënne Blessing
Cambridge and Berlin, November 2006

Contents

1 Introduction 1
1.1 The Engineering Designer 1
1.1.1 Tasks and Activities 1
1.1.2 Position of the Design Process within a Company 6
1.1.3 Trends 6
1.2 Necessity for Systematic Design 9
1.2.1 Requirements and the Need for Systematic Design 9
1.2.2 Historical Background 10
1.2.3 Current Methods 14
1.2.4 Aims and Objectives of this Book 19

2 Fundamentals 27
2.1 Fundamentals of Technical Systems 27
2.1.1 Systems, Plant, Equipment, Machines, Assemblies and Components 27
2.1.2 Conversion of Energy, Material and Signals 29
2.1.3 Functional Interrelationship 31
2.1.4 Working Interrelationship 38
2.1.5 Constructional Interrelationship 42
2.1.6 System Interrelationship 42
2.1.7 Systematic Guideline 43
2.2 Fundamentals of the Systematic Approach 45
2.2.1 Problem Solving Process 45
2.2.2 Characteristics of Good Problem Solvers 49
2.2.3 Problem Solving as Information Processing 51
2.2.4 General Working Methodology 53
2.2.5 Generally Applicable Methods 58
2.2.6 Role of Computer Support 62

3 Product Planning, Solution Finding and Evaluation 63
3.1 Product Planning 63
3.1.1 Degree of Novelty of a Product 64

3.1.2 Product Life Cycle ... 64
3.1.3 Company Goals and Their Effect ... 65
3.1.4 Product Planning ... 66
3.2 Solution Finding Methods ... 77
3.2.1 Conventional Methods ... 78
3.2.2 Intuitive Methods ... 82
3.2.3 Discursive Methods ... 89
3.2.4 Methods for Combining Solutions ... 103
3.3 Selection and Evaluation Methods ... 106
3.3.1 Selecting Solution Variants ... 106
3.3.2 Evaluating Solution Variants ... 109

4 Product Development Process ... 125
4.1 General Problem Solving Process ... 125
4.2 Flow of Work During the Process of Designing ... 128
4.2.1 Activity Planning ... 128
4.2.2 Timing and Scheduling ... 134
4.2.3 Planning Project and Product Costs ... 136
4.3 Effective Organisation Structures ... 138
4.3.1 Interdisciplinary Cooperation ... 138
4.3.2 Leadership and Team Behaviour ... 141

5 Task Clarification ... 145
5.1 Importance of Task Clarification ... 145
5.2 Setting Up a Requirements List (Design Specification) ... 146
5.2.1 Contents ... 146
5.2.2 Format ... 147
5.2.3 Identifying the Requirements ... 149
5.2.4 Refining and Extending the Requirements ... 151
5.2.5 Compiling the Requirements List ... 152
5.2.6 Examples ... 153
5.3 Using Requirements Lists ... 153
5.3.1 Updating ... 153
5.3.2 Partial Requirements Lists ... 156
5.3.3 Further Uses ... 157
5.4 Practical Application of Requirements Lists ... 157

6 Conceptual Design ... 159
6.1 Steps of Conceptual Design ... 159
6.2 Abstracting to Identify the Essential Problems ... 161
6.2.1 Aim of Abstraction ... 161
6.2.2 Broadening the Problem Formulation ... 162
6.2.3 Identifying the Essential Problems from the Requirements List ... 164
6.3 Establishing Function Structures ... 169

6.3.1 Overall Function ... 169
6.3.2 Breaking a Function Down into Subfunctions .. 170
6.3.3 Practical Applications of Function Structures .. 178
6.4 Developing Working Structures ... 181
6.4.1 Searching for Working Principles ... 181
6.4.2 Combining Working Principles ... 184
6.4.3 Selecting Working Structures ... 186
6.4.4 Practical Application of Working Structures ... 186
6.5 Developing Concepts ... 190
6.5.1 Firming Up into Principle Solution Variants ... 190
6.5.2 Evaluating Principle Solution Variants ... 192
6.5.3 Practical Application of Developing Concepts .. 198
6.6 Examples of Conceptual Design ... 199
6.6.1 One-Handed Household Water Mixing Tap ... 199
6.6.2 Impulse-Loading Test Rig ... 210

7 Embodiment Design ... 227
7.1 Steps of Embodiment Design ... 227
7.2 Checklist for Embodiment Design ... 233
7.3 Basic Rules of Embodiment Design ... 234
7.3.1 Clarity ... 235
7.3.2 Simplicity ... 242
7.3.3 Safety ... 247
7.4 Principles of Embodiment Design ... 268
7.4.1 Principles of Force Transmission ... 269
7.4.2 Principle of the Division of Tasks ... 281
7.4.3 Principle of Self-Help ... 290
7.4.4 Principles of Stability and Bi-Stability ... 301
7.4.5 Principles for Fault-Free Design ... 305
7.5 Guidelines for Embodiment Design ... 308
7.5.1 General Considerations ... 308
7.5.2 Design to Allow for Expansion ... 309
7.5.3 Design to Allow for Creep and Relaxation ... 321
7.5.4 Design Against Corrosion ... 328
7.5.5 Design to Minimise Wear ... 340
7.5.6 Design for Ergonomics ... 341
7.5.7 Design for Aesthetics ... 348
7.5.8 Design for Production ... 355
7.5.9 Design for Assembly ... 375
7.5.10 Design for Maintenance ... 385
7.5.11 Design for Recycling ... 388
7.5.12 Design for Minimum Risk ... 402
7.5.13 Design to Standards ... 410
7.6 Evaluating Embodiment Designs ... 416
7.7 Example of Embodiment Design ... 417
7.8 Detail Design ... 436

8 Mechanical Connections, Mechatronics and Adaptronics 439
8.1 Mechanical Connections 439
8.1.1 Generic Functions and General Behaviour 440
8.1.2 Material Connections 440
8.1.3 Form Connections 441
8.1.4 Force Connections 443
8.1.5 Applications 447
8.2 Mechatronics 448
8.2.1 General Architecture and Terminology 448
8.2.2 Goals and Limitations 450
8.2.3 Development of Mechatronic Solutions 450
8.2.4 Examples 451
8.3 Adaptronics 458
8.3.1 Fundamentals and Terminology 458
8.3.2 Goals and Limitations 459
8.3.3 Development of Adaptronic Solutions 460
8.3.4 Examples 461

9 Size Ranges and Modular Products 465
9.1 Size Ranges 465
9.1.1 Similarity Laws 466
9.1.2 Decimal-Geometric Preferred Number Series . . 469
9.1.3 Representation and Selection of Step Sizes 472
9.1.4 Geometrically Similar Size Ranges 476
9.1.5 Semi-Similar Size Ranges 481
9.1.6 Development of Size Ranges 493
9.2 Modular Products 495
9.2.1 Modular Product Systematics 496
9.2.2 Modular Product Development 499
9.2.3 Advantages and Limitations of Modular Systems 508
9.2.4 Examples 510
9.3 Recent Rationalisation Approaches 514
9.3.1 Modularisation and Product Architecture 514
9.3.2 Platform Construction 515

10 Design for Quality 517
10.1 Applying a Systematic Approach 517
10.2 Faults and Disturbing Factors 521
10.3 Fault-Tree Analysis 522
10.4 Failure Mode and Effect Analysis (FMEA) 529
10.5 Quality Function Deployment (QFD) 531

11 Design for Minimum Cost 535
11.1 Cost Factors 535
11.2 Fundamentals of Cost Calculations 537
11.3 Methods for Estimating Costs 539
11.3.1 Comparing with Relative Costs 539
11.3.2 Estimating Using Share of Material Costs 544
11.3.3 Estimating Using Regression Analysis 545
11.3.4 Extrapolating Using Similarity Relations 547
11.3.5 Cost Structures 558
11.4 Target Costing 560
11.5 Rules for Minimising Costs 561

12 Summary 563
12.1 The Systematic Approach 563
12.2 Experiences of Applying the Systematic Approach in Practice 567

References 571

English Bibliography 603

Index 609

1 Introduction

1.1 The Engineering Designer

1.1.1 Tasks and Activities

The main task of engineers is to apply their scientific and engineering knowledge to the solution of technical problems, and then to optimise those solutions within the requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations. Problems become concrete tasks after the problems that engineers have to solve to create new technical products (artefacts) are clarified and defined. This happens in individual work as well as in teams in order to realise interdisciplinary product development. The mental creation of a new product is the task of design and development engineers, whereas its physical realisation is the responsibility of production engineers.

In this book, *designer* is used synonymously to mean design and development engineers. Designers contribute to finding solutions and developing products in a very specific way. They carry a heavy burden of responsibility, since their ideas, knowledge and skills determine the technical, economic and ecological properties of the product in a decisive way.

Design is an interesting engineering activity that:

- affects almost all areas of human life
- uses the laws and insights of science
- builds upon special experience
- provides the prerequisites for the physical realisation of solution ideas
- requires professional integrity and responsibility.

Dixon [1.39] and later Penny [1.144] placed the work of engineering designers at the centre of two intersecting cultural and technical streams (see Figure 1.1).

However, other models are also available. In *psychological* respects, designing is a creative activity that calls for a sound grounding in mathematics, physics, chemistry, mechanics, thermodynamics, hydrodynamics, electrical engineering, production engineering, materials technology, machine elements and design theory, as well as knowledge and experience of the domain of interest. Initiative,

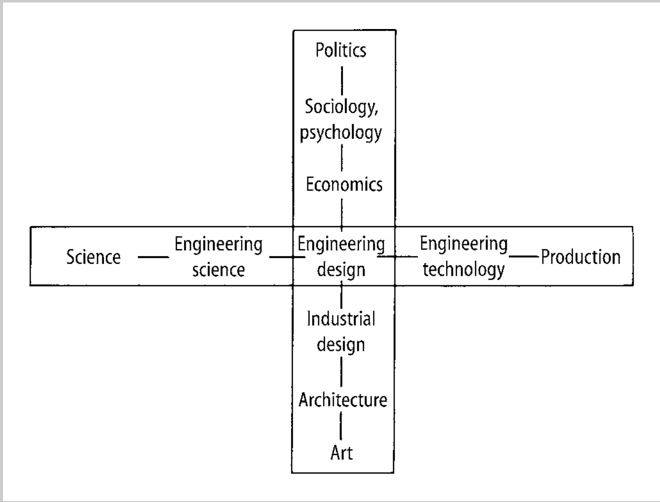


Figure 1.1. The central activity of engineering design. After [1.39, 1.144]

resolution, economic insight, tenacity, optimism and teamwork are qualities that stand all designers in good stead and are indispensable to those in responsible positions [1.130] (see Section 2.2.2).

In *systematic* respects, designing is the optimisation of given objectives within partly conflicting constraints. Requirements change with time, so that a particular solution can only be optimised for a particular set of circumstances.

In *organisational* respects, design is an essential part of the product life cycle. This cycle is triggered by a market need or a new idea. It starts with product planning and ends—when the product's useful life is over—with recycling or environmentally safe disposal (see Figure 1.2). This cycle represents a process of converting raw materials into economic products of high added value. Designers must undertake their tasks in close cooperation with specialists in a wide range of disciplines and with different skills (see Section 1.1.2).

The tasks and activities of designers are influenced by several characteristics.

Origin of the task: Projects related to mass production and batch production are usually started by a product planning group after carrying out a thorough analysis of the market (see Section 3.1). The requirements established by the product planning group usually leave a large solution space for designers.

In the case of a customer order for a specific one-off or small batch product, however, there are usually tighter requirements to fulfil. In these cases it is wise for designers to base their solutions on the existing company know-how that has been built up from previous developments and orders. Such developments usually take place in small incremental steps in order to limit the risks involved.

If the development involves only part of a product (assembly or module), the requirements and the design space are even tighter and the need to interact with other design groups is very high. When it comes to the production of a product,

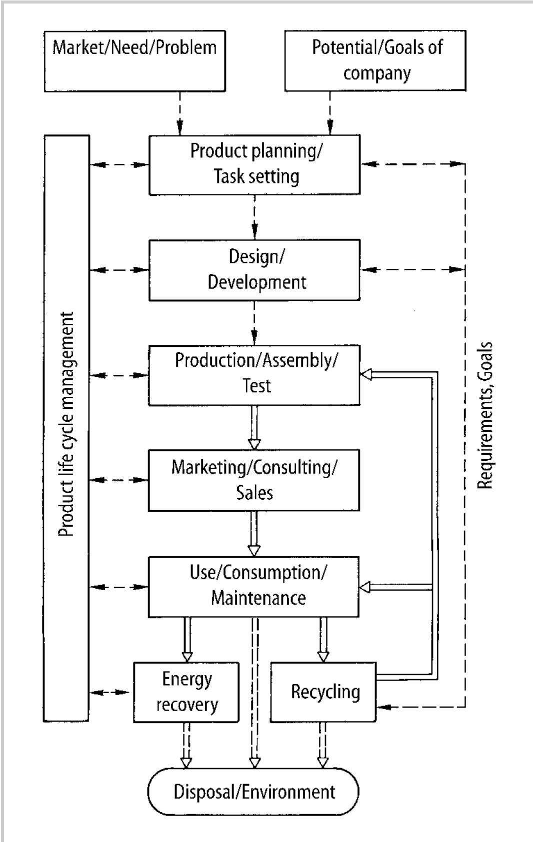


Figure 1.2. Life cycle of a product

there are design tasks related to production machines, jigs and fixtures, and inspection equipment. For these tasks, fulfilling the functional requirements and technological constraints is especially important.

Organisation: The organisation of the design and development process depends in the first instance on the overall organisation of the company. In product-oriented companies, responsibility for product development and subsequent production is split between separate divisions of the company based on specific product types (e.g. rotary compressor division, piston compressor division, accessory equipment division).

Problem-oriented companies split the responsibility according to the way the overall task is broken down into partial tasks (e.g. mechanical engineering, control systems, materials selection, stress analysis). In this arrangement the project manager must pay particular attention to the coordination of the work as it passes from group to group. In some cases the project manager leads independent temporary project teams recruited from the various groups. These teams report directly to the head of development or senior management (see Section 4.3).

Other organisational structures are possible, for example based on the particular phase of the design process (conceptual design, embodiment design, detail design), the domain (mechanical engineering, electrical engineering, software development), or the stage of the product development process (research, design, development, pre-production) (see Section 4.2). In large projects with clearly delineated domains, it is often necessary to develop individual modules for the product in parallel.

Novelty: New tasks and problems that are realised by *original designs* incorporate new solution principles. These can be realised either by selecting and combining known principles and technology, or by inventing completely new technology. The term original design is also used when existing or slightly changed tasks are solved using new solution principles. Original designs usually proceed through all design phases, depend on physical and process fundamentals and require a careful technical and economic analysis of the task. Original designs can involve the whole product or just assemblies or components.

In *adaptive design*, one keeps to known and established solution principles and adapts the embodiment to changed requirements. It may be necessary to undertake original designs of individual assemblies or components. In this type of design the emphasis is on geometrical (strength, stiffness, etc.), production and material issues.

In *variant design*, the sizes and arrangements of parts and assemblies are varied within the limits set by previously designed product structures (e.g. size ranges and modular products, see Chapter 9). Variant design requires original design effort only once and does not present significant design problems for a particular order. It includes designs in which only the dimensions of individual parts are changed to meet a specific task. In [1.124, 1.167] this type of design is referred to as *principle design* or *design with fixed principle*.

In practice it is often not possible to define precisely the boundaries between the three types of design, and this must be considered to be only a broad classification.

Batch size: The design of one-off and small batch products requires particularly careful design of all physical processes and embodiment details to minimise risk. In these cases it is usually not economic to produce development prototypes. Often functionality and reliability have a higher priority than economic optimisation.

Products to be made in large quantities (large batch or mass production) must have their technical and economic characteristics fully checked prior to full-scale production. This is achieved using models and prototypes and often requires several development steps (see Figure 1.3).

Branch: Mechanical engineering covers a wide range of tasks. As a consequence the requirements and the type of solutions are exceptionally diverse and always require the application of the methods and tools used to be adapted to the specific task in hand. Domain-specific embodiments are also common. For example, food processing machines have to fulfil specific requirements regarding hygiene; machine tools have to fulfil specific requirements regarding precision and operating speed; prime movers have to fulfil specific requirements regarding power-to-weight ratio and efficiency; agricultural machines have to fulfil specific requirements re-

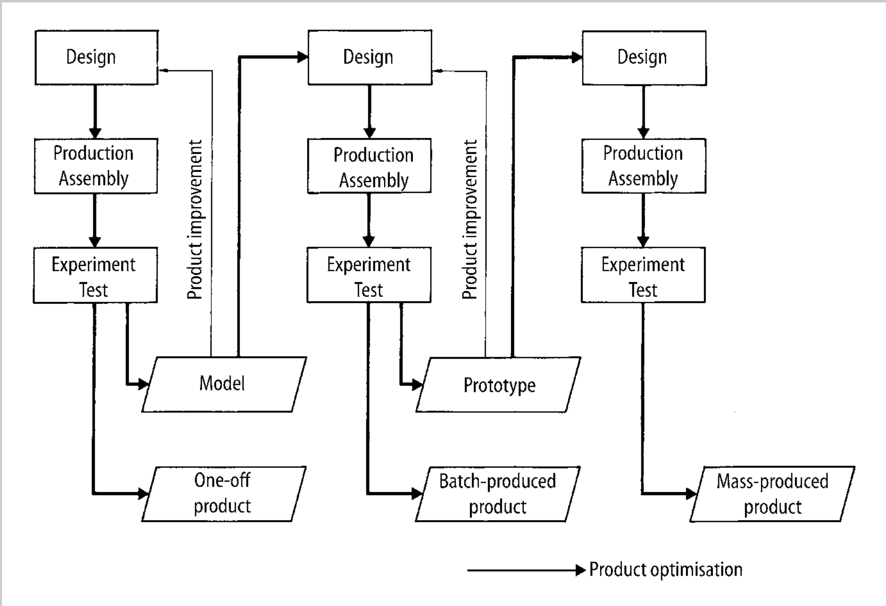


Figure 1.3. Stepwise development of a mass-produced product. After [1.191]

garding functionality and robustness; and office machines have to fulfil specific requirements regarding ergonomics and noise levels.

Goals: Design tasks must be directed towards meeting the goals to be optimised, taking into account the given restrictions. New functions, longer life, lower costs, production problems, and changed ergonomic requirements are all examples of possible reasons for establishing new design goals.

Moreover, an increased awareness of environmental issues frequently requires completely new products and processes for which the task and the solution principle have to be revisited. This requires a holistic view on the part of designers and collaboration with specialists from other disciplines.

To cope with this wide variety of tasks, designers have to adopt different approaches, use a wide range of skills and tools, have broad design knowledge and consult specialists on specific problems. This becomes easier if designers master a general working procedure (see Section 2.2.4), understand generation and evaluation methods (see Chapter 3) and are familiar with well-known solutions to existing problems (see Chapters 7 and 8).

The activities of designers can be roughly classified into:

- Conceptualising, i.e. searching for solution principles (see Chapter 6). Generally applicable methods can be used along with the special methods described in Chapter 3.
- Embodying, i.e. engineering a solution principle by determining the general arrangement and preliminary shapes and materials of all components. The methods described in Chapters 7 and 9 are useful.

- Detailing, i.e. finalising production and operating details.
- Computing, representing and information collecting. These occur during all phases of the design process.

Another common classification is the distinction between *direct* design activities (e.g. conceptualising, embodying, detailing, computing), and *indirect* design activities (e.g. collecting and processing information, attending meetings, coordinating staff). One should aim to keep the proportion of the indirect activities as low as possible.

In the design process, the required design activities have to be structured in a purposeful way that forms a clear sequence of main phases and individual working steps, so that the flow of work can be planned and controlled (see Chapter 4).

1.1.2 Position of the Design Process within a Company

The design and development department is of central importance in any company. Designers determine the properties of every product in terms of function, safety, ergonomics, production, transport, operation, maintenance, recycling and disposal. In addition, designers have a large influence on production and operating costs, on quality and on production lead times. Because of this weight of responsibility, designers must continuously reappraise the general goals of the task in hand (see Section 2.1.7).

A further reason for the central role of designers in the company is the position of design and development in the overall product development process. The links and information flows between departments are shown in Figure 1.4, from which it can be seen that production and assembly depend fundamentally on information from product planning, design and development. However, design and development are strongly influenced by knowledge and experience from production and assembly.

Because of current market pressures to increase product performance, lower prices and reduce the time-to-market, product planning, sales and marketing must draw increasingly upon specialised engineering knowledge. Because of their key position in the product development process, it is therefore particularly important to make full use of the theoretical knowledge and product experience of designers (see Section 3.1 and Chapter 5).

Current product liability legislation [1.12] demands not only professional and responsible product development using the best technology but also the highest possible production quality.

1.1.3 Trends

The most important impact in recent years on the design process, and on the activities of designers, has come from computer-based data processing. Computer-aided design (CAD) is influencing design methods, organisational structures, the division of work, e.g. between conceptual designers and detail designers,

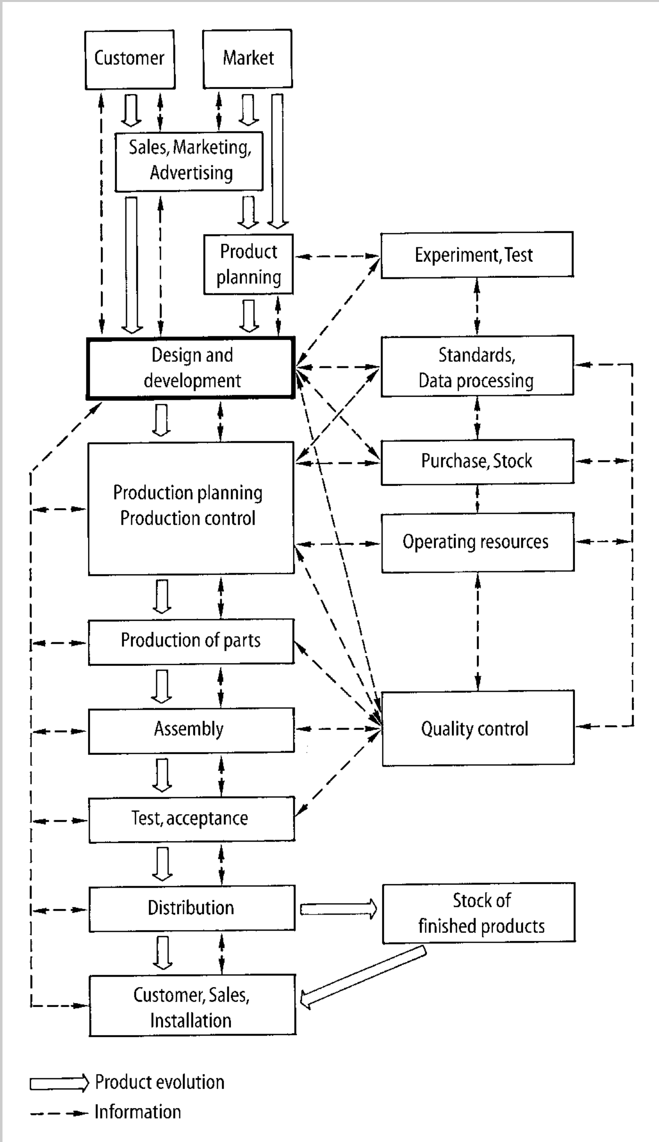


Figure 1.4. Information flows between departments

as well as the creativity and thought processes of individual designers (see Section 2.2). New staff, e.g. system managers, CAD specialists, etc., are being introduced into the design process. In the future, routine tasks such as variant designs will be largely undertaken by the computer, leaving designers free to concentrate on new designs and customer-specific one-off products. These tasks will be supported by computer tools that enhance the creativity, engineering knowledge and experience of designers. The development of knowledge-based systems (expert systems) [1.72, 1.108, 1.178, 1.183] and electronic component catalogues [1.19, 1.20, 1.53, 1.151, 1.183] will increase the ease with which information can be retrieved, including specific design data, details of standard components, information about existing products as well as their design processes and other design knowledge. These systems will also aid the analysis, optimisation and combination of solutions, but they will not replace designers. On the contrary, the decision-making abilities of designers will be even more crucial because of the very large number of solutions it will be possible to generate, and also because of the need to coordinate the inputs from the many specialists now required in modern multidisciplinary projects.

A further strong trend is for companies to concentrate their design and development activities on so-called core competences, and thus acting as system integrators, buying in assemblies and components as required from other companies (outsourcing). Designers therefore need the ability to assess and evaluate these outsourced items, even though they have not created these themselves. This critical assessment process is enhanced through broad technical knowledge, accumulated experience and a systematic use of evaluation procedures (see Section 3.3).

Computer-integrated manufacturing (CIM) has consequences for designers in terms of company organisation and information exchange. The system within a CIM structure makes better planning and control of the design process necessary and possible. The same holds true for *simultaneous engineering* (see Section 4.3 [1.13, 1.40, 1.188]), where development times are reduced by focusing on the flexible and partially parallel activities of product optimisation, production optimisation and quality optimisation. The trend is to bring production planning forward into the design process through the application of computers.

Apart from these developments that influence the working methods of designers, designers must increasingly take into account rapid technological developments (e.g. new production and assembly procedures, microelectronics and software) and new materials (e.g. composites, ceramics and recyclable materials). The integration of mechanical, electronic and software engineering (mechatronics) has led to many exciting product developments. Designers now have to give equal weight to these three aspects of modern products.

In summary, it can be concluded that there is already much pressure on designers and this pressure will increase further. This requires continuous further education for existing designers. However, the initial education of designers must take into account the many changes taking place [1.127, 1.187]. It is essential that future designers not only understand traditional science and engineering fundamentals (physics, chemistry, mathematics, mechanics, thermodynamics, fluid mechanics, electronics, electrical engineering, materials science, machine elements) but also specific domain knowledge (instrumentation, control, transmission technology, production technology, electrical drives, electronic controls). The education of future designers should include courses where they actually apply their design knowledge in order to solve design tasks. They also need specialist courses in design methodology, including CAD and CAE.

1.2 Necessity for Systematic Design

1.2.1 Requirements and the Need for Systematic Design

In view of the central responsibility of designers for the technical and economic properties of a product, and the commercial importance of timely and efficient product development, it is important to have a defined design procedure that finds good solutions. This procedure must be flexible and at the same time be capable of being planned, optimised and verified. Such a procedure, however, cannot be realised if the designers do not have the necessary domain knowledge and cannot work in a systematic way. Furthermore, the use of such a procedure should be encouraged and supported by the organisation.

Nowadays one distinguishes between design science and design methodology [1.90]. *Design science* uses scientific methods to analyse the structures of technical systems and their relationships with the environment. The aim is to derive rules for the development of these systems from the system elements and their relationships.

Design methodology, however, is a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology, and from practical experience in different domains. It includes plans of action that link working steps and design phases according to content and organisation. These plans must be adapted in a flexible manner to the specific task at hand (see Chapter 4). It also includes strategies, rules and principles to achieve general and specific goals (see Chapter 7 and Chapters 9–11) as well as methods to solve individual design problems or partial tasks (see Chapters 3 and 6).

This is not meant to detract from the importance of *intuition* or experience; quite the contrary—the additional use of systematic procedures can only serve to increase the output and inventiveness of talented designers. Any logical and systematic approach, however exacting, involves a measure of intuition; that is, an inkling of the overall solution. No real success is likely without intuition.

Design methodology should therefore foster and guide the abilities of designers, encourage creativity, and at the same time drive home the need for objective evaluation of the results. Only in this way is it possible to raise the general standing of designers and the regard in which their work is held. Systematic procedures help to render designing comprehensible and also enable the subject to be taught. However, what is learned and recognised about design methodology should not be taken as dogma. Such procedures merely try to steer the efforts of designers from unconscious into conscious and more purposeful paths. As a result, when they collaborate with other engineers, designers will not merely be holding their own, but will be able to take the lead [1.130].

Systematic design provides an effective way to *rationalise* the design and production processes. In original design, an ordered and stepwise approach—even if this is on a partially abstract level—will provide solutions that can be used again. Structuring the problem and task makes it easier to recognise application possibilities for established solutions from previous projects and to use design catalogues. The stepwise concretisation of established solution principles makes it possible to select and optimise them at an early stage with a smaller amount of effort. The approach of developing size ranges and modular products is an important start to rationalisation in the design area, but is especially important for the production process (see Chapter 9).

A design methodology is also a prerequisite for flexible and continuous *computer support* of the design process using product models stored in the computer. Without this methodology it is not possible to: develop knowledge-based systems; use stored data and methods; link separate programs, especially geometric modellers with analysis programs; ensure the continuity of data flow; and link data from different company divisions (CIM, PDM). Systematic procedures also make it easier to divide the work between designers and computers in a meaningful way.

A rational approach must also cover the cost of computation and quality considerations. More accurate and speedy preliminary calculations with the help of better data are a necessity in the design field, as is the early recognition of weak points in a solution. All this calls for systematic processing of the design documentation.

A *design methodology*, therefore, must:

- allow a problem-directed approach; i.e. it must be applicable to every type of design activity, no matter which specialist field it involves
- foster inventiveness and understanding; i.e. facilitate the search for optimum solutions
- be compatible with the concepts, methods and findings of other disciplines
- not rely on finding solutions by chance
- facilitate the application of known solutions to related tasks
- be compatible with electronic data processing
- be easily taught and learned
- reflect the findings of cognitive psychology and modern management science; i.e. reduce workload, save time, prevent human error, and help to maintain active interest
- ease the planning and management of teamwork in an integrated and interdisciplinary product development process
- provide guidance for leaders of product development teams.

1.2.2 Historical Background

It is difficult to determine the origins of systematic design. Can we trace it back to Leonardo da Vinci? Anyone looking at the sketches of this early master must be surprised to see—and the modern systematist delights in discovering—the great extent to which Leonardo used systematic variation of possible solutions [1.118]. Right up to the industrial era, designing was closely associated with arts and crafts.

With the rise of mechanisation in the nineteenth century, as Redtenbacher [1.150] pointed out early on in his *Prinzipien der Mechanik und des Maschinenbaus* (Principles of Mechanics and of Machine Construction), attention became increasingly focused on a number of characteristics and principles that continue to be of great importance, namely: sufficient strength, sufficient stiffness, low wear, low friction, minimum use of materials, easy handling, easy assembly and maximum rationalisation.

Redtenbacher's pupil Reuleaux [1.152] developed these ideas but, in view of their often conflicting requirements, suggested that the assessment of their relative importance must be left to the intelligence and discretion of individual designers. They cannot be treated in a general way or be taught.

Important contributions to the development of engineering design were also made by Bach [1.11] and Riedler [1.153], who realised that the selection of materials, the choice of production methods and the provision of adequate strength are of equal importance and that they influence one another.

Rotscher [1.164] mentions the following essential characteristics of design: specified purpose, effective load paths, and efficient production and assembly. Loads should be conducted along the shortest paths, and if possible by axial forces rather than by bending moments. Longer load paths not only waste materials and increase costs but also require considerable changes in shape. Calculation and laying out must go hand-in-hand. Designers start with what they are given and with ready-made assemblies. As soon as possible, they should make scale drawings to ensure the correct spatial layout. Calculation can be used to obtain either rough estimates for the preliminary layout or precise values that are used to check the detail design.

Laudien [1.107], upon examining the load paths in machine parts, gave the following advice: for a rigid connection, join the parts in the direction of the load; if flexibility is required, join the parts along indirect load paths; do not make unnecessary provisions; do not over-specify; do not fulfil more demands than are required; save by simplification and economical construction.

Modern systematic ideas were pioneered by Erkens [1.46] in the 1920s. He insisted on a *step-by-step approach* based on *constant testing and evaluation*, and also on the *balancing of conflicting demands*, a process that must be continued until a network of ideas—the design—emerges.

A more comprehensive account of the "technique of design" has been presented by Wögerbauer [1.206], whose contribution we consider to be the origin of systematic design. He divides the *overall task* into *subsidiary tasks*, and these into operational and implementational tasks. He also examines (but fails to present in systematic form) the numerous interrelationships between the identifiable constraints designers must take into account. Wögerbauer himself does not proceed to a systematic elaboration of solutions. His systematic search starts with a solution discovered more or less intuitively and varied as comprehensively as possible in respect to the basic form, materials and method of production. The resulting profusion of possible solutions is then reduced by tests and evaluations, with cost being a crucial criterion. Wögerbauer's very comprehensive list of *characteristics* helps in the search for an optimum solution and also when testing and evaluating the results.

Franke [1.54] discovered a comprehensive structure for transmission systems using a logical–functional analogy based on elements with different physical effects (electrical, mechanical, hydraulic effects for identical logical functions guiding, coupling and separating). For this reason he is regarded as a representative of those working on the functional comparison of physically different solution elements. Rodenacker in particular used this analogical approach [1.155].

Though some need to improve and rationalise the design process was felt even before World War II, progress was impeded by the absence of a reliable means of representing abstract ideas and the widespread view that designing is a form of art, not a technical activity like any other. A period of staff shortages in the 1960s [1.190] created a strong impetus to adopt systematic thinking more widely. Important pioneers were Kesselring, Tschochner, Niemann, Matousek and Leyer. Their work continues to provide most useful suggestions for handling the individual phases and steps of systematic design.

Kesselring [1.98] first explained the basis of his method of successive approximations in 1942 (for a summary see [1.96, 1.97] and VDI Guideline 2225 [1.195]). Its salient feature is the evaluation of form variants according to *technical* and *economic criteria*. In his theory, he mentions five overlying principles:

- the principle of minimum production costs
- the principle of minimum space requirement
- the principle of minimum weight
- the principle of minimum losses
- the principle of optimum handling.

The design and optimisation of individual parts and simple technical artefacts is the aim of the theory of form design. It is characterised by the simultaneous application of physical and economic laws, and leads to a determination of the shape and dimensions of components and an appropriate choice of materials, production methods, etc. If selected optimisation characteristics are taken into account, the best solution can be found with the help of mathematical methods.

Tschochner [1.179] mentions four fundamental design factors, namely the *working principle*, the *material*, the *form* and the *size*. They are interconnected and dependent on the requirements, the number of units, costs, etc. Designers start from the solution principle, determine the other fundamental factors—material and form—and match them with the help of the chosen dimensions.

Niemann [1.121] starts out with a scale layout of the overall design, showing the main dimensions and the general arrangement. Next he divides the overall design into parts that can be developed in parallel. He proceeds from a *definition of the task* to a systematic *variation of possible solutions* and finally to a *critical and formal selection of the optimum solution*. These steps are in general agreement with those used in more recent methods. Niemann also draws attention to the then lack of methods for arriving at new solutions. He must be considered a pioneer of systematic design inasmuch as he consistently demanded and encouraged its development.

Matousek [1.112] lists four essential factors: *working principle*, *material*, *production* and *form* design, and then, following Wögerbauer [1.206], elaborates an overall working plan based on these four factors considered in the order given. He adds that, if the cost aspect is unsatisfactory, these factors have to be reexamined in an iterative manner.

Leyer [1.109] is mainly concerned with form design, for which he develops fundamental *guidelines* and *principles*. He distinguishes three main design phases. In the first, the working principle is laid down with the help of an idea, an invention, or established facts; the second phase is that of actual design; the third phase is that of implementation. His second phase is essentially that of embodiment; that is, layout and form design supported by calculations. During this phase, principles or rules have to be taken into account—for instance, the principle of constant wall thickness, the principle of lightweight construction, the principle of shortest load paths, and the principle of homogeneity. Leyer's rules of form design are so valuable because, in practice, failure is still far less frequently the result of bad working principles than of poor detail design.

These preliminary attempts made way for the intensive development of methods, mainly by university professors who had learnt the fundamentals of design by designing technical products of increasing complexity in industry before becoming professors. They realised that a greater reliance on physics, mathematics and information theory, and the use of systematic methods, were not only possible but, with the growing division of labour, quite indispensable. Needless to say, these developments were strongly affected by the requirements of the particular industries in which they originated. Most came from precision, power transmission and electromechanical engineering, in which systematic relationships are more obvious than in heavy engineering.

Hansen and other members of the *Ilmenau School* (Bischoff, Bock) first put forward their systematic design proposals in the early 1950s [1.21, 1.25, 1.78]. Hansen presented a more comprehensive design system in the second edition of his standard work published in 1965 [1.77].

Hansen's approach is defined in a so-called *basic system*. The four working steps in this approach are applied in the same way in conceptual, embodiment and detail design. Hansen begins with the analysis, critique, and specification of the task, which leads to the *basic principle* of the development (the crux of the task). The basic principle encompasses the overall function that has been derived from the task, the prevailing conditions, as well as the required measures. The overall function (the goal and the constraints) and the context (elements and properties) constitute the crux of the task together with the given constraints.

The second working step is a systematic search for solution elements and their combination into *working means* and *working principles*.

Hansen attaches great importance to the third step, in which any shortcomings of the developed working means are analysed with respect to their properties and quality characteristics, and then, if necessary, improved.

In the fourth and last step, these improved working means are evaluated to determine the optimum working means for the task.

In 1974 Hansen published another work, entitled *Konstruktionswissenschaft* (Science of Design) [1.76]. The book is more concerned with theoretical fundamentals than with rules of practical design.

Similarly, Müller [1.116] in his *Grundlagen der systematischen Heuristik* (Fundamentals of Systematic Heuristics) presents a theoretical and abstract picture of the design process. This book offers essential foundations of design science. Further important publications are [1.114, 1.115, 1.117].

After Hansen, it is Rodenacker [1.155–1.157] who became preeminent by developing an original design method. His approach is characterised by developing the required overall *working interrelationship* by defining in sequence the *logical*, *physical* and *embodiment* relationships. He emphasises the recognition and suppression of disturbing influences and failures as early as possible during formulation of the physical process; the adoption of a general selection strategy from simple to complex; and the evaluation of all parameters of the technical system against the criteria *quantity*, *quality* and *cost*. Other characteristics of his method are the emphasis on logical function structures based on *binary logic* (connecting and separating), and on a conceptual design stage based on the recognition that product optimisation can only take place once a suitable solution principle has been found. The most important aspect of Rodenacker's systematic design approach is undoubtedly his emphasis on establishing the physical process. Based on this, he not only deals with the systematic processing of concrete design tasks, but also with a methodology for inventing new technical systems. For the latter he starts with the question: For what new application can a known physical effect be used? He then searches systematically to discover completely new solutions.

In addition to the methods we have been describing, there is a view that a one-sided emphasis on discursive methods does not present the complete picture. Thus Wächtler [1.199, 1.200] argues, by analogy with cybernetic concepts such as control and learning, that creative design is the most complex form of the "learning process". Learning represents a higher form of control, one that involves not only quantitative changes at constant quality (rules), but also changes in the quality itself.

What matters is that, for the purpose of optimisation, the design process should be treated, not statically, but dynamically as a control process in which the information feedback must be repeated until the information content has reached the level at which the optimum solution can be found. The learning process thus keeps increasing the level of information and hence facilitates the search for a solution.

The systematic design methods of Leyer, Hansen, Rodenacker and Wächtler are still being applied today, having been integrated into the more recent developments in design methodology.

1.2.3 Current Methods

1. Systems Theory

In socio–economic–technical processes, procedures and methods of *systems theory* are becoming increasingly important. The interdisciplinary science of systems theory uses special methods, procedures and aids for the analysis, planning, selection and optimum design of complex systems [1.14–1.16, 1.23, 1.29, 1.30, 1.143, 1.208].

Technical artefacts, including the products of light and heavy engineering industry, are artificial, concrete and mostly dynamic systems consisting of sets of ordered elements, interrelated by virtue of their properties. A system is also characterised by the fact that it has a boundary which cuts across its links with the environment (see Figure 1.5). These links determine the external behaviour of the system, so that it is possible to define a function expressing the relationship between inputs and outputs, and hence changes in the magnitudes of the system variables (see Section 2.1.3).

From the idea that technical artefacts can be represented as systems, it was a short step to the application of systems theory to the design process, the more so as the objectives of systems theory correspond very largely to the expectations we have of a good design method, as specified at the beginning of this chapter [1.16]. The systems approach reflects the general appreciation that complex problems are best tackled in fixed steps, each involving analysis and synthesis (see Section 2.2.5).

Figure 1.6 shows the steps of the systems approach. The first of these is the gathering of information about the system under consideration by means of market analyses, trend studies or known requirements. In general this step can be called problem analysis. The aim here is the clear formulation of the problem (or subproblem) to be solved, which is the actual starting point for the development of the system. In the second step, or perhaps even during the first step, a programme is drawn up in order to give formal expression to the goals of the system (problem formulation). Such goals provide important criteria for the subsequent evaluation of solution variants and hence for the discovery of the optimum solution. Several solution variants are then synthesised on the basis of the information acquired during the first two steps.

Before these variants can be evaluated, the performance of each must be analysed for its properties and behaviour. In the evaluation that follows, the performance of each variant is compared with the original goals, and on the basis of this a decision is made and the optimum system selected. Finally, information is given out in the form of system implementation plans. As Figure 1.6 shows, the steps do not always lead straight to the final goal, so that iterative procedures may be needed. Built-in decision steps facilitate this optimisation process, which constitutes a transformation of information.

In a systems theory process model [1.23, 1.52], the steps repeat themselves in so-called life cycle phases of the system in which the chronological progression of a system goes from abstract to concrete (see Figure 1.7).

2. Value Analysis

The main aim of *Value Analysis*, as described in DIN 69910 [1.37, 1.66, 1.196–1.198], is to reduce cost (see Chapter 11). To that end a systematic overall approach is proposed which is applicable, in particular, to the further development of existing

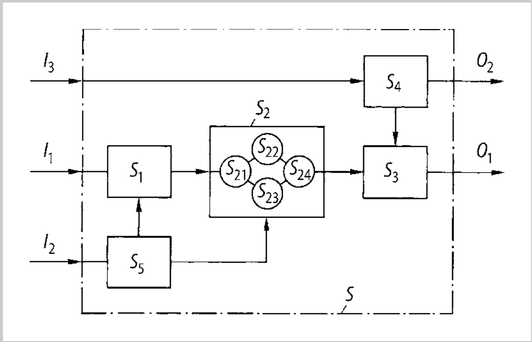


Figure 1.5. Structure of a system. S: system boundary; S_1–S_5: subsystems of S; S_{21}–S_{24}: subsystems or elements of S_2; I_1–I_3: inputs; O_1–O_2 outputs

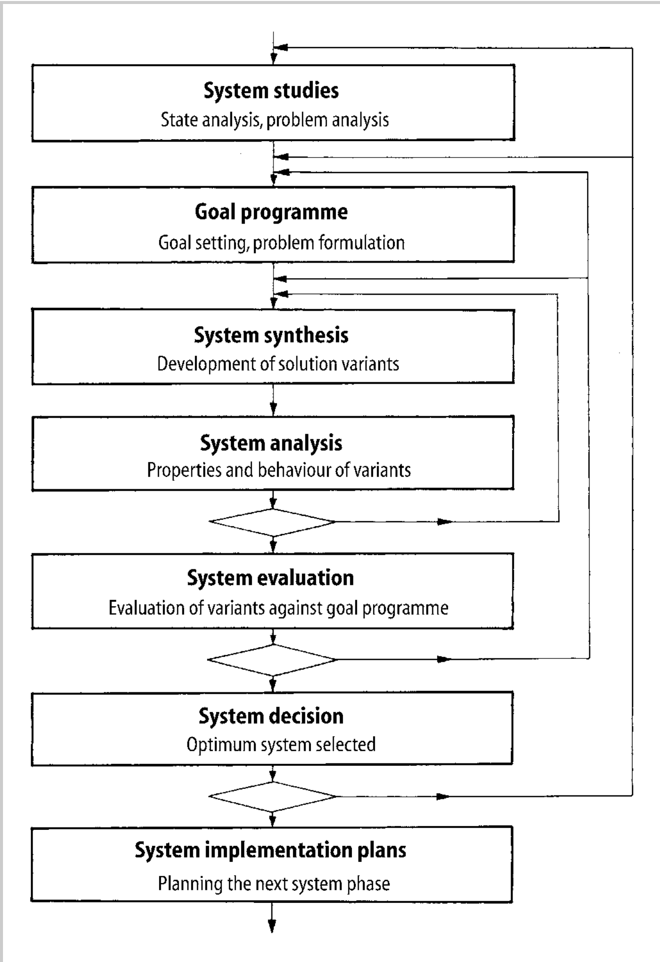


Figure 1.6. Steps of the systems approach

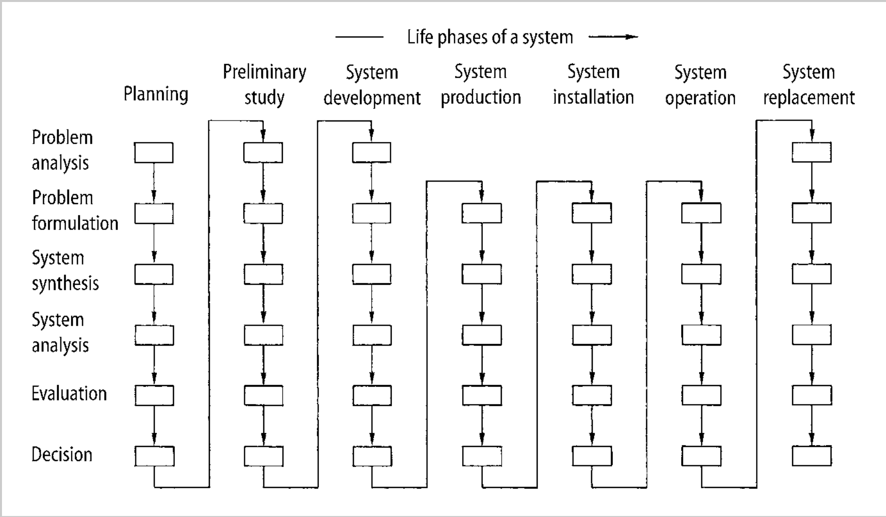


Figure 1.7. Model of the systems approach. After [1.23, 1.52]

Prepare project

- Assemble team
- Define scope of Value Analysis
- Define organisation and procedure

Analyse actual state

- Recognise functions
- Determine function costs

Determine target state

- Define target functions
- Identify additional requirements
- Match target costs with target functions

Develop solution ideas

- Collect existing ideas
- Search for new ideas

Determine solutions

- Evaluate ideas
- Develop ideas into solutions
- Evaluate and decide upon solutions

Realise solutions

- Detail chosen solutions
- Plan their implementation

Figure 1.8. Basic working steps of Value Analysis. After DIN 69910

products. Figure 1.8 shows the basic working steps of Value Analysis. In general, a start is made with an existing design, which is analysed with respect to the required functions and costs. Solution ideas are then proposed to meet the new targets. Because of its emphasis on functions and the stepwise search for better solutions, Value Analysis has much in common with systematic design.

Various methods are available to estimate costs and assess cost breakdowns (see Chapter 11). Teamwork is essential. Good communication between staff in sales, purchase, design, production and cost estimation (the Value Analysis team) ensures a holistic view of the requirements, embodiment design, materials selection, production processes, storage requirements, standards and marketing.

A further essential aspect is the division of the required overall function into subfunctions in the order of descending complexity along with their allocation to function carriers (assemblies, individual components). The costs of fulfilling all of the functions up to and including the overall function can be estimated from the costs calculated for the individual components. Such "function costs" can then provide the basis for evaluating the concepts or embodiment variants. The aim is to minimise these function costs and where possible eliminate functions that are not really necessary.

It has been suggested that the application of the Value Analysis method should not be left until after the layout and detail drawings have been finalised, but should be started during conceptual design in order to "design in" value [1.65]. In this way, Value Analysis approaches the goals of systematic design.

3. Design Methods

VDI Guideline 2222 [1.192, 1.193] defines an approach and individual methods for the conceptual design of technical products and is therefore particularly suitable for the development of new products. The more recent *VDI Guideline 2221* [1.191] (English translation: [1.186]) proposes a generic approach to the design of technical systems and products, emphasising the general applicability of the approach in the fields of mechanical, precision, control, software and process engineering. The approach (see Figure 1.9) includes seven basic working steps that accord with the fundamentals of technical systems (see Section 2.1) and company strategy (see Chapter 4). Both guidelines have been developed by a VDI Committee comprising senior designers from industry and many of the previously mentioned design methodologists from the former West Germany. Because the aim is for general applicability, the design process has been only roughly structured, thus permitting product-specific and company-specific variations. Figure 1.9 should therefore be regarded as a guideline to which detailed working procedures can be assigned. Special emphasis is placed on the iterative nature of the approach and the sequence of the steps must not be considered rigid. Some steps might be omitted, and others repeated frequently. Such flexibility is in accordance with practical design experience and is very important for the application of all design methods.

The design methodologists and senior designers from industry who collaborated to produce these VDI Guidelines often represented different schools of thought or had developed their own design methods. Several contributions to design methodology were made by colleagues in other countries. In this book, references are made to all of these many inputs when the individual methods and procedures are discussed in detail.

A comprehensive overview of the international design teaching and research activities since 1981 can be found in the proceedings of the ICED conference series (International Conference on Engineering Design) [1.148].

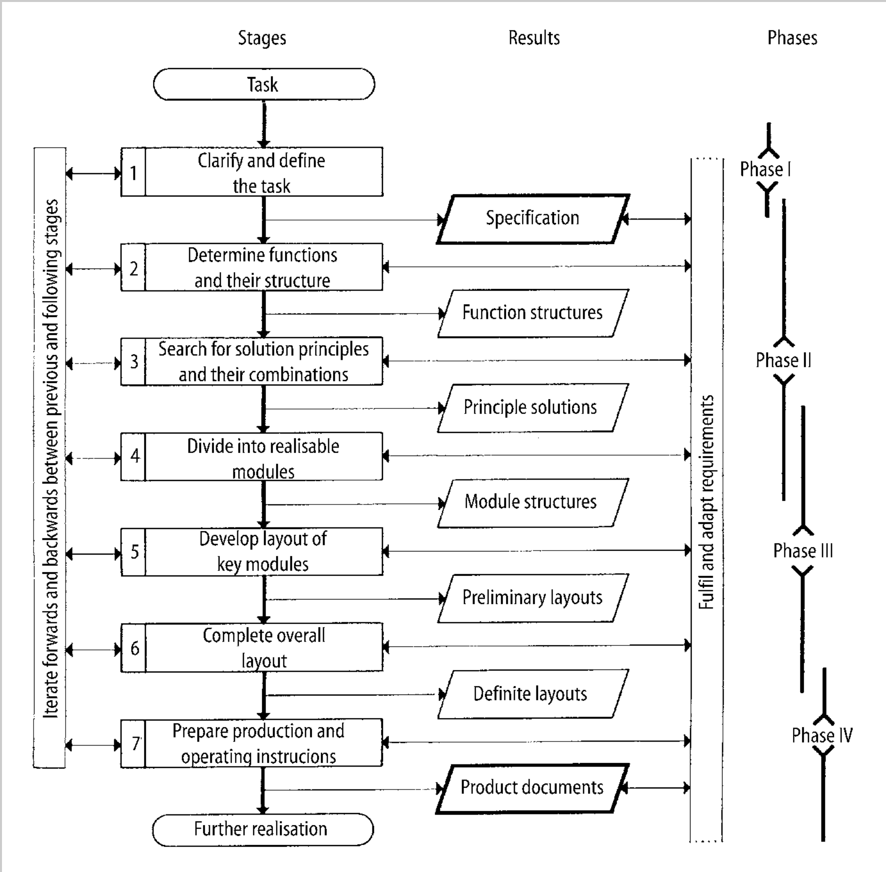


Figure 1.9. General approach to design. After [1.191]

In Table 1.1, the main publications on design methodology are given in chronological order. This table replaces and extends in a more compact form the individual efforts and achievements that were described in Chapter 1 of the second English edition of this book. Further contributions from the authors listed in the table can be seen from their entries in the list of references at the end of the book.

1.2.4 Aims and Objectives of this Book

On closer examination the methods we have been describing have been strongly influenced by their authors' specialist fields. They nevertheless resemble one another far more closely than the various concepts and terms might suggest. VDI Guidelines 2222 and 2221 confirm these resemblances as they were developed in collaboration with a wide range of experienced contributors.

Based on our experience in the heavy machinery industry and railway and automotive engineering and many years spent in engineering design education at

Table 1.1. Chronological overview of the development of design methodology

Year	Author	Theme/Title	Country	Literature
1953	Bischoff, Hansen	Rationelles Konstruieren	DDR	[1.21]
1955	Bock	Konstruktionssystematik—die Methode der ordnenden Gesichtspunkte	DDR	[1.25]
1956	Hansen	Konstruktionssystematik	DDR	[1.78]
1963	Pahl	Konstruktionstechnik im thermischen Maschinenbau	DE	[1.131]
1966	Dixon	Design Engineering: Inventiveness, Analysis and Decision-Making	USA	[1.39]
1967	Harrisberger	Engineermanship	USA	[1.79]
1968	Roth	Systematik der Maschinen und ihrer mechanischen elementaren Funktionen	DE	[1.163]
1969	Glegg	The Design of the Design, The Development of Design, The Science of Design	GB	[1.68–1.70]
	Tribus	Rational Descriptions, Decisions and Design	USA	[1.177]
1970	Beitz	Systemtechnik im Ingenieurbereich	DE	[1.16]
	Gregory	Creativity in Engineering	GB	[1.71]
	Pahl	Wege zur Lösungsfindung	DE	[1.129]
	Rodenacker	Methodisches Konstruieren (4th Edition 1991)	DE	[1.155]
1971	French	Conceptual Design for Engineers, 1st Edition (3rd Edition 1999)	GB	[1.58]
1972	Pahl, Beitz	Series of articles „Für die Konstruktionspraxis“ (1972–1974)	DE	[1.142]
1973	Altschuller	Erfinden: Anleitung für Neuerer und Erfinder	USSR	[1.5]
	VDI	VDI-Richtlinie 2222, Blatt 1 (Entwurf): Konzipieren technischer Produkte	DE	[1.192]
1974	Adams	Conceptual Blockbusting: A Guide to Better Ideas	USA	[1.1]
1976	Hennig	Methodik der Verarbeitungsmaschinen	DDR	[1.82]
1977	Flursheim	Engineering Design Interfaces	GB	[1.49, 1.50]
	Ostrofsky	Design, Planning and Development Methodology	USA	[1.126]
	Pahl, Beitz	Konstruktionslehre, 1st Edition (6th Edition 2005)	DE	[1.134]
	VDI	VDI-Richtlinie 2222 Blatt 1: Konzipieren technischer Produkte	DE	[1.192]
1978	Rugenstein	Arbeitsblätter Konstruktionstechnik	DDR	[1.165]
1979	Frick	Integration der industriellen Formgestaltung in den Erzeugnis-Entwicklungsprozess, Arbeiten zum Industrial Design	DDR	[1.60–1.62]
	Klose	Zur Entwicklung einer speicherunterstützten Konstruktion von Maschinen unter Wieder-verwendung von Baugruppen	DDR	[1.99, 1.100]
	Polovnikin	Untersuchung und Entwicklung von Konstruktionsmethoden	USSR	[1.146, 1.147]
1981	Gierse	Wertanalyse und Konstruktionsmethodik in der Produktentwicklung	DE	[1.67]
	Kozma, Straub (Pahl/Beitz)	Hungarian translation of Pahl/Beitz Engineering Design	H	[1.141]
	Nadler	The Planning and Design Approach	USA	[1.119]

Table 1.1. (continued)

Year	Author	Theme/Title	Country	Literature
	Proceedings of ICED by Hubka	WDK Series biannually from 1981 to 2001; Design Society Series from 2003	CH	[1.148]
	Schregenberger	Methodenbewusstes Problemlösen	CH	[1.170]
1982	Dietrych, Rugenstein	Einführung in die Konstruktions-wissenschaft	PL/D	[1.36]
	Roth	Konstruieren mit Konstruktions-katalogen, 1st Edition (3rd Edition 2001)	DE	[1.160, 1.161], [1.162]
	VDI	VDI-Richtlinie 2222 Blatt 2: Erstellung und Anwendung von Konstruktionskatalogen	DE	[1.193]
1983	Andreasen et al.	Design for Assembly	DK	[1.8]
	Höhne	Struktursynthese und Variationstechnik beim Konstruieren	DDR	[1.84]
1984	Hawkes, Abinett	The Engineering Design Process	GB	[1.80]
	Altschuller	Erfinden – Wege zur Lösung technischer Probleme	USSR	[1.4]
	Hubka	Theorie technischer Systeme	CH	[1.86, 1.87]
	Walczack (Pahl/Beitz)	Polish translation of Pahl/Beitz Engineering Design	PL	[1.139]
	Wallace (Pahl/Beitz)	English translation of Pahl/Beitz Engineering Design, 1st Edition (3rd Edition 2006)	GB	[1.140]
	Yoshikawa	Automation in Thinking in Design	J	[1.207]
1985	Archer	The Implications for the Study for Design Methods of Recent Development in Neighbouring Disciplines	GB	[1.10]
	Ehrlenspiel, Lindemann	Kostengünstig Entwickeln und Konstruieren	DE	[1.41, 1.43]
	Franke	Konstruktionsmethodik und Konstruktions-praxis—eine kritische Betrachtung	DE	[1.51]
	Koller	Konstruktionslehre für den Maschinenbau. Grundlagen, Arbeitsschritte, Prinziplösungen. (3rd Edition 1994)	DE	[1.101, 1.102], [1.103, 1.104]
	van den Kroonenberg	Design Methodology as a Condition for Computer-Aided Design	NL	[1.185]
1986	Odrin	Morphologische Synthese von Systemen	USSR	[1.122]
	Altschuller	Theory of Inventive Problem Solving	USSR	[1.2, 1.3]
	Taguchi	Introduction of Quality Engineering	J	[1.175]
1987	Andreasen, Hein	Integrated Product Development	DK	[1.7]
	Erlenspiel, Figel	Application of Expert Systems in Machine Design	DE	[1.42]
	Gasparski	On Design Differently	PL	[1.63]
	Hales	Analysis of the Engineering Design Process in an Industrial Context, Managing Engineering Design	GB	[1.73–1.75]
	Schlottmann	Konstruktionslehre	DDR	[1.169]
	VDI/Wallace	VDI Design Handbook 2221: Systematic Approach to the Design of Technical Systems and Products. English translation	DE/GB	[1.186]
	Wallace, Hales	Detailed Analysis of an Engineering Design Project	GB	[1.203]
1988	Dixon	On Research Methodology—Towards A Scientific Theory of Engineering Design	USA	[1.38]

Table 1.1. (continued)

Year	Author	Theme/Title	Country	Literature
	French	Form, Structure and Mechanism, Invention and Evolution	GB	[1.57, 1.58]
	Hubka, Eder	Theory of Technical Systems—A Total Concept Theory for Engineering Design	CH/CA	[1.88, 1.89]
	Jakobsen	Functional Requirements in the Design Process	N	[1.92]
	Suh	The Principles of Design, Axiomatic Design	USA	[1.173, 1.174]
	Ullmann, Stauffer, Dietterich	A Model of the Mechanical Design Process Based on Empirical Data	USA	[1.182]
	Winner, Pennell, et al.	The Role of Concurrent Engineering in Weapon Acquisition	USA	[1.205]
1989	Cross	Engineering Design Methods	GB	[1.33]
	De Boer	Decision Methods and Techniques	NL	[1.35]
	Elmaragh, Seering, Ullmann	Design Theory and Methodology	USA	[1.45]
	Jung	Funktionale Gestaltbildung—Gestaltende Konstruktionslehre für Vorrichtungen, Geräte, Instrumente und Maschinen	DE	[1.93, 1.94]
	Pahl/Beitz	Chinese translation of Pahl/Beitz Engineering Design	PRC	[1.138]
	Ulrich, Seering	Synthesis of Schematic Description in Mechanical Design	USA	[1.184]
1990	Birkhofer	Von der Produktidee zum Produkt—Eine kritische Betrachtung zur Auswahl und Bewertung in der Konstruktion	DE	[1.17, 1.18]
	Konttinnen (Pahl/Beitz)	Finnish translation of Pahl/Beitz Engineering Design	FIN	[1.137]
	Kostelic	Design for Quality	YU	[1.105]
	Müller	Arbeitsmethoden der Technikwissenschaften—Systematik, Heuristik, Kreativität	DDR	[1.114]
	Pighini	Methodological Design of Machine Elements	I	[1.145]
	Pugh	Total Design; Integrated Methods for Successful Product Engineering	GB	[1.149]
	Rinderle	Design Theory and Methodology	USA	[1.154]
	Roozenburg, Eekels	Evaluation and Decision in Design	NL	[1.158, 1.159]
1991	Andreasen	Methodical Design Frame by New Procedures	DK	[1.6]
	Bjärnemo	Evaluation and Decision Techniques in the Engineering Design Process	S	[1.22]
	Boothroyd, Dieter	Assembly Automation and Product Design	USA	[1.26]
	Clark, Fujimoto	Product Development Performance: Strategy, Organisation and Management	USA	[1.31]
	Flemming	Die Bedeutung der Bauweisen für die Konstruktion	CH	[1.47, 1.48]
	Hongo, Nakajima	Relevant Features of the Decade 1981–1991 of the Theories of Design in Japan	J	[1.85]

Table 1.1. (continued)

Year	Author	Theme/Title	Country	Literature
	Kannapan, Marshek	Design Synthetic Reasoning: A Methodology for Mechanical Design	USA	[1.95]
	Stauffer (ed)	Design Theory and Methodology	USA	[1.172]
	Walton	Engineering Design: From Art to Practice	USA	[1.204]
1992	O'Grady, Young	Constraint Nets for Life Cycle: Concurrent Engineering	USA	[1.123]
	Seeger	Integration von Industrial Design in das methodische Konstruieren	DE	[1.171]
	Ullmann	The Mechanical Design Process	USA	[1.180, 1.181]
1993	Breiing, Flemming	Theorie und Methoden des Konstruierens	CH	[1.28]
	Linde, Hill	Erfolgreich Erfinden. Widerspruchsorientierte Innovationsstrategie	DE	[1.110]
	Miller	Concurrent Engineering Design	USA	[1.113]
	VDI	VDI-Richtlinie 2221: Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte	DE	[1.191]
1994	Clausing	Total Quality Development	USA	[1.32]
	Blessing	A Process-Based Approach to Computer-Supported Engineering Design	GB	[1.24]
	Pahl (Editor)	Psychologische und pädagogische Fragen beim methodischen Konstruieren	DE	[1.127]
1995	Ehrlenspiel	Integrierte Produktentwicklung	DE	[1.40]
	Pahl/Beitz	Japanese translation of Pahl/Beitz Engineering Design	J	[1.136]
	Wallace, Blessing; Bauert (Pahl/Beitz)	English translation of Pahl/Beitz Engineering Design, 2nd Edition	GB	[1.135]
1996	Bralla	Design for Excellence	USA	[1.27]
	Cross, Christiaans, Dorst	Analysing Design Activity	NL	[1.34]
	Hazelrigg	Systems Engineering: An Approach to Information-Based Design	USA	[1.81]
	Waldron, Waldron	Mechanical Design: Theory and Methodology	USA	[1.202]
1997	Frey, Rivin, Hatamura	Introduction of TRIZ in Japan	J	[1.59]
	Magrab	Integrated Product and Process Design and Development	USA	[1.111]
1998	Frankenberger, Badke-Schaub, Birkhofer	Konstrukteure als wichtigster Faktor einer erfolgreichen Produktentwicklung	DE	[1.55]
	Hyman	Fundamentals of Engineering Design	USA	[1.91]
	Pahl/Beitz	Korean translation of Pahl/Beitz Engineering Design	KR	[1.133]
	Terninko, Zusman, Zlotin, Herb (ed)	Systematic Innovation: An Introduction to TRIZ	USA	[1.176]
1999	Pahl	Denk- und Handlungsweisen beim Konstruieren	DE	[1.128]
	Samuel, Weir	Introduction to Engineering Design	AU	[1.168]

Table 1.1. (continued)

Year	Author	Theme/Title	Country	Literature
	VDI	VDI-Richtlinie 2223 (Entwurf): Methodisches Entwerfen technischer Produkte	DE	[1.194]
2000	Pahl/Beitz	Portuguese translation of Pahl/Beitz Engineering Design	BR	[1.132]
2001	Antonsson, Cagan	Formal Engineering Design Synthesis	USA	[1.9]
	Gausemeyer, Ebbesmeyer, Kallmeyer	Produktinnovation mit strategischer Planung	DE	[1.64]
	Kroll, Condoor, Jansson	Innovative Conceptual Design: Parameter Analysis	USA	[1.106]
2002	Sachse	Entwurfsdenken und Darstellungshandeln, Verfestigung von Gedanken beim Konzipieren	DE	[1.166]
	Eigner, Stelzer	Produktdatenmanagement-Systeme	DE	[1.44]
	Neudörfer	Konstruieren sicherheitsgerechter Produkte	DE	[1.120]
	Orloff	Grundlagen der klassischen TRIZ	DE	[1.125]
	Wagner	Wegweiser für Erfinder	DE	[1.201]

the undergraduate and graduate levels, this book sets out a comprehensive design methodology for all phases of the product planning, design and development processes for technical systems. Most of the arguments are elaborations of a seminal series of papers published by the authors Pahl and Beitz [1.142] and previous editions of this book. It should be emphasised that between the publication of the first German edition of the book in 1977 and the latest edition, none of the statements had to be dropped because they were outdated.

As before, although our own approach to design does not claim to be the final word on the subject it tries to:

- be useful in design practice and design education
- provide a "toolbox" of design methods presented in a compatible way without expressing a particular school of thought or including short-lived trends
- emphasise the importance of design fundamentals, principles and guidelines at a time when more and more products are designed with the help of computers and many assemblies and components are outsourced
- serve as a guide to help designers and design leaders manage successful product development irrespective of the organisational structure (project management, however, is not the focus of this book).

We hope that this systematic approach to engineering design may serve as an introduction and springboard for the learner, as a help and illustration for the teacher, and as a source of information and further learning for the practitioner. It is important to realise that the methods and guidelines presented here underpin successful product development and product improvement.

Readers who are familiar with the application of generally applicable design methods and the fundamentals of systematic design can jump to Chapter 5 and start directly with the systematic approach to product development, returning to the fundamentals described in Chapters 2–4 when necessary. However, it is extremely important that students and novices build a solid foundation and do not ignore these early chapters.

2 Fundamentals

To develop an approach to design that can serve as a strategy for the development of solutions, we must first examine the fundamentals of technical systems and procedures along with the prerequisites for computer support. Only when that has been done is it possible to make detailed recommendations for design work.

2.1 Fundamentals of Technical Systems

2.1.1 Systems, Plant, Equipment, Machines, Assemblies and Components

Technical tasks are performed with the help of *technical artefacts* that include plant, equipment, machines, assemblies and components, listed here in approximate order of their complexity. These terms may not have identical uses in different fields. Thus, a piece of equipment (reactor, evaporator) is sometimes considered to be more complex than a plant, and artefacts described as "plant" in certain fields may be described as "machines" in others. A machine consists of assemblies and components. Control equipment is used in plant and machines alike and may also be made up of assemblies and components, and perhaps even of small machines. The variation in use of these terms reflect historical developments and application areas. There are attempts to define standards in which energy-transforming technical artefacts are referred to as machines, material-transforming artefacts as apparatus and signal-transforming artefacts as devices. It is evident that a clear division on the basis of these characteristics is not always possible and that the current terminology is not ideal.

There is much to be said for Hubka's suggestion [2.22–2.24] that technical artefacts should be treated as *systems* connected to the environment by means of *inputs* and *outputs*. A system can be divided into subsystems. What belongs to a particular system is determined by the *system boundary*. The inputs and outputs cross the system boundary (see Section 1.2.3). With this approach, it is possible to define appropriate systems at every stage of abstraction, analysis or classification. As a rule, such systems are parts of larger, superior systems.

A concrete example is the combined coupling shown in Figure 2.1. It can be considered as a system "coupling" which, within a machine, or when joining two

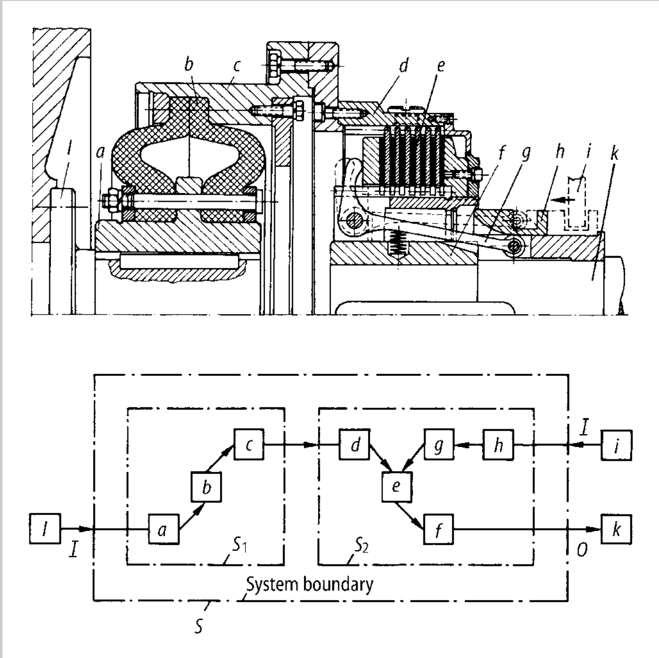


Figure 2.1. System "coupling": $a \ldots h$ system elements; $i \ldots l$ connecting elements, S overall system; S_1 subsystem "flexible coupling"; S_2 subsystem "clutch"; I inputs; O outputs

machines, can be considered to be an assembly. This coupling assembly can be treated as two *subsystems*—a "flexible coupling" and a "clutch". Each subsystem can, in turn, be subdivided into system elements, in this case components.

The system depicted in Figure 2.1 is based on its mechanical construction, referred to as the *construction structure*, see Figure 2.13. It is, however, equally possible to consider it in terms of its functions (see Section 2.1.3). In that case, the total system "coupling" can be split up into the subsystems "damping" and "clutching"; the second subsystem into the further subsystems "changing clutch operating force into normal force" and "transferring torque".

For example, the system element g could be treated as a subsystem whose *function* is to convert the actuating force into a larger normal force acting on the friction surface, and through its flexibility provide some equalisation of the wear.

Which viewpoint is used to divide the system depends on the intended purpose of the division. Common viewpoints are:

- Function: used to identify or describe the functional relationships
- Assembly: used to plan assembly operations
- Production: used to facilitate production and production planning.

Depending on their use, any number of such subdivisions may be made. Designers have to establish particular systems for particular purposes, and must specify their various inputs and outputs and fix their boundaries. In doing this, they may use what terminology they prefer or is customary in their particular field.

2.1.2 Conversion of Energy, Material and Signals

One encounters matter in many shapes and forms. Its natural form, or the form imposed upon it, provides information about its possible uses. Matter without form is inconceivable—form is a primary source of information about the state of matter. With the development of physics, the concept of force became essential. Force was conceived as being the means by which the motion of matter was changed. Ultimately this process was explained in terms of energy. The theory of relativity postulated the equivalence of energy and matter. Weizsacker [2.61] lists energy, matter and information as basic concepts. If change or flow is involved, time must be introduced as a fundamental quantity. Only by reference to time does the physical event in question become comprehensible, and can the interplay of energy, matter and information be adequately described.

In the technical sphere the previous terminology is usually linked to concrete physical or technical representations. *Energy* is often specified by its manifest form. We speak of, say, mechanical, electrical or optical energy. For matter, it is usual to substitute *material* with such properties as weight, colour, condition, etc. The general concept of information is generally given more concrete expression by means of the term *signal*—that is, the physical form in which the information is conveyed. Information exchanged between people is often called a message [2.20].

The analysis of technical systems—plant, equipment, machine, device, assembly or component—makes it clear that all of them involve technical processes in which energy, material and signals are channelled and converted. Such conversions of energy, material and signals have been analysed by Rodenacker [2.46].

Energy can be converted in a variety of ways. An electric motor converts electrical into mechanical and thermal energy, a combustion engine converts chemical into mechanical and thermal energy, a nuclear power station converts nuclear into thermal energy, and so on.

Materials too can be converted in a variety of ways. They can be mixed, separated, dyed, coated, packed, transported, reshaped and have their state changed. Raw materials are turned into part-finished and finished products. Mechanical parts are given particular shapes and surface finishes and some are destroyed for testing purposes.

Every plant must process information in the form of *signals*. Signals are received, prepared, compared and combined with others, transmitted, displayed, recorded, and so on.

In technical processes, one type of conversion (of energy, material or signals) may prevail over the others, depending on the problem or the type of solution. It is useful to consider these conversions as flows, and the prevailing one as the *main flow*. It is usually accompanied by a second type of flow, and quite frequently all three come into play. There can, for example, be no flow of material or signals without an accompanying flow of energy, however small. The provision and conversion of energy in such cases may not dominate, but it remains necessary to allow for them. Energy flow also involves the transfer of forces, torques, currents, etc., which are then referred to as force flow, torque flow and current flow.

The conversion of energy to produce electrical power, for example, is associated with a material conversion, even though no continuous material flow is visible in a nuclear power station compared to a coal-fired one. The associated flow of signals constitutes an important subsidiary flow for the control and regulation of the entire process.

However, numerous measuring instruments receive, transform and display signals without any flow of material. In many cases energy has to be specially provided for this purpose; in other cases latent energy can be drawn upon directly. Every flow of signals is associated with a flow of energy, though not necessarily with a flow of material.

In what follows, we shall be dealing with:

- Energy: mechanical, thermal, electrical, chemical, optical, nuclear ..., also force, current, heat ...
- Material: gas, liquid, solid, dust ..., also raw material, test sample, workpiece ..., end-product, component ...
- Signals: magnitude, display, control impulse, data, information ...

In this book technical systems whose main flow is energy-based are referred to as machines, those whose main flow is material-based as apparatus, and those whose main flow is signal-based as devices, unless these terms are not in line with established terminology.

In every type of proposed conversion, *quantity* and *quality* must be taken into consideration if rigorous criteria for the definition of the task, for the choice of solutions and for evaluation are to be established. No statement is fully defined unless its quantitative as well as its qualitative aspects are taken into account. Thus, the statement "100 kg/s of steam at 80 bar and 500 °C" is not a sufficient definition of the input of a steam turbine unless there is the further specification that these figures refer to a nominal quantity of steam and not, for instance, to the maximum flow capacity of the turbine, and the admissible fluctuations in the state of the steam are fixed at, say, 80 bar ± 5 bar and 500 °C ± 10 °C, that is, extended by a qualitative aspect.

In many applications, it is also essential to stipulate the *cost* or value of the inputs and the maximum permissible cost of the outputs (see [2.46], Categories: Quantity–Quality–Cost).

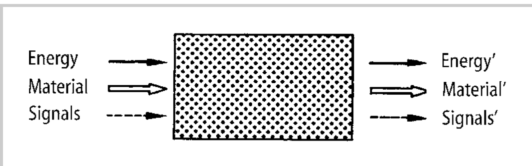


Figure 2.2. The conversion of energy, material and signals. Solution not yet known; task or function described on the basis of inputs and outputs

All technical systems, therefore, involve the conversion of energy, material and signals, which must be defined in quantitative, qualitative and economic terms (see Figure 2.2).

2.1.3 Functional Interrelationship

1. Task-Specific Description

In order to solve a technical problem, we need a system with a clear and easily reproduced relationship between inputs and outputs. In the case of material conversions, for instance, we require identical outputs for identical inputs. Also, between the beginning and the end of a process, for instance filling a tank, there must be a clear and reproducible relationship. Such relationships must always be planned—that is, designed to meet a specification. For the purpose of describing and solving design problems, it is useful to apply the term *function* to the intended input/output relationship of a system whose purpose is to perform a task.

For static processes it is enough to determine the inputs and outputs; for processes that change with time (dynamic processes), the task must be defined further by a description of the initial and final magnitudes. At this stage there is no need to stipulate what solution will satisfy this kind of function. The function thus becomes an abstract formulation of the task, independent of any particular solution. If the overall task has been adequately defined—that is, if the inputs and outputs of all the quantities involved and their actual or required properties are known—then it is possible to specify the *overall function*.

An overall function can often be divided directly into identifiable *subfunctions* corresponding to subtasks. The relationship between subfunctions and the overall function is very often governed by certain constraints, inasmuch as some subfunctions have to be satisfied before others.

On the other hand, it is usually possible to link subfunctions in various ways and hence to create variants. In all such cases, the links must be compatible.

The meaningful and compatible combination of subfunctions into an overall function produces a so-called *function structure*, which may be varied to satisfy the overall function. To that end it is useful to make a block diagram in which the processes and subsystems inside a given block (black box) are initially ignored, as shown in Figure 2.3 (see also Figure 2.2). The symbols used to represent subfunctions in a function structure are summarised in Figure 2.4.

Functions are usually defined by statements consisting of a verb and a noun, for example "increase pressure", "transfer torque" and "reduce speed". They are derived for each task from the conversions of energy, material and signals discussed in Section 2.1.2. So far as is possible, all of these data should be accompanied by specifications of the physical quantities. In most mechanical engineering applications, a combination of all three types of conversion is usually involved, with the conversion either of material or of energy influencing the function structure decisively. An analysis of all the functions involved is always useful (see also [2.59]).

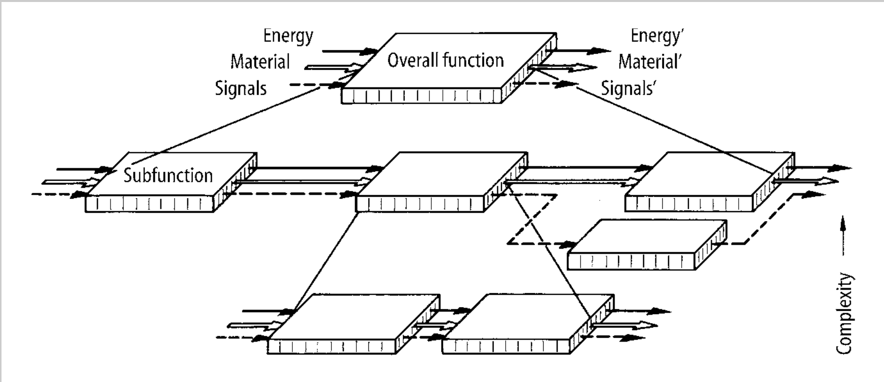


Figure 2.3. Establishing a function structure by breaking down an overall function into subfunctions

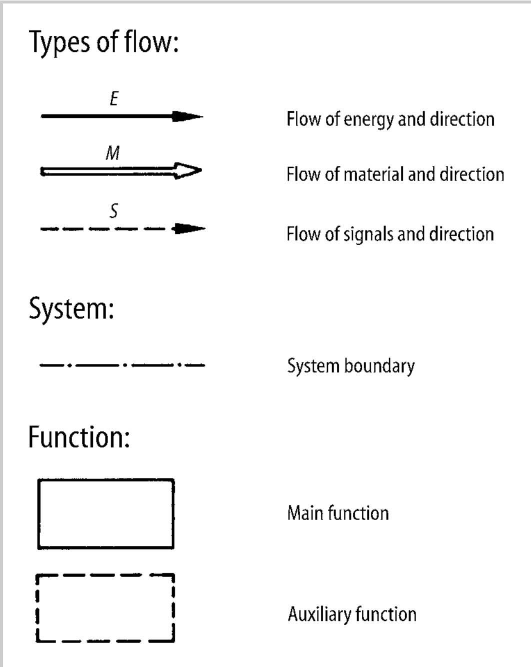


Figure 2.4. Symbols used to represent subfunctions in a function structure

It is useful to distinguish between main and auxiliary functions. While *main functions* are those subfunctions that serve the overall function directly, *auxiliary functions* are those that contribute to it indirectly. They have a supportive or complementary character and are often determined by the nature of the solutions for the main functions. These definitions are derived from Value Analysis [2.7,2.58, 2.60]. Although it may not always be possible to make a clear distinction between main and auxiliary functions, the terms are nevertheless useful. The division between them should be managed in a flexible manner. For example, a change in the system boundary resulting from a change of focus can transform an auxiliary function into a main function and vice versa.

It is also necessary to examine the relationship between the various subfunctions, and to pay particular attention to their logical sequence or required arrangement.

As an example, consider the packing of carpet tiles stamped out of a length of carpet. The first task is to introduce a method of control so that perfect tiles can be selected, counted and packed in specified lots. The main flow here is that of material, as shown in the form of a block diagram in Figure 2.5, which, in this case, is the only possible sequence. On closer examination we discover that this chain of subfunctions requires the introduction of auxiliary functions because:

- the stamping-out process creates offcuts that must be removed
- rejects must be removed separately and reprocessed
- packing material must be brought in.

The result is the function structure shown in Figure 2.6. It will be seen that the subfunction "count tiles" can also give the signal to pack the tiles into lots of a specified size, so it seems useful to introduce a signal flow with the subfunction "send signal to combine n tiles into one lot" into the function structure. The functions in this case are *task-specific functions*, whose definitions are derived from the terminology appropriate for the task being considered.

Outside the design domain, the term function is sometimes used in a broader sense, and sometimes in a narrower sense, depending on the context.

Brockhaus [2.40] has defined functions in general as activities, effects, goals and constraints. In mathematics, a function is the association of a magnitude y with a magnitude x such that a unique value (single-valued function) or more than one value (multi-valued function) of y is assigned for every value of x. According to the value analysis definition given in [2.7], functions define the behaviour of artefacts (tasks, activities, characteristics).

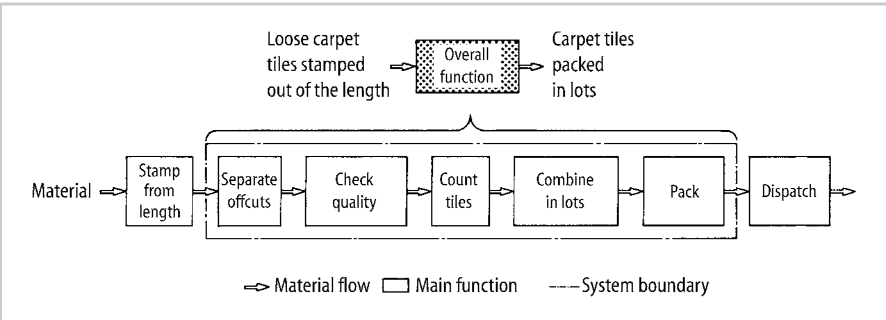


Figure 2.5. Function structure for the packing of carpet tiles

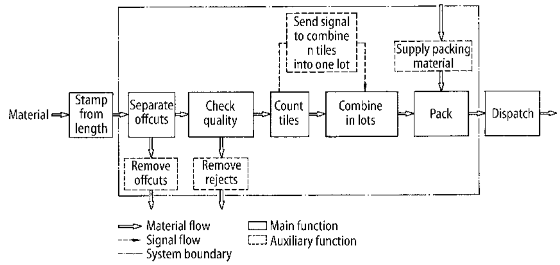


Figure 2.6. Function structure for the packing of carpet tiles as shown in Figure 2.5 but with auxiliary functions added

2. Generally Valid Description

Various design methodologists (see Section 1.2.3) have put forward wider or stricter definitions of *generally valid functions*. In theory, it is possible to classify functions so that the lowest level of the function structure consists exclusively of functions that cannot be subdivided further while remaining generally applicable. They therefore represent a high level of abstraction.

Rodenacker [2.46] has defined generally valid functions in terms of binary logic, Roth [2.47, 2.49] in terms of their general applicability, and Koller [2.28, 2.29] in terms of the required physical effects. Krumhauer [2.31] has examined general functions in the light of possible computer applications during the conceptual design phase, paying special attention to the relationship between inputs and outputs after changes in type, magnitude, number, place and time. By and large, he arrives at the same functions as Roth, except that by "change" he refers exclusively to changes in the type of input and output, while by "increase or decrease" he refers exclusively to changes in magnitude.

In the context of the design methodology presented here, the generally valid functions of Krumhauer will be used (see Figure 2.7).

The function chain shown in Figure 2.5 can be represented using generally valid functions, as shown in Figure 2.8.

A comparison between the functional representations in Figures 2.5 and 2.8 shows that the description that uses generally valid functions has a higher level of abstraction. For this reason, it leaves open all possible solutions and makes a systematic approach easier. However, using generally valid functions can represent a problem because such an abstract level can sometimes hinder the direct search for solutions. For more about the application of task-specific and generally valid functions, along with further examples, see Section 6.3.

3. Logical Description

The logical analysis of functional relationships starts with the search for the essential ones that must necessarily appear in a system if the overall problem is to

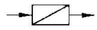
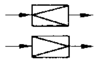
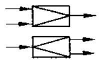
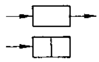
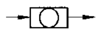
Characteristic Input (I)/Output (O)	Generally valid functions	Symbols	Explanations
Type	Change		Type and outward form of I and O differ
Magnitude	Vary		I < O I > O
Number	Connect		Number of I > O Number of I < O
Place	Channel		Place of I ≠ O Place of I = O
Time	Store		Time of I ≠ O

Figure 2.7. Generally valid functions derived from the characteristics type, magnitude, number, place and time for the conversion of energy, materials and signals

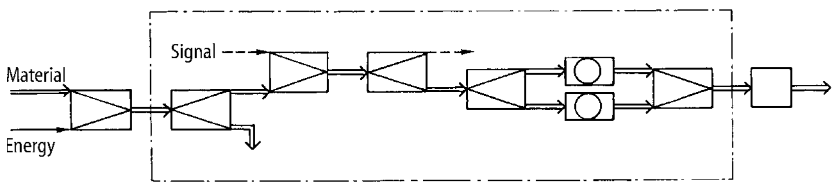


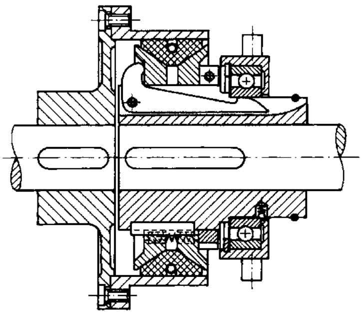
Figure 2.8. Same function structure as shown in Figure 2.5 but represented using generally valid functions, as defined in Figure 2.7

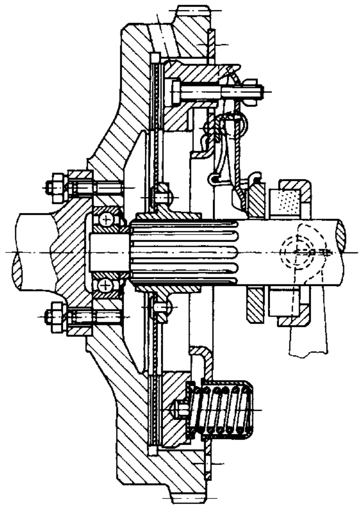
be solved. It may equally well be the relationships between subfunctions as those between inputs and outputs of particular subfunctions.

Let us first of all look at the relationships between subfunctions. As we have pointed out, certain subfunctions must be satisfied before another subfunction can be meaningfully introduced. The so-called "if–then" relationship helps to clarify this point: if subfunction *A* is present, then subfunction *B* can come into effect, and so on. Often several subfunctions must all be satisfied simultaneously before another subfunction can be put into effect. The arrangement of subfunctions thus determines the structure of the energy, material and signal conversions under consideration. Thus, during a test of tensile strength, the first subfunction—"load specimen"—must be satisfied before the other subfunctions—"measure force" and "measure deformation"—can be deployed. The last two subfunctions, moreover, must be satisfied simultaneously. Attention must be paid to consistency and order within the flow under consideration, and this is done by the unambiguous combination of the subfunctions.

Designation	AND-function (Conjunction)	OR-function (Disjunction)	NOT-function (Negation)
Symbol	X_1, X_2 — [&] — Y	X_1, X_2 — [≥1] — Y	X — [1]o— Y
Truth table	X_1 | 0 | 1 | 0 | 1 X_2 | 0 | 0 | 1 | 1 Y | 0 | 0 | 0 | 1	X_1 | 0 | 1 | 0 | 1 X_2 | 0 | 0 | 1 | 1 Y | 0 | 1 | 1 | 1	X | 0 | 1 Y | 1 | 0
Boolean algebra (Function)	$Y = X_2 \wedge X_1$	$Y = X_1 \vee X_2$	$Y = \overline{X}$

Figure 2.9. Logical functions. X independent statement (signal); Y dependent statement; "0", "1" value of statement, e.g. "off", "on"





AND

X_1, X_2 — [&] — $Y = X_1 \wedge X_2$

X_1	(Signal supplied)	0	1	0	1
X_2	(Clutch engaged)	0	0	1	1
Y	(Torque transmitted)	0	0	0	1

INHIBITION

X_1 o—, X_2 — [&] — $Y = \overline{X}_1 \wedge X_2$

X_1	0	1	0	1
X_2	1	0	0	1
Y	1	0	0	0

Figure 2.10. Logical function of two clutches

Logical relationships, moreover, must also be established between the inputs and outputs of a particular subfunction. In most cases there are several inputs and outputs whose relationships can be treated like propositions in binary logic. *Elementary logical links* of the input and output magnitudes exist for this purpose. In binary logic these are statements such as true/false, yes/no, in/out, fulfilled/unfulfilled, present/not present, which can be computed using Boolean algebra.

We distinguish between AND functions, OR functions and NOT functions, and also between their combination into more complex NOR functions (OR with NOT), NAND functions (AND with NOT) and storage functions with the help of flip-flops [2.4, 2.45, 2.46]. Grouped together, these are called *logical functions.*

In the case of AND functions, all signals on the input side must have the same validity if a valid signal is to appear on the output side.

In the case of OR functions, only one signal needs to be valid on the input side if a valid signal is to appear on the output side.

In the case of NOT functions, the signal on the input side is negated so that the negated signal appears on the output side.

All of these logical functions can be expressed by standard symbols, which can be found in [2.4]. The logical validity of any signal can be read from the truth table shown in Figure 2.9, in which all of the inputs are combined systematically to yield the relevant outputs. The Boolean equations have been added for the sake of completeness. Using logical functions it is possible to construct complex switchess and thus to increase the safety and reliability of control and communication systems.

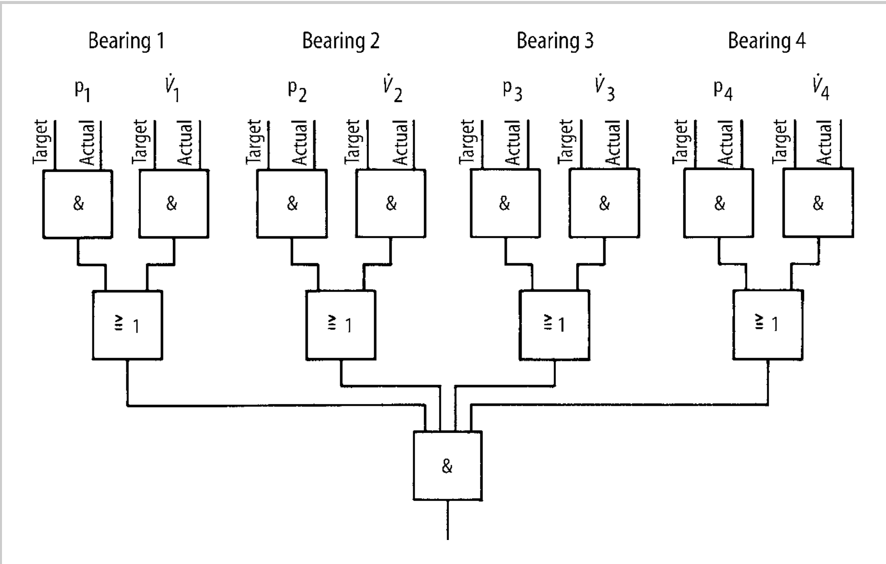


Figure 2.11. Logical functions for monitoring a bearing lubrication system. A positive signal for every bearing (oil present) permits operation. Monitor pressure p; monitor oil flow $\dot{V}$

Figure 2.10 shows two mechanical clutches with their characteristic logical functions. The workings of the clutch on the left can be represented by a simple AND function (the signal must be sent and the clutch engaged before the torque can be transmitted). The clutch on the right has been constructed such that, when the operating signal is given, the clutch is disengaged, meaning that X_1 must be negative if the torque is to be transmitted. In other words, only X_2 must be present or positive if the desired effect is to be produced.

Figure 2.11 shows a logical system for monitoring the bearing lubrication system of a multi-bearing machine shaft involving AND and OR functions. Every bearing position is monitored for oil pressure and oil flow by comparing a specified or target value with the actual value. However, only one positive value for each bearing position is needed to allow the system to operate.

2.1.4 Working Interrelationship

Establishing a function structure facilitates the discovery of solutions because it simplifies the general search for them, and also because solutions to subfunctions can be elaborated separately.

Individual subfunctions, originally represented by "black boxes", must now be replaced with more concrete statements. Subfunctions are usually fulfilled by physical, chemical or biological processes—mechanical engineering solutions are based mainly on physical processes whereas process engineering solutions are based mainly on chemical and biological processes. If, in what follows, we refer to *physical processes*, we tacitly include the effects of possible chemical and biological processes.

A physical process realised by the selected *physical effects* and the determined *geometric* and *material characteristics* results in a *working interrelationship* that ensures the function is fulfilled in accordance with the task. Hence a working interrelationship comes into existence through physical effects in combination with the chosen geometric and material characteristics.

1. Physical Effects

Physical effects can be described quantitatively by means of the physical laws governing the physical quantities involved. Thus, the friction effect is described by Coulomb's law, $F_F = \mu F_N$; the lever effect by the lever law $F_A \cdot a = F_B \cdot b$; and the expansion effect by the expansion law $\Delta l = \alpha \cdot l \cdot \Delta\vartheta$ (see Figure 2.12). Rodenacker [2.46] and Koller [2.28], in particular, have collated such effects.

Several physical effects may have to be combined in order to fulfil a subfunction. Thus the operation of a bimetallic strip is the result of a combination of two effects, namely thermal expansion and elasticity.

A subfunction can often be fulfilled by one of a number of physical effects. Thus a force can be amplified by the lever effect, the wedge effect, the electromagnetic effect, the hydraulic effect, etc. The physical effect chosen for a particular subfunction must, however, be compatible with the physical effects of other related

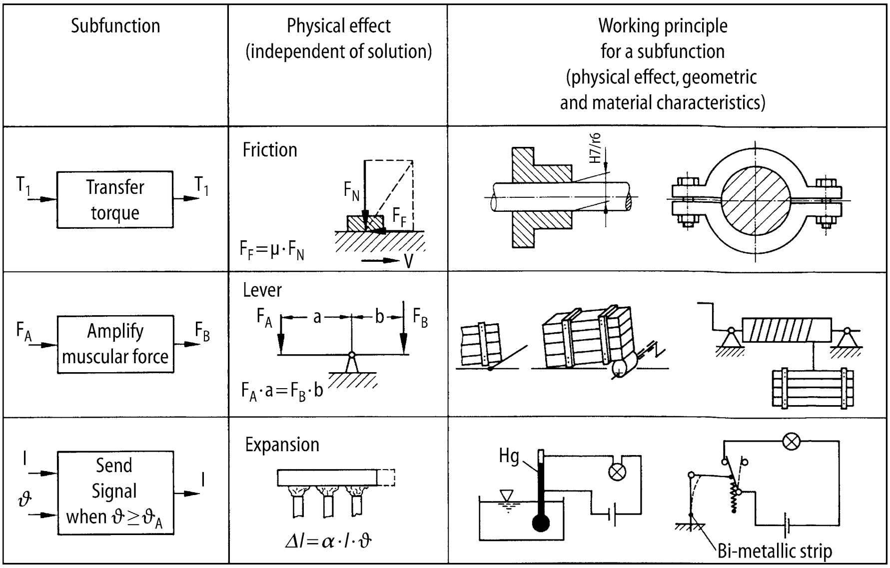


Figure 2.12. Fulfilling subfunctions by working principles built up from physical effects and geometric and material characteristics

subfunctions. A hydraulic amplifier, for instance, cannot be powered directly by an electric battery. Moreover, a particular physical effect can only fulfil a subfunction optimally under certain conditions. Thus a pneumatic control system will be superior to a mechanical or electrical control system only in particular circumstances.

As a rule, compatibility and optimal fulfilment can only be realistically assessed in relation to the overall function once the geometric and material characteristics have been established more concretely.

2. Geometric and Material Characteristics

The place where the physical process actually takes effect is the *working location*, i.e. the specific active location that is the focus of interest at the time. A function is fulfilled by the physical effect, which is realised by the *working geometry*, i.e. the arrangement of *working surfaces* (or working spaces), and by the choice of *working motions* [2.33].

The working surfaces are varied with respect to and determined by:

- Type
- Shape
- Position
- Size
- Number [2.46].

Similarly, the required working motions are determined by:

- Type: translation–rotation
- Nature: regular–irregular
- Direction: in x-, y-, z-directions and/or about x-, y-, z-axes
- Magnitude: velocity, etc.
- Number: one, several, etc.

In addition, we need a general idea of the *type of material* with which the working surfaces are to be produced, for example, whether it is solid, liquid or gaseous; rigid or flexible; elastic or plastic; stiff, hard or tough; or corrosion-resistant. A general idea of the final embodiment is often insufficient; the *main material properties* must be specified before a working interrelationship can be formulated adequately (see Figure 3.18).

Only the combination of the physical effect with the geometric and material characteristics (working surfaces, working motions and materials) allows the principle of the solution to emerge. This interrelationship is called the *working principle* (Hansen [2.19] refers to this as the working means), and it is the first concrete step in the implementation of the solution.

Figure 2.12 shows some examples:

- Transferring the torque through friction against a cylindrical *working surface* in accordance with Coulomb's law will, depending on the way in which the normal force is applied, lead to the selection of a shrink fit or a clamp connection as the working principle.
- Amplifying muscular force with the help of a lever in accordance with the lever law after determining the pivot and force application points (*working geometry*) and considering the necessary *working motion* will lead to a description of the working principle (lever solution, eccentric solution, etc.).
- Making electrical contact by bridging a gap using the expansion effect, applied in accordance with the linear expansion law, only leads to an overall working principle after determination of the sizes (e.g. the diameter and length) and the positions of the *working surfaces* needed for the *working motion* of the expanding medium: a *material*. For example, either mercury expanding by a fixed amount or a bimetallic strip serving as a switch.

To satisfy the overall function, the working principles of the various subfunctions have to be combined (see Section 3.2.4). There are obviously several ways in which this can be done. Guideline VDI 2222 [2.55] calls each combination a *combination of principles*.

The combination of several working principles results in the *working structure* of a solution. It is through this combination of working principles that the solution principle for fulfilling the overall task can be recognised. The working structure derived from the function structure thus represents how the solution will work at the fundamental principle level. Hubka refers to the working structure as the organ structure [2.22–2.24].

For known elements, a circuit diagram or a flow chart is sufficient as a means of representing a working structure. Mechanical artefacts can be effectively represented using engineering drawings, though new or uncommon elements may require additional explanatory sketches (see Figures 2.12 and 2.13).

Often the working structure alone will not be concrete enough to evaluate the solution principle. It may need to be quantified, for example by preliminary calculations and rough scale drawings, before the solution principle can be fixed. The result is called a *principle solution*.

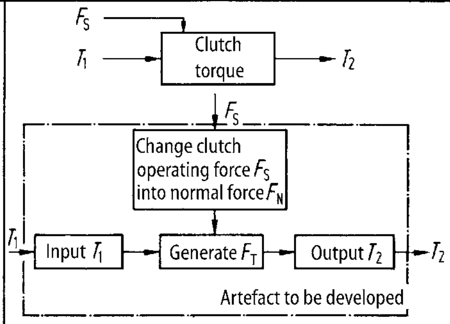
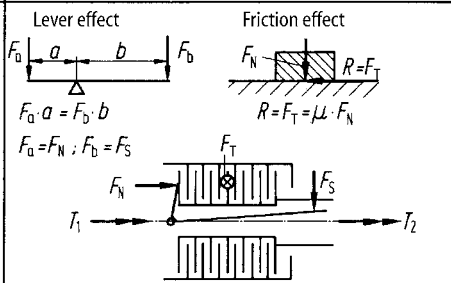
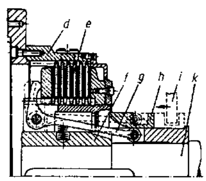
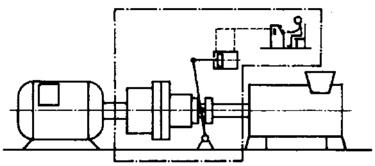
Interrelationships	Elements	Structures	Examples
Functional interrelationship	Functions	Functions structure	
Working interrelationship	Physical effects and geometric and material characteristics ↓ Working principles	Working structure	
Constructional interrelationship	Components Joints Assemblies	Construction structure	
System interrelationship	Artefacts Human beings Environment	System structure	

Figure 2.13. Interrelationships in technical systems

2.1.5 Constructional Interrelationship

The working interrelationship established in the working structure is the starting point for further concretisation leading to the *construction structure*. This interrelationship represents the concrete technical artefact or system by defining the components, assemblies and machines and their interconnections. The construction structure takes into account the needs of production, assembly, transport, etc. Figure 2.13 shows the fundamental interrelationships for the clutch shown in Figure 2.1. The increasing levels of concretisation can be seen clearly.

The concrete elements of a construction structure must satisfy the requirements of the selected working structure plus any other requirements necessary for the technical system to operate as intended. To identify these requirements fully, it is usually necessary to consider the system interrelationship.

2.1.6 System Interrelationship

Technical artefacts and systems do not operate in isolation and are, in general, part of a larger system. To fulfil its overall function, such a system often involves human beings who influence it through *input effects* (operating, controlling, etc.). The system returns *feedback effects* or signals that lead to further actions (see Figure 2.14). In this way, human beings support or enable the *intended effect* of the technical system.

Apart from desired inputs, undesired ones from the environment and from neighbouring systems can affect a technical system. Such *disturbing effects* (e.g. excess temperatures) can cause undesired *side-effects* (e.g. deviations from shape or shifts in position). Also, it is possible that in addition to the desired working interrelationship (intended effects), unwanted phenomena can occur (e.g. vibrations) as side-effects from individual components within the system or from the overall system itself. These side-effects can have an adverse effect on humans or the environment.

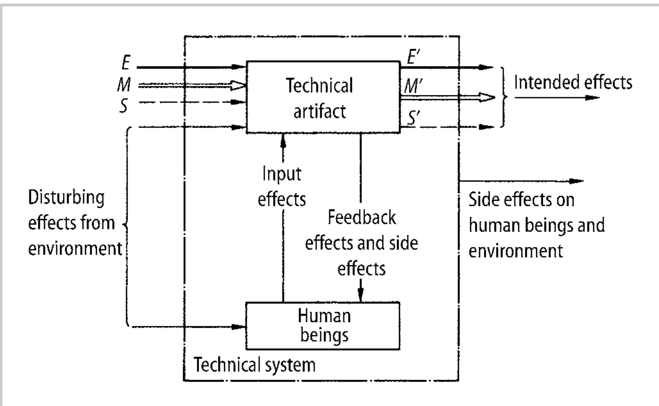


Figure 2.14. Interrelationships in technical systems including human beings

In accordance with Figure 2.14 it is useful to make the following distinctions (after [2.56]):

Intended effect:	Functionally desired effect in the sense of system operation.
Input effect:	Functional relationship due to human action on a technical system.
Feedback effect:	Functional relationship due to the action of a technical system on a human or another technical system.
Disturbing effect:	Functionally undesired influence from outside on a technical system or human that makes it difficult for a system to fulfil its function.
Side effect:	Functionally undesired and unintended effect of a technical system on a human or on the environment.

The overall interrelationship of all these effects must be carefully considered during the development of technical systems. To help recognise them in time, so that desired effects can be used and undesired ones avoided, it is helpful to follow a systematic guideline that adheres to the general objectives and constraints in Section 2.1.7.

2.1.7 Systematic Guideline

The solution of technical tasks is determined by the general objectives and constraints. The *fulfilment of the technical function*, the *attainment of economic feasibility* and the *observance of safety requirements* for humans and the environment can be considered as general objectives. The fulfilment of the technical function alone does not complete the task of designers; it would simply be an end unto itself. Economic feasibility is another essential requirement, and concern with human and environmental safety must impose itself for ethical reasons. Every one of these objectives has direct repercussions on the rest.

In addition, the solution of technical tasks imposes certain constraints or requirements resulting from ergonomics, production methods, transport facilities, the intended operation, etc., no matter whether these constraints are the result of the particular task or the general state of technology. In the first case we speak of task-specific constraints, in the second of general constraints that, although often not specified explicitly, must nevertheless be taken into account.

Hubka [2.22–2.24] separates the properties affected by the constraints into categories based variously on industrial, ergonomic, aesthetic, distribution, delivery, planning, design, production and economic factors.

Besides satisfying the functional and working interrelationships, a solution must also satisfy certain general or task-specific constraints. These can be classified under the following headings:

- Safety — also in the wider sense of reliability and availability
- Ergonomics — human–machine context, also aesthetics
- Production — production facilities and type of production

• Quality control	throughout the design and production process
• Assembly	during and after the production of components
• Transport	inside and outside of the factory
• Operation	intended use, handling
• Maintenance	upkeep, inspection and repair
• Expenditure	costs and schedules
• Recycling	reuse, reconstitution, disposal, final storage.

The characteristics that can be derived from these constraints, which are generally formulated as requirements (see Section 5.2), affect the function, working and construction structures, and also influence one another. Hence they should be treated as *guidelines* throughout the design process, and adapted to each level of embodiment (see Figs. 2.15 and 12.3).

In addition there are influences from the designer, the development team and the suppliers as well as the customer, the specific context and the environment.

It is advisable to consider these guidelines even during the *conceptual phase*, at least in essence. During the *embodiment phase*, when the layout and form design of the more or less qualitatively elaborated working structure is first quantified, both the objectives of the task and also the general and task-specific constraints must be considered in concrete detail. This involves several steps—the collection of further information, layout and form design, and the elimination of weak spots, together with a fresh, if limited, search for solutions for a variety of subtasks, until finally,

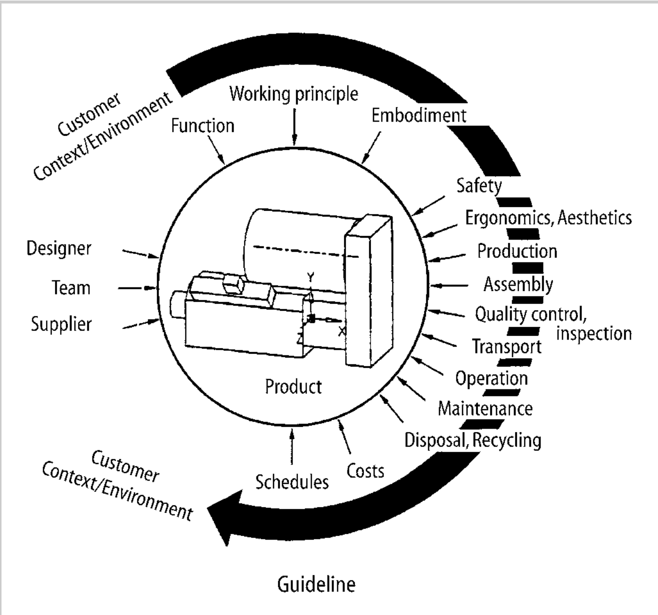


Figure 2.15. Influences and constraints during design and development. These can provide a guideline for quality control

in the *detail phase*, the elaboration of detailed production instructions brings the design process to a conclusion (see Chapters 5 to 7).

2.2 Fundamentals of the Systematic Approach

Before we deal with the specific steps and rules of systematic design, we must first discuss cognitive psychological relationships and general methodical principles. These help to structure the proposed procedures and individual methods so that they can be applied to the solution of design tasks in a purposeful way. The ideas come from a host of different disciplines, mainly non-technical ones, and are usually built on interdisciplinary fundamentals. Work science, psychology and philosophy are among the main inspirations, which is not surprising when we consider that methods designed to improve working procedures impinge on the qualities, capacities and limitations of human thought [2.41].

2.2.1 Problem Solving Process

Designers are often confronted with tasks containing problems they cannot solve immediately. Problem solving in different areas of application and at different levels of concretisation is a characteristic of their work. Researching the essence of human thinking is the focus of cognitive psychology. The results of this research must be taken into account in engineering design. The following sections are based largely on the work of Dörner [2.8, 2.10].

A *problem* has three components:

- an undesirable initial state, i.e. the existence of an unsatisfactory situation
- a desirable goal state, i.e. the realisation of a satisfactory situation
- obstacles that prevent a transformation from the undesirable initial state to the desirable goal state at a particular point in time.

An *obstacle* that prevents a transformation can arise from the following:

- The means to overcome the obstacle are unknown and have to be found (synthesis or operator problem).
- The means are known, but they are so numerous or involve so many combinations that a systematic investigation is impossible (interpolation problem, combination and selection problem).
- The goals are only known vaguely or are not formulated clearly. Finding a solution involves continuous deliberation and the removal of conflicts until a satisfactory situation is reached (dialectic problem, search and application problem).

A *problem* has the following typical characteristics:

- *Complexity:* many components are involved and these components, through links of different strength, influence each other.

- *Uncertainty:* not all requirements are known; not all criteria are established; the effect of a partial solution on the overall solution or on other partial solutions is not fully understood, or only emerges gradually. The difficulties become more pronounced if the characteristics of the problem area change with time.

A *task* is distinct from a problem because:

- A *task* imposes mental requirements for which various means and methods are available to assist. An example is the design of a shaft with given loads, connecting dimensions and production methods.

Tasks and problems occur in design in a number of ways, often combined and not clearly separable initially. A specific design task can, for example, turn out to be a problem when looked at more closely. Many large tasks can be divided into subtasks, some of which can reveal difficult subproblems. On the other hand, it is sometimes possible for a problem to be solved by fulfilling several subtasks in a previously unknown combination.

Thinking processes take place in the brain and involve changes in memory content. When thinking, the contents of the memory, and the way in which they are linked, play an important role.

In simple terms, one can say that in order to start solving a problem humans need a certain level of *factual knowledge* about the domain of the problem. In cognitive psychology, when this knowledge has been transferred into memory it represents the *epistemic structure*.

Humans also need certain *procedures* (methods) to find solutions and to find these effectively. This aspect involves the *heuristic structure* of human thought.

It is possible to distinguish between short-term and long-term memory. Short-term memory is a kind of working storage. It has limited capacity and can only retain about seven arguments or facts at the same time. Long-term memory probably has unlimited capacity and contains factual and heuristic knowledge that appears to be stored in a structured way.

In this way, humans are able to recognise specific relationships in many possible ways, to use these relationships and to create new ones. Such relationships are very important in the technical domain, for example:

- concrete—abstract relationship

  e.g. angular contact bearing—ball bearing—rolling element bearing—bearing—guide—transfer force and locate component.

- whole—part relationship (hierarchy)

  e.g. plant—machine—assembly—component.

- space and time relationships

  e.g. arrangement: front—back, below—above,

  e.g. sequence: this first—that next.

The memory can be thought of as a semantic network with nodes (knowledge) and connections (relationships) which can be modified and extended. Figure 2.16 shows a possible, though not necessarily complete, semantic network related to

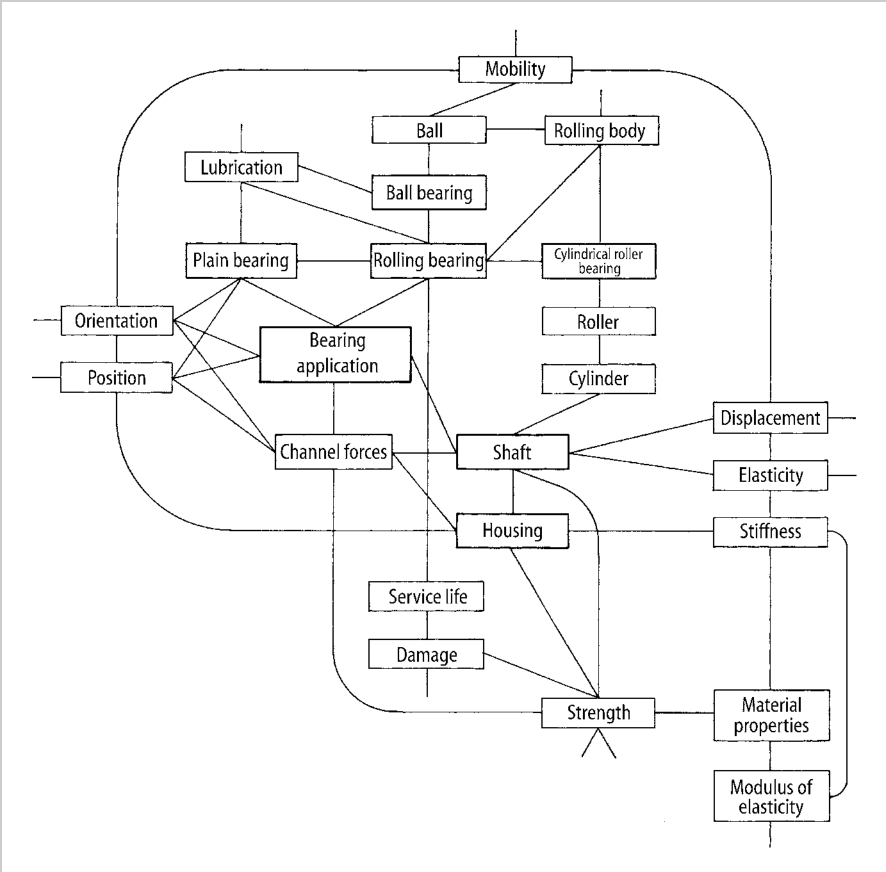


Figure 2.16. Extract of a semantic network related to bearings

the term "bearing". In this network it is possible to recognise the relationships mentioned above as well as others, such as property relationships and ones indicating opposites (polar relationships). Thinking involves building and restructuring such semantic networks, and the thinking process itself can proceed intuitively or discursively.

Intuitive thinking is strongly associated with flashes of inspiration. The actual thinking process takes place to a large extent unconsciously. Insights appear in the conscious mind suddenly, caused by some trigger or association. This is referred to as primary creativity [2.2,2.30] and involves processing quite complex relations. In this context, Müller [2.36] refers to "silent knowledge", which includes common and background knowledge. This is also the knowledge that is available when one deals with episodic memories, vague concepts and imprecise definitions. It is activated by both conscious and unconscious thinking activities.

Generally time is needed for undisturbed and unconscious "thinking" before sudden insights appear. The length of this incubation period cannot be predetermined. Insights can be triggered, for example, by producing freehand sketches or engineering drawings of solution ideas. According to [2.14], these manual activities focus concentration on the subject, but still leave space in the mind that can by used by unconscious thinking processes, which can also be stimulated by such activities.

Discursive thinking is a conscious process that can be communicated and influenced. Facts and relationships are consciously analysed, varied, combined in new ways, checked, rejected, and considered further. In [2.2,2.30] this is referred to as secondary creativity. This type of thinking involves checking exact and scientific knowledge and building this into a knowledge structure. In contrast to intuitive thinking, this process is slow and involves many small conscious steps.

In the memory structure, explicit and consciously acquired knowledge cannot be separated precisely from the vaguer common or background knowledge. Besides, the two types of knowledge influence each other. For knowledge to be easily retrieved and combined, it is thought that an ordered and logical structure of factual knowledge in the mind of the problem solver (epistemic structure) is decisive, and that this is true whether the thinking process is intuitive or discursive.

The *heuristic structure* includes explicit knowledge (i.e. knowledge that can be explained) as well as implicit knowledge. This is necessary in order to organise the sequence of thinking operations, including modifying operations (searching and finding) and testing operations (checking and assessing). It appears that problem solvers often start without a fixed plan in the hope of immediately finding a solution from their knowledge bases without much effort. Only when this approach fails, or when contradictions emerge, do they adopt a more clearly planned or systematic sequence of thinking operations.

The so-called TOTE model [2.33] represents an important fundamental sequence for thinking processes (see Figure 2.17). It consists of two processes: a modification process and a testing process. The TOTE model shows that before an operation of change takes place, an operation of testing (*T*est) is invoked to analyse the initial state. Only then is the chosen operation of change (*O*peration) executed. This is followed by another operation of testing (*T*est), during which the resulting state is checked. If the result is satisfactory, the process is exited (*E*xit); if not, the operation is adapted and repeated.

In more complex thinking processes, the TOTE sequences are linked in a chain or several modification processes are executed before a testing process takes place. Thus, when linking mental processes, many combinations and sequences are possible, but all of them can be mapped onto the basic TOTE model.

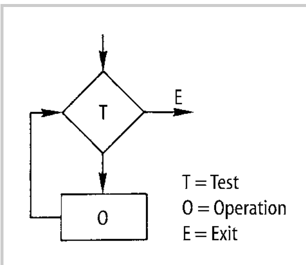


Figure 2.17. Basic TOTE model for thinking processes [2.8, 2.33]

2.2.2 Characteristics of Good Problem Solvers

The following statements are the result of the work of Dörner [2.9] and of research which has been undertaken with him by Ehrlenspiel and Pahl. The results of the research led by Ehrlenspiel and Pahl can be found in the publications of Rutz [2.50], Dylla [2.11, 2.12] and Fricke [2.15, 2.16]. This section provides a summary of their findings [2.42].

1. Intelligence and Creativity

In general, *intelligence* is thought to involve a certain cleverness, combined with the ability to understand and judge. Analytical approaches are often emphasised.

Creativity is an inspirational force that generates new ideas or produces novel combinations of existing ideas, leading to further solutions or deeper understanding. Creativity is often associated with an intuitive, synthesising approach.

Intelligence and creativity are personal characteristics. Up until now it has not been possible to come up with precise scientific definitions of or a clear distinction between intelligence and creativity. Attempts have been made to measure the level of intelligence of individuals using intelligence tests. The resulting Intelligence Quotients provide measures compared to the average of a large sample. Because of the different forms in which intelligence appears, various tests are needed to get a complete picture and draw tentative conclusions. The same is true for creativity tests.

For problem solving, a minimum level of intelligence is required and it appears that people with high Intelligence Quotients are more likely to be good problem solvers. However, according to [2.8, 2.9], intelligence tests on their own do not give much insight into which combination of factors makes a particular individual a good problem solver. The reason, according to Dörner [2.8], is that intelligence tests use tasks or problems that only require a few thinking steps to find a solution, so the sequence of steps seldom becomes conscious. Few intelligence tests require a large number of steps to be organised into a specific problem solving procedure. Such organisation requires switching between the different levels and possibilities of a general problem solving procedure, and is essential for the execution of long-term thinking activities.

Creativity tests too are often at such a low level that they do not address complex problem solving which involves planning and guiding one's own approach. Furthermore, in engineering design, creativity is always focused on a specific goal. Purely unfocused generation of ideas and variants can in fact hinder the problem solving process [2.2] or at best support a specific phase of the process.

2. Decision Making Behaviour

Apart from having well-structured factual knowledge, applying a systematic approach, and using focused creativity, designers have to master decision making processes. For decision making, the following mental activities and skills are essential:

- *Recognising Dependencies*

  In complex systems the dependencies between the individual elements can vary in strength. Recognising the types and strengths of such dependencies is an essential prerequisite for dividing the problem into more manageable, less complex subproblems or subgoals so that these can be addressed separately. However, those working on each separate subproblem must check to see how the short- and long-term effects of their own decisions influence the overall design.

- *Estimating Importance and Urgency*

  Good problem solvers know how to recognise *importance* (factual significance) and *urgency* (temporal significance), and how to use this information to modify their approach to problems.

  They try to resolve the most important things first and then tackle the dependent subproblems. They have the courage to be satisfied with suboptimal solutions for less significant problems if they have good or acceptable solutions for the most significant ones. By doing this they avoid immersing themselves in less relevant issues and thereby losing valuable time.

  The same is true when estimating the urgency. Good problem solvers estimate the time they need accurately. They prepare a demanding—but not impossible—time plan. Janis and Mann [2.25] have concluded that mild (i.e. bearable) stress is important for creativity. Therefore, realistic time planning has a positive effect on thinking processes, and new developments should take place under reasonable time pressure. But, of course, individuals react differently to time pressure.

- *Continuity and Flexibility*

  Continuity means an appropriate and continuous focus on achieving the goals, but there is a danger that excessive focus leads to a rigid approach. Flexibility means a ready ability to adapt to changing requirements. However, this should not lead to purposeless jumping from one approach to another.

  Good problem solvers find a suitable balance between continuity and flexibility. They demonstrate continuous and consistent, but at the same time flexible, behaviour. They stick to the given goals despite any hold-ups and difficulties they encounter. On the other hand, they adapt their approach immediately when the situation changes and when new problems occur.

  They consider heuristics, procedures and instructions first of all as guidelines and not as rigid prescriptions. Dörner states [2.8]: "Heuristics or heuristic plans should not degenerate into automatic procedures. Individuals should learn to develop what they have learnt. Heuristics should not be misinterpreted as prescriptions, but should be treated as guidelines that can, and often should, be developed."

- *Failures Cannot be Avoided*

  In complex systems with strong internal dependencies, at least partial failures are difficult to avoid because it is not possible to recognise all the potential effects simultaneously. When recognising such failures, the most important thing is the way one reacts. Being flexible is crucial, supported by the ability to analyse one's approach and the ability to make decisions that lead to corrective actions.

The results of cognitive psychology research are summarised below.

Good problem solvers:

- have a sound and structured technical knowledge, i.e. they have a well-structured model in their minds
- find an appropriate balance between concreteness and abstraction, depending on the situation
- can deal with uncertainty and fuzzy data
- continuously focus on the goals while adopting a flexible decision making behaviour.

Such heuristic competence depends largely on personal characteristics, but can be developed considerably through training on different types of problem.

The research mentioned earlier reveals that good designers demonstrate the following behaviour [2.42]:

- They thoroughly analyse the goals at the beginning of a task and continue to do so throughout the design process when formulating partial goals, in particular when the original problem formulation is vague.
- They first generate or identify the most suitable solution principles in a conceptual phase before developing concrete embodiments.
- They initially adopt a diverging search without generating too many variants and then quickly converge onto a small number of solutions; they choose the appropriate level of concretisation and switch easily between perspectives, e.g. abstract/concrete, overall problem/subproblem, working interrelationship/constructional interrelationship.
- They regularly assess their solutions using a comprehensive set of criteria, avoiding emphasising personal preferences.
- They continuously reflect on their approach and adapt it to the situation at hand.

These characteristics are in line with the aims and proposals for the design approach in this book.

2.2.3 Problem Solving as Information Processing

When we discussed the basic ideas of the systems approach (see Section 1.2.3), we found that problem solving demands a large and constant flow of information. Dörner [2.8] also views problem solving as information processing. The most important terms used in the theory of information processing are described in [2.5, 2.6]. Information is *received*, *processed* and *transmitted* (see Figure 2.18).

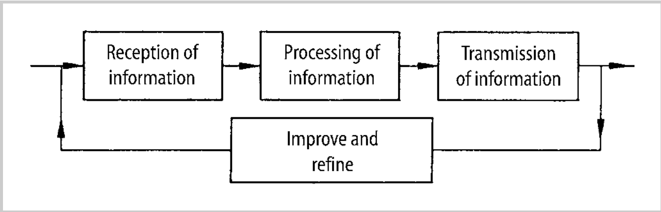


Figure 2.18. The conversion of information with iteration

Information is *received* from market analyses, trend studies, patents, technical journals, research results, licenses, inquiries from customers, concrete assignments, design catalogues, analyses of natural and artificial systems, calculations, experiments, analogies, general and in-house standards and regulations, stock sheets, delivery instructions, computer data, test reports, accident reports, and also by "asking questions". Data collection is an essential element of problem solving [2.3].

Information is *processed* by analysis and synthesis, the development of solution concepts, calculation, experiment, the elaboration of layout drawings and also the evaluation of solutions.

Information is *transmitted* by means of sketches, drawings, reports, tables, production documents, assembly manuals, user manuals, etc. These can be both in hard copy and electronic forms. Quite often provision must also be made for information to be *stored*.

In [2.32] some *criteria* for characterising information are given, and these can be used for formulating user information requirements. They include:

- Reliability: the probability of the information being available, trustworthy and correct.
- Sharpness: the precision and clarity of the information content.
- Volume and density: an indication of the number of words and pictures needed for the description of a system or process.
- Value: the importance of the information to the recipient.
- Actuality: an indication of the point in time when the information can be used.
- Form: the distinction between graphic and alphanumeric data.
- Originality: an indication of whether or not the original character of the information must be preserved.
- Complexity: the structure of, or connectivity between, information symbols and information elements, units or complexes.
- Degree of refinement: the quantity of detail in the information.

Information conversion is usually a very complicated process. Solving problems requires information of different types, content and range. In addition, to raise the level of information and improve it, it may be necessary to reiterate certain steps.

Iteration is the process by which a solution is approached step-by-step. In this process, one or more steps are repeated, each time at a higher level of information based on the results of the previous loop. Only in this way is it possible to obtain the information to refine a solution and ensure continuous improvement (see Figure 2.18). Such iterations occur frequently at all stages of the problem-solving process.

2.2.4 General Working Methodology

A general working methodology should be widely applicable, independent of discipline and should not require specific technical knowledge from the user. It should support a structured and effective thinking process. The following general ideas appear time and time again in specific approaches, either directly or slightly amended to adapt them to the special requirements of developing technical systems. The purpose of this section is to provide a general introduction to systematic procedures. The following procedures are based not only on our own professional experience and on the findings of cognitive psychology mentioned in Section 2.2.1, but also on the work of Holliger [2.20, 2.21], Nadler [2.38, 2.39], Müller [2.35, 2.36] and Schmidt [2.51]. They are also known as "heuristic principles" (a *heuristic* is a method for generating ideas and finding solutions) or "creativity techniques".

The following conditions must be satisfied by anyone using a systematic approach:

- *Define goals* by formulating the overall goal, the individual subgoals and their importance. This ensures the motivation to solve the task and supports insight into the problem.
- *Clarify conditions* by defining the initial and boundary constraints.
- *Dispel prejudice* to ensure the most wide-ranging search for solutions possible and to avoid logical errors.
- *Search for variants* to find a number of possible solutions or combinations of solutions from which the best can be selected.
- *Evaluate* based on the goals and conditions.
- *Make decisions*. This is facilitated by objective evaluations. Without decisions and experiencing their consequences there can be no progress.

To make these general methods work, the following *thinking* and *acting operations* must be considered.

1. Purposeful Thinking

As described in Section 2.2.1, intuitive and discursive thinking are possible. The former tends to be more unconscious, the latter more conscious.

Intuition has led to a large number of good and even excellent solutions. The prerequisite is, however, always a very conscious and intensive involvement with the given problem. Nevertheless, a purely intuitive approach has the following disadvantages:

- the right idea rarely comes at the right moment, since it cannot be elicited and elaborated at will
- the result depends strongly on individual talent and experience
- there is a danger that solutions will be circumscribed by preconceived ideas based on one's special training and experience.

It is therefore advisable to use more deliberate procedures that tackle problems step-by-step, and such procedures are denoted *discursive*. Here the steps are chosen intentionally; they can be influenced and communicated. Usually individual ideas or solution attempts are consciously analysed, varied and combined. It is an important aspect of this procedure that a problem is rarely tackled as a whole, but is first divided into manageable parts and then analysed.

It must, however, be stressed that intuitive and discursive methods are not opposites. Experience has shown that intuition is stimulated by discursive thought. Thus, while complex assignments must always be tackled one step at a time, the subsidiary problems involved may, and often should, be solved in intuitive ways.

In addition, it should be realised that creativity can be inhibited or encouraged by different influences [2.2]. It is, for example, often necessary to encourage intuitive thinking by interrupting the activity to provide some periods of incubation (see Section 2.2.1). On the other hand, too many interruptions can be disturbing and thereby inhibit creativity. A systematic approach including discursive elements and adopting different viewpoints encourages creativity. Examples include using different solution methods; moving between abstract and concrete ideas; collecting information using solution catalogues; and dividing work between team members. Furthermore, according to [2.25], realistic planning encourages rather than inhibits motivation and creativity.

2. Individual Working Styles

Designers should be given some freedom of action in their work to enable them to realise their own optimised working style. They should be free to select their preferred methods, the sequence in which they undertake individual working steps, and the sources of information they wish to consult. They should therefore be allowed to make their own plans for their area of responsibility and for them to have control over these plans. Obviously the individual working plans have to be compatible with the overall approach and make a useful contribution.

In general it is necessary to consider several subfunctions (subproblems) when developing new products. These functions, or combinations of them, lead to partial solutions. In such situations designers can proceed in different ways. One possibility is to search for working principles (solution principles) for every subfunction (or group of subfunctions), to roughly check their compatibility, and then to combine them into an overall working structure (solution concept). Finally the components are embodied, making sure their overall combination is compatible.

From a methodical point of view, this approach is systematic, stepwise and process-oriented; that is, the designer develops the different functional areas in parallel, from abstract (idea generation) to concrete (final embodiment) (see Figure 2.19a).

Another possibility is to proceed from idea generation to final embodiment for every problem or functional area, one after the other, and finally combine and modify these to make them all fit together. From a methodical point of view, this approach is problem-oriented; that is, the designer develops the different functional areas in sequence (see Figure 2.19b).

The investigations of Dylla [2.11, 2.12] and Fricke [2.15, 2.16] show that novices educated in systematic design tend to follow the process-oriented approach, whereas experienced designers tend to follow the problem-oriented approach. Experienced designers apply their wealth of experience, know a wide range of possible subsolutions, and are able to represent these solutions quickly. Hence they arrive relatively quickly at a concrete result. Then, using a corrective approach, they bring this together into an overall solution. This type of approach is successful in those cases where the individual components do not influence each other strongly and their properties are apparent. If these conditions are not met, this approach can lead to a relatively late recognition of a possible lack of compatibility between the functional areas. This approach can also result in different subsolutions being selected for identical, or similar, subfunctions, which is often not economic. In such cases further iterations are required to find other solutions.

The process-oriented approach largely avoids the potential disadvantages of the problem-oriented approach. However, more time is required because of the wider, more systematic perspective. This carries the danger of generating an unnecessarily large solution space. The process-oriented approach therefore requires designers to achieve an appropriate balance between abstract and concrete; that is, to know when a sufficiently large, but not too large, number of solution ideas has been generated (divergence), and the time has come to combine these into a concrete concept (convergence).

In practice, these two approaches (process-oriented and problem-oriented) are often not found in their pure form. They usually appear in various combinations depending on the problem situation. However, individual designers naturally tend to adopt one approach in preference to the other. Process-oriented approaches are recommended when subproblems are strongly interrelated and when breaking new ground. A problem-oriented approach is useful when the connectivity between functional areas is low and when subsolutions are known to exist in the area of application.

Similarly individual differences in approach can be observed during the search for solutions. If designers develop and investigate different solution principles or embodiment variants in parallel while searching for solutions for the individual subfunctions, and then compare these with one another to find the most suitable, this approach is called a *generative search for solutions* (see Figure 2.20a). If, on the other hand, a particular idea or example is used as a starting point and is then improved and adapted in a stepwise approach until a satisfactory solution emerges, this is called a *corrective search for solutions* (see Figure 2.20b). Adopting

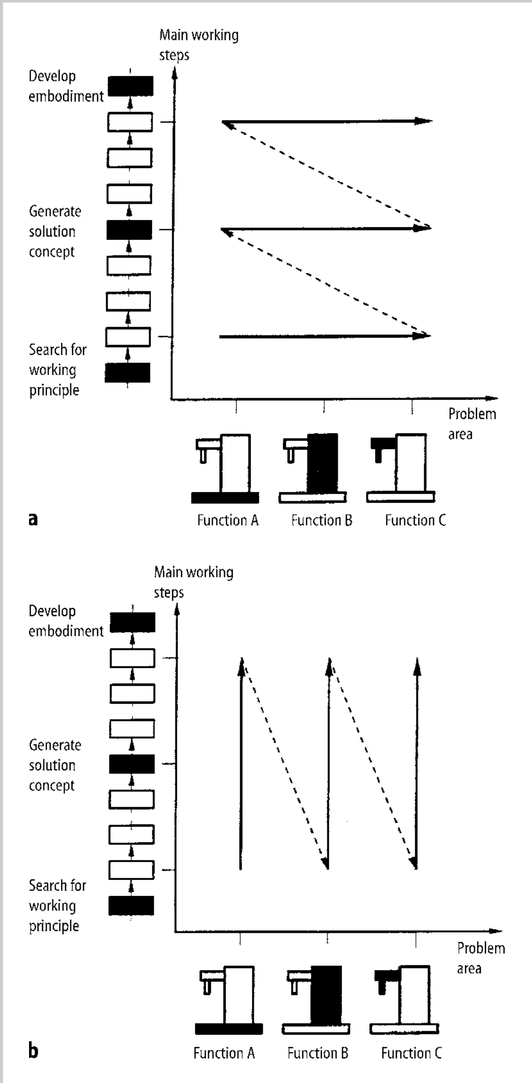


Figure 2.19. Different individual approaches during the development of solutions for a tea-making machine with several linked functional areas: baseplate/control (function A), water reservoir and heating element (function B), spout and closure (function C). **a** Systematic, stepwise, process-oriented, i.e. in every stage of development all functional areas are taken forward; **b** Problem-oriented, i.e. functional areas are developed in sequence before combining them (idealised process representation after Fricke [2.15, 2.16])

this latter approach will also result in a range of solution variants, if individual variants are not rejected.

A generative search for solutions increases the chances of finding new and unconventional ideas and considers many different principles, and thus may result in a larger solution space. The challenge, however, is a timely and goal-oriented

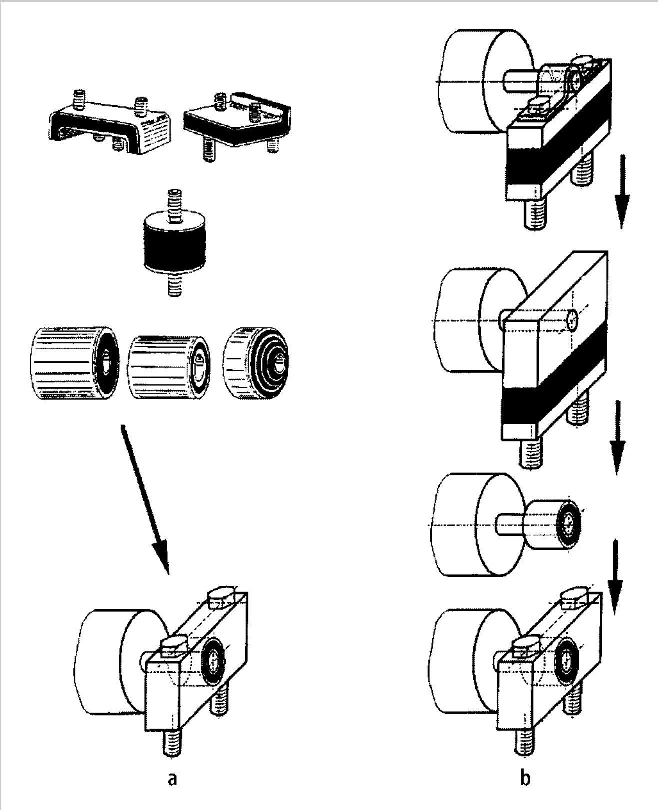


Figure 2.20. Different individual approaches during the search for solutions for an elastic support. **a** Generative, i.e. generation of various solutions and goal-oriented selection. **b** Corrective, i.e. search for solutions by improvement and adaptation of one idea

selection to avoid wasting time on unfeasible solutions. This type of search is typical for novices who have been taught systematic design and for designers who have adopted the systematic approach.

A corrective search for solutions is often used by inexperienced designers, in particular when they can think of a similar known solution in the application area. The advantage is that it is possible to concretise the solutions relatively quickly, even if these initial solutions are not really satisfactory. When adopting this type of search, designers tend to remain in their area of expertise and only expand this slowly. Possible dangers include fixating on solution ideas that are less suitable in principle and failing to recognise other better solution principles.

In practice, designers tend to adopt a mixture of search types with the main aim of minimising their work effort. However, designers clearly favour one or the other search type because of their individual talents and experience, usually without being aware of the advantages or dangers of their particular styles.

The consciously or unconsciously applied approaches depend on education and experience and can be influenced. Designers should not be forced into adopting a particular approach. On the contrary, it is better to make them aware of the advantages and dangers of the various approaches and leave the final decision up to them. It is, however, useful through training and further education, along with appropriate management during the project, to identify the most suitable overall approach and to agree on this.

2.2.5 Generally Applicable Methods

The following general methods provide further support for systematic work, and are widely used [2.21]. Often so-called "new" methods only involve repackaging one of the general methods described below.

1. Analysis

Analysis is the resolution of anything complex into its elements and the study of these elements and their interrelationships. It calls for identification, definition, structuring and arrangement. The acquired information is transformed into knowledge. If errors are to be minimised, then problems must be formulated clearly and unambiguously. To that end, they have to be analysed. *Problem analysis* means separating the essential from the nonessential and, in the case of complex problems, preparing a discursive solution by resolution into individual, more transparent, subproblems. If the search for the solution proves difficult, a new formulation of the problem may provide a better starting point. The reformulation of statements is often an effective means of finding new ideas and insights. Experience has shown that careful analysis and formulation of problems are among the most important steps of the systematic approach.

The solution of a problem can also be brought nearer by *structure analysis*, that is, the search for hierarchical structures or logical connections. In general, this type of analysis can be said to aim at the demonstration of similarities or repetitive features in different systems, for example by means of analogical reasoning (see Section 3.2.1).

Another helpful approach is *weak spot analysis*. It is based on the fact that every system has weaknesses caused by ignorance, mistaken ideas, external disturbances, physical limitations and production errors. During the development of a system it is therefore important to analyse the design concept or design embodiment for the express purpose of discovering possible weak spots and prescribing remedies. To that end, special selection and evaluation procedures (see Section 3.3) and weak spot identification methods (see Section 10.2) have been developed. Experience has shown that this type of analysis may not only lead to specific improvements of the chosen solution principle, but may also trigger off new solution principles.

2. Abstraction

Through abstraction it is possible to find a higher level interrelationship, that is, one which is more generic and comprehensive. Such a procedure reduces complexity and emphasises the essential characteristics of the problem and thereby provides an opportunity to search for and find other solutions containing the identified characteristics. At the same time new structures emerge in the minds of designers and these assist with the organisation and retrieval of the many ideas and representations. So abstraction supports both creativity and systematic thinking. It makes possible the definition of a problem in such a way that a coincidental solution path is avoided and a more generic solution is found (see example in Section 6.2).

3. Synthesis

Synthesis is the fitting together of parts or elements to produce new effects and to demonstrate that these effects create an overall order. It involves search and discovery, and also composition and combination. An essential feature of all design work is the combination of individual findings or subsolutions into an overall working system—in other words, the association of components to form a whole. During the process of synthesis the information discovered by analyses is processed as well. In general, it is advisable to base synthesis on a holistic or systems approach; in other words, to bear in mind the general task or course of events while working on subtasks or individual steps. Unless this is done, there is the grave risk that, despite the optimisation of individual assemblies or steps, no suitable overall solution will be reached. Appreciation of this fact is the basis of the interdisciplinary method known as Value Analysis, which proceeds from the analysis of the problem and structure to a holistic systems approach involving the early collaboration of all departments concerned with product development. Such an approach is also needed in large-scale projects, especially when preparing schedules by such techniques as critical path analysis (see Section 4.2.2). The entire systems approach and its methods are strongly based on holistic thinking, which is particularly important in the selection of evaluation criteria, because the value of a particular solution can only be gauged after overall assessment of all of the expectations, requirements and constraints (see Section 3.3.2).

4. Method of Persistent Questions

When using systematic procedures it is often a good idea to keep asking questions of both oneself and of others as a stimulus to fresh thought and intuition. A standard list of questions also fosters the discursive method. In short, asking questions is one of the most important methodological tools. This explains why many authors have drawn up special checklists for various working steps to support this method.

5. Method of Negation

The method of deliberate negation starts from a known solution, splits it into individual parts or describes it by individual statements, and negates these statements one-by-one or in groups. This deliberate inversion often creates new solution possibilities. Thus, when considering a "rotating" machine element, one might also examine the "static" case. Moreover, the mere omission of an element can be tantamount to a negation. This method is also known as "systematic doubting" [2.21].

6. Method of Forward Steps

Starting from a first solution attempt, one follows as many paths as possible to produce further solutions. This method is also called the method of divergent thought. It is not necessarily systematic, but frequently starts with an unsystematic divergence of ideas. The method is illustrated in Figure 2.21 for the development of a shaft–hub connection. The arrows indicate the direction of the thinking process.

Such a thinking process can be improved by using classifying criteria (see Figure 3.18) to support the systematic variation of the characteristics (see Figure 3.21). Where variation is done without conscious thought, even with well-structured representations, the identified characteristics are not used to their full potential.

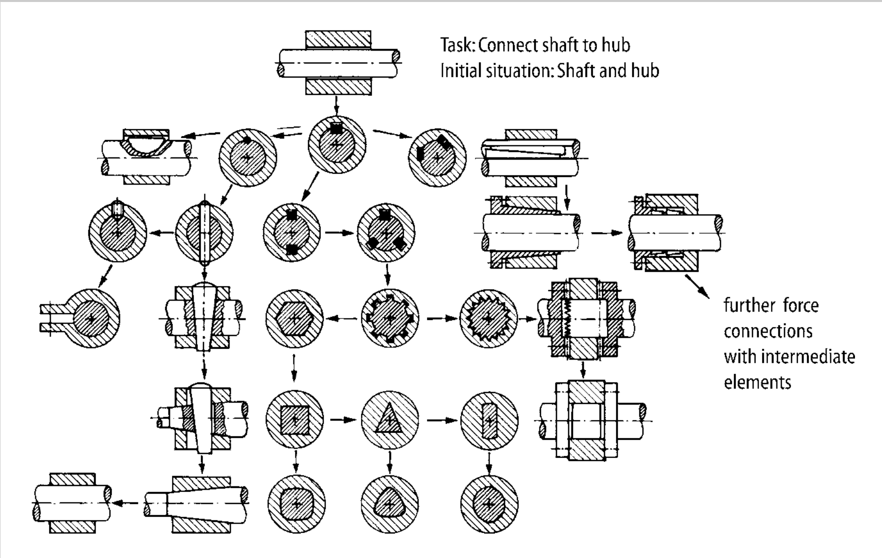


Figure 2.21. Development of shaft–hub connections in accordance with the method of forward steps

7. Method of Backward Steps

The starting point for this method is the goal rather than the initial problem. Beginning with the final objectives of the development, one retraces all of the possible paths that may have led up to it. This method is also called the method of convergent thought, because only ideas that converge on the ultimate goal are developed.

The method is particularly useful for drawing up production plans and developing systems for the production of components.

It is similar to the method of Nadler [2.38], who has proposed the construction of an ideal system that will satisfy all demands. This system is not developed in practice but formulated in the mind. It demands optimum conditions, such as an ideal environment which causes no external disturbances. Having formulated such a system, this is followed by a step-by-step investigation of what concessions must be made to turn this purely theoretical and ideal system into a technologically feasible one, and then finally into one that meets all the concrete requirements. Unfortunately, it is rarely possible to specify the ideal system in advance, because the ideal state of all functions, system elements and modules is difficult to specify, especially if they are linked together in a complex system.

8. Method of Factorisation

Factorisation involves breaking down a complex interrelationship or system into manageable, less complex and more easily definable individual elements (factors). The overall problem or task is divided into separate subproblems or subtasks that are, to a certain degree, independent (see Figure 2.3). Each of these subproblems or subtasks can initially be solved on its own, though the links between them in the overall structure must be kept in mind. Factorisation not only creates more manageable subtasks but it also clarifies their importance and influence in the overall structure, allowing priorities to be set. This approach is used in systematic design to divide an overall function into subfunctions and to develop function structures (see Sections 2.1.3 and 6.3), to search for working principles for subfunctions (see Section 6.4), and to plan the working steps during conceptual and embodiment design (see Section 4.2).

9. Method of Systematic Variation

Once the required characteristics of the solution are known, it is possible, by systematic variation, to develop a more or less complete solution field. This involves the construction of a generalised classification, that is, a schematic representation of the various characteristics and possible solutions (see Section 3.2.3). From the viewpoint of work science, too, it is obvious that the discovery of solutions is assisted by the construction and use of classification schemes. Nearly all authors consider systematic variation to be one of the most important methods.

10. Division of Labour and Collaboration

An essential finding of work science is that the implementation of large and complex tasks calls for the division of labour; more so as specialisation increases. This is also demanded by the increasingly tight schedules of modern industry. Now, division of labour implies interdisciplinary collaboration which, in turn, involves special organisational and staff arrangements along with appropriate staff attitudes, including receptiveness to the ideas of others. It must, however, be stressed that interdisciplinary collaboration and teamwork also demand a rigorous allocation of responsibility. Thus, the product manager should be in sole charge of the development of a particular product, regardless of departmental boundaries (see Section 4.3).

Systematic design, in combination with methods that make use of group dynamics, such as brainstorming, gallery method (see Section 3.2.3) and group evaluation (see Section 3.3), can overcome any lack of information exchange caused by the division of work, and can also help the search for solutions by stimulating ideas between team members.

2.2.6 Role of Computer Support

The systematic approach to design presented in this book can, in principle, be applied without the use of computers. However, the approach provides a sound basis for computer support of the design and development process that goes far beyond the use of complex analytical tools such as FEA and CFD, and the production of complex 3-D models. Computer support can be provided continuously throughout the process, for example, through the use of CAD, CAE, CAM, CIM, PDM and PLM software suites. The general use of IT also supports product improvement and reduces design and production effort.

It is not the purpose of this book, nor is there space, to describe the fundamental support that computers provide throughout the design process in detail. This topic is comprehensively covered in other texts, such as [2.1, 2.13, 2.17, 2.18, 2.27, 2.34, 2.37, 2.43, 2.44, 2.48, 2.52, 2.54, 2.57].

3 Product Planning, Solution Finding and Evaluation

A “methods toolbox” is presented in this chapter. Several of the methods, in particular the solution finding and evaluation ones, can be applied equally well in the different phases of the design process. Solution finding methods, such as brainstorming or the gallery method, can be useful, for example, in product planning and during conceptual design to find solution principles, as well as during embodiment design to find solutions for auxiliary functions. Evaluation methods can also be used in all of the phases. The only difference is the level of concretisation of the solutions under consideration.

Not every method is used in every product development process. Only those that seem appropriate for the problem situation and that contribute to a successful outcome are used. We provide recommendations for the practical application of each method to help the user assess its suitability in a given situation. Chapter 12 provides an overview of all recommendations.

3.1 Product Planning

One source of design and development tasks is a direct request (order) from a known client. This so-called business-to-business model [3.37, 3.47] is typical of made-to-order systems and process engineering equipment as well as for supply chain companies. For this type of order, there is a trend from client orientation to client integration [3.37], which has an influence on the work of the design and development department [3.2].

Assignments are set not only by clients, but increasingly—particularly in the case of original designs—they originate in the special planning departments of companies. In this case, designers are bound by the planning ideas of others (see Figure 1.2). Even then, however, the special skills of designers prove to be most useful in the medium- and long-term planning of products. The senior staff of the design department should therefore maintain close contacts not only with the production department, but also with the product planning department.

Planning can also be done by outside bodies, for instance by clients, by authorities, by consultancies, etc.

As will be discussed in Section 4.2 (see Figure 4.3), the design process for original designs starts with conceptualisation based on a requirements list (design specification). This preliminary list is usually based on requirements identified by product planning. It is therefore important for designers to know the essential points and steps of the product planning process. This will help them to understand the origin of the requirements and if necessary to add to the list. If there has not been a formal product planning phase, designers can organise the relevant steps using their own knowledge about product planning, or can undertake this phase themselves using simpler procedures.

In this chapter, and as shown in Figure 4.3, product planning and clarifying the task are consciously combined into one main phase. This is to emphasise the importance of integrating both activities. This remains important even when product planning and clarifying the task are undertaken separately within an organisation.

3.1.1 Degree of Novelty of a Product

As discussed in Section 1.1, the tasks of designers can have different degrees of novelty. The majority of tasks are adaptations to and variations on existing designs. This does not imply that these tasks are less challenging for designers. For product planning, the following differentiation of design tasks is of interest:

- *Original design:* New tasks and problems are solved using new or novel combinations of known solution principles. Two different cases can be distinguished:
  1. An invention is something truly new and is often based on the application of the latest scientific knowledge and insights [3.66].
  2. An innovation is a product that realises new functions and properties. This could be through novel or new combinations of existing solutions.
- *Adaptive design:* The solution principle remains unchanged; only the embodiment is adapted to new requirements and constraints.
- *Variant design:* The sizes and arrangements of parts and assemblies are varied within the limits set by previously designed product structures, which is typical of size ranges and modular products (see Chapter 9).

3.1.2 Product Life Cycle

Every product has a life cycle (see Figure 1.2), as illustrated in Figure 3.1. This is based on an economic viewpoint showing turnover, as well as profit and loss.

The *cycle time* depends strongly on the type of product and the branch of engineering, but in general cycles times are becoming shorter. This trend is likely to continue. This has a large effect on work in the design and development department because the time allocated for tasks that are identical, or very similar, to previous ones is reduced. As a consequence, it is necessary to adapt the product development process (see Chapter 4) as well as the methods discussed in this chapter.

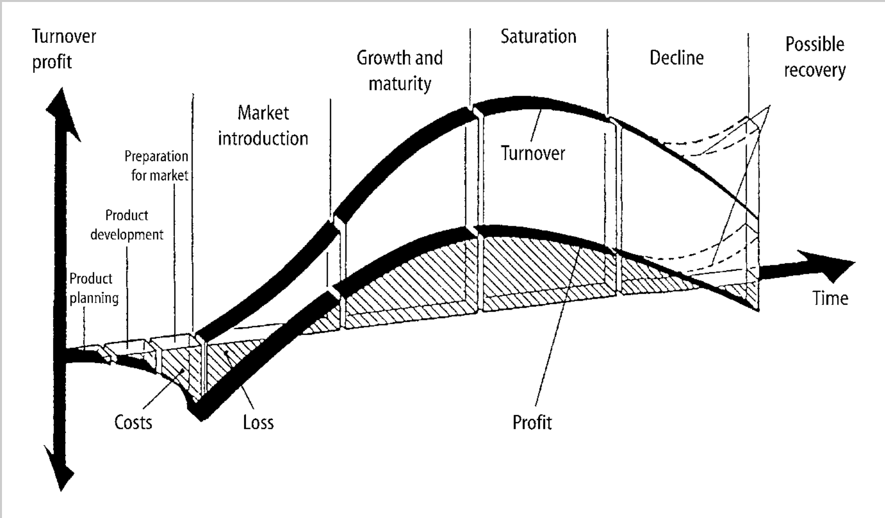


Figure 3.1. Life cycle of a product. After [3.45]

Measures to reactivate the market or generate new products have to be introduced when the saturation phase has been reached, at the latest. The introduction of these measures is an important task of product monitoring. A related activity in this context is the development of *market share*.

3.1.3 Company Goals and Their Effect

The main goal of every company is to make a profit. This goal has to be broken down into more concrete subgoals and related measures. To secure a lasting market presence, two generic strategies can be distinguished. The first strategy aims at achieving cost leadership. The corresponding company goals and implementation strategies are a broad sales base, large volumes, and rigorous product standardisation. The second strategy is that of performance differentiation. In this case, the goals and strategies focus on sales in special areas, highly effective flexible production, and specialisation in design and development. Both strategies have a time component, which is reflected in the company goal of being quicker to reach the market with a new product than its competitors.

One extreme strategy combines both strategies mentioned above, which, due to increasing competition, is becoming increasingly important.

Both of these goals—cost leadership and performance differentiation—affect the design and development department. At the next level down, many detailed goals are established, including those relating to the:

- *Product:* Such as functionality and properties
- *Market:* Such as time-to-market, which influences the time and budget made available (see Chapter 11) [3.12].

It is therefore very important for the design and development department to know the company's goals, their interrelationship and their relative importance. An important task for senior engineering managers is to convey the company goals relevant to engineering effectively to every member of staff.

3.1.4 Product Planning

1. Task and General Approach

Design and development start their work using a task description that, depending on the type of company, can come from different sources. In many cases, in particular in small- and medium-sized companies, it is left to the good sense of a director, or an individual member of staff, to develop and introduce the right product ideas at the right time and to formulate the necessary tasks. In larger companies, however, systematic procedures are increasingly used to find new products. An important aspect of this systematic approach is its potential to monitor the time and cost of product planning and product development more accurately. Those involved in product planning include marketing staff and product managers.

In many companies, therefore, the product planning department is expected to follow the development of a product idea through the design and production departments, and then to watch over its market behaviour. This includes monitoring the financial position and market success of the product and, if necessary, taking appropriate corrective measures (see Figure 1.2). In this book we shall only be dealing with product planning in the narrower sense, that is, as a preparation for product development.

The most important factor in finding new product ideas is client focus, which is increasingly directed towards client integration [3.2, 3.37]. One established method of identifying client wishes and translating these into product requirements is known as *Quality Function Deployment* (QFD) (see Section 10.5 [3.11, 3.38]).

Several systematic product planning approaches exist [3.5, 3.23, 3.33, 3.34, 3.42, 3.45, 3.69] and all of them have much in common (see Figure 3.2).

The stimuli for product plans come from outside (from the *market* or the *environment*) or from inside (from the *company* itself). These stimuli are usually identified by marketing.

Stimuli from the *market* include:

- the technical and economic position of the company's products in the market, in particular when changes occur, such as a reduction in turnover or a drop in market share
- changes in market requirements, for example new functions or fashions
- suggestions and complaints from customers
- the technical and economic superiority of competing products.

Stimuli from the *environment* include:

- economic and political changes, for example oil price increases, resource shortages, transport restrictions

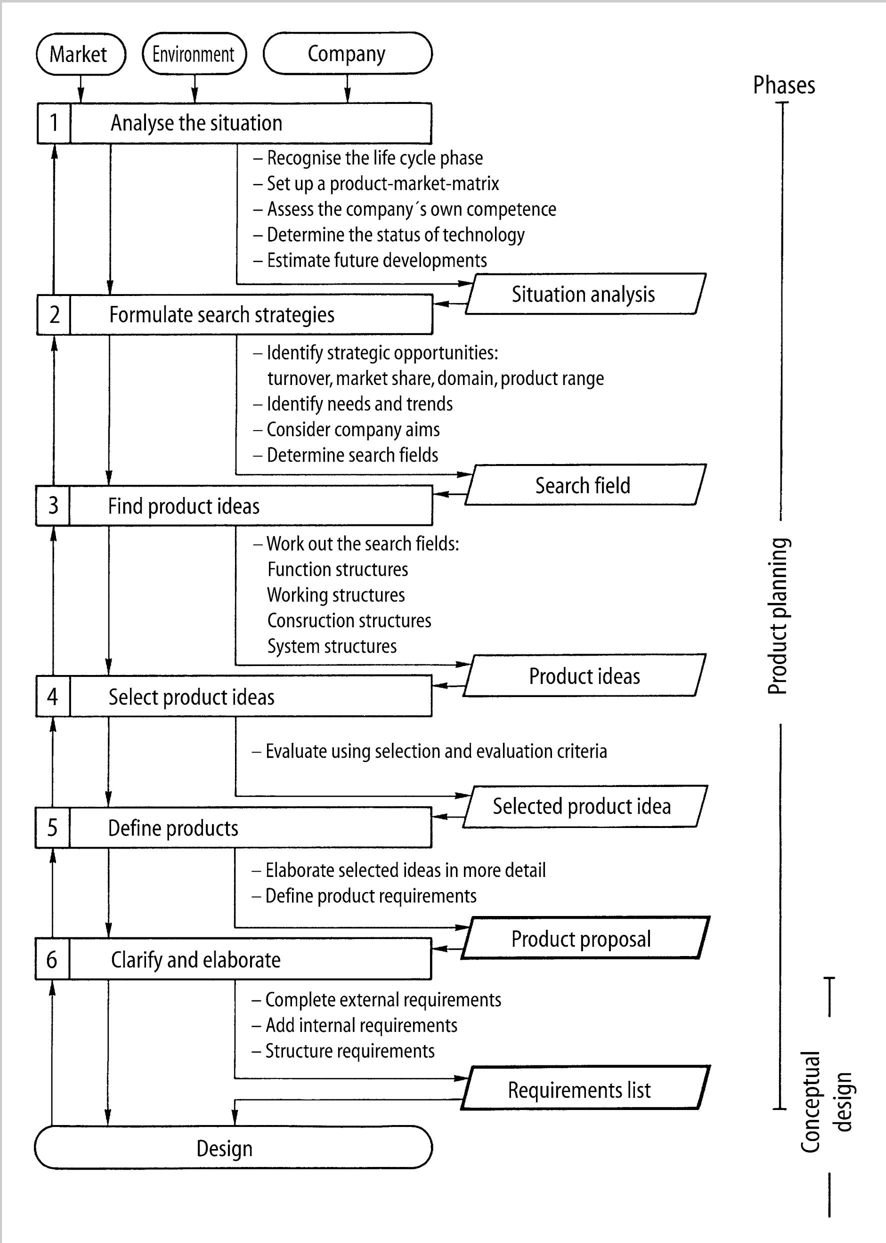


Figure 3.2. Product planning procedure. After [3.45, 3.69]

- new technologies and research results, for example microelectronics replacing mechanical solutions or laser cutting replacing flame cutting
- environmental and recycling issues.

Stimuli from within the *company* include:

- new ideas and results from company research applied during development and production
- new functions added to extend or satisfy the market
- the introduction of new production methods
- rationalisation of the product range and production
- increasing the degree of product diversification, that is, creating a range of products with life cycles that are intended to overlap.

These external and internal stimuli initiate five main working steps, which are illustrated, along with their outputs, in Figure 3.2.

These main working steps relate strongly to the general working methods described in Section 2.2 and more or less conform to systematic conceptual design (see Chapter 6 and Figure 4.3), and will be discussed in more detail in the following sections.

2. Analysing the Situation

The situation at the beginning of the product planning stage involves several aspects, and these must be clarified through a number of investigations, each with a different aim. The following steps have been found to be useful when analysing the situation, see also Figure 3.2.

Recognising the Life Cycle Phase

Consider the issues discussed in Sections 3.1.2 and 3.1.3. Life cycle analysis can also be used to recognise the need for diversification, in other words the phased development and sale of several different products. This will help to realise a balance of overlapping life cycles.

Setting Up a Product–Market Matrix

Recognising and clarifying the statuses of existing products from the company and from competitors in the various markets (field I in Figure 3.3) with respect to turnover, profit and market share should reveal the strengths and weaknesses of each of the products. A comparison with strong competitors is of particular interest.

Assessing the Company's Own Competence

This part of the analysis extends the previous one and provides the reasons for the current market position through an assessment of the company's technical weaknesses and through a comparison with competing companies (Figure 3.4). This analysis should not be based solely on orders, because these represent a selection that are already profitable for the company, but also on customer enquires and complaints, as well as installation and test reports.

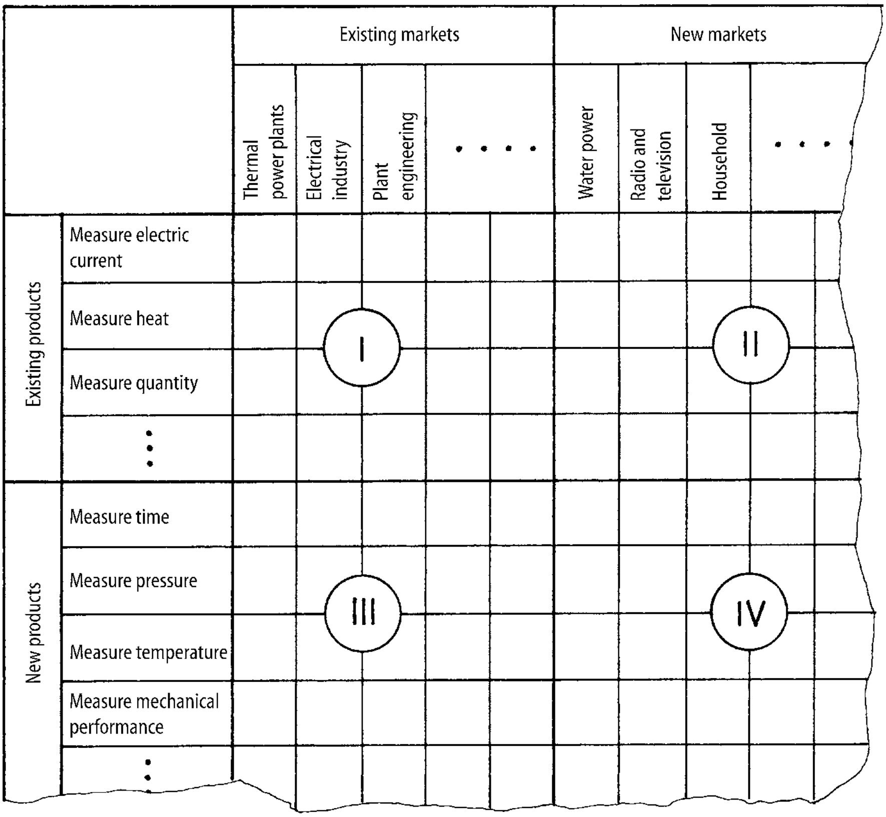


Figure 3.3. Product–market matrix, after [3.19] and [3.42], for a company producing measuring devices for industry

Determining the Status of Technology

This includes reviewing the products of the company, related technologies, concepts and products in the literature and patents, as well as competitors' products. In addition, the latest standards, guidelines and regulations are important.

Estimating Future Developments

Guidance can be obtained from knowledge of future projects, expected customer behaviour, technological trends, environmental requirements and the results of fundamental research.

A well-known method of visualising the technological situation, the international situation, the company situation and the competitive situation is portfolio analysis, which uses a multidimensional representation to present strategic business areas [3.38]. A distinction is made between the portfolios representing the present situation and the target situation. Figure 3.5 schematically shows a nine-cell portfolio matrix. It is also possible to use a simpler four-cell matrix. A distinction is made between business areas that are not profitable any more (cells 1, 2 and 3) and areas that should be targeted (cells 7, 8 and 9). If a business area is situated inbetween these (cells 4, 5 and 6), it is an indication that some action needs to be taken. Good examples of the factors labelled 1 and 2 in Fig-

Criteria	Competitors				
	A	B	C	D	.
Turnover					
Market share %					
Market situation					
– Conditions					
– Service					
– Delivery times					
–					
Product					
Management					
Product programme					

= same as us; + better; – worse

Figure 3.4. Analysis of competing companies. After [3.44]

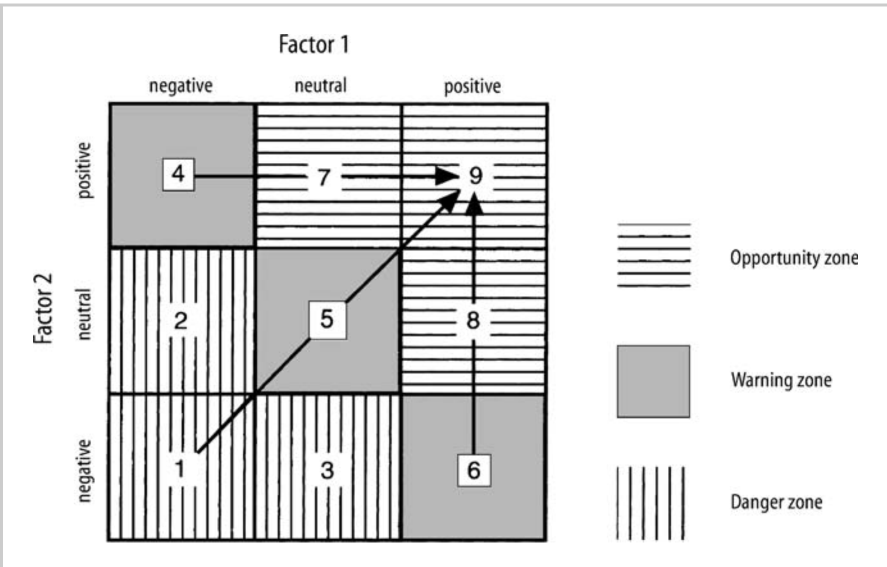


Figure 3.5. General structure of a portfolio matrix [3.21, 3.38, 3.45]

ure 3.5 would be: market growth—relative market share; market appeal—strength of competition; technological appeal—relative technological position; and market priority—technological priority [3.21].

Situation analysis determines the search strategies and the search fields that have to be addressed.

3. Formulating Search Strategies

Identifying Strategic Opportunities

It is possible that some gaps in the current product range or in the market are identified during the situation analysis. The task now is to determine which strategy to adopt: to introduce new products into the current market (field III in Figure 3.3); to open new markets with existing products (field II); or even to enter into new markets with new products (field IV). The latter involves the highest risk.

A promising gap that determines the search field [3.5, 3.33] must be found by taking into account the company's goals, strengths and market (see Table 3.1). Kramer [3.43] calls these strategic opportunities. They can relate to profit, market share, type of industry and product range. The weightings listed in Table 3.1 indicate that company goals are the most important criteria.

Table 3.1. Decision criteria for product planning

Criteria	Weighting
Company goals	$\geq$ 50%
Adequate financial cover	
High turnover	
High market growth	
Large market share (market leader)	
Short-term market opportunity	
Large functional advantages for users and excellent quality	
Differentiation from competitors	
Company strengths	$\geq$ 30%
Extensive know-how	
Favourable extension to range and/or product programme (diversification)	
Strong market position	
Limited need for investment	
Few sourcing problems	
Favourable rationalisation potential	
Market and other sources	$\geq$ 20%
Low danger of substitution	
Weak competition	
Favourable patent status	
Few general restrictions	

Identifying Needs and Trends

Most important for determining search fields is the identification of customer needs and market trends. Clues for these come from changes in customer behaviour caused, for example, by social developments such as environmental awareness, disposal problems, reduction in the working week, and transport problems. Another starting point could be changes in the length of the production supply chain, which can lead to new markets for suppliers. A commonly used tool is the *need–strength matrix* [3.42] (see Figure 3.6). In this matrix, one axis lists customer needs in decreasing order of importance, while the other lists the strengths and potentials of the company. The crossed fields in the top left corner of the matrix are the preferred search fields to be used in the preparation of the search field proposal. *Client–problem analysis* provides another tool [3.46].

Under subheading 1 of Section 3.1.4 we highlighted the importance of focussing on clients when planning new products and business areas. Here we describe an approach to achieve this objective. In the first step, the benefits currently required by the clients of a product or product group are extrapolated into the future. This is done to determine how the desired benefits are likely to change. If possible, all statements should be quantified, e.g. a noise reduction of 5 dB by the year 2006 and a reduction in energy consumption by 3 kW by 2007. In the second step, these requirements are allocated to suitable function carriers, i.e. assemblies or components. Next, the potential of the individual function carriers regarding the degree of fulfilment of future client requirements is estimated. In this step, requirements will

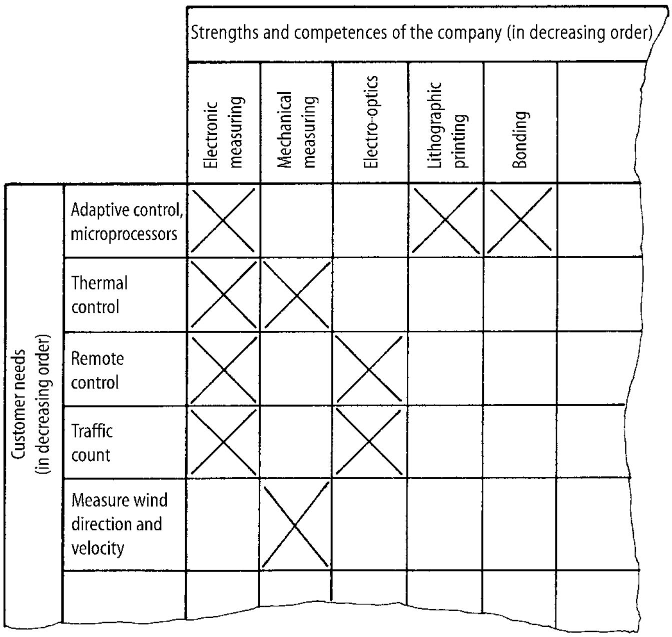


Figure 3.6. Need–strength matrix developed by a company, based on Figure 3.3 [3.42]

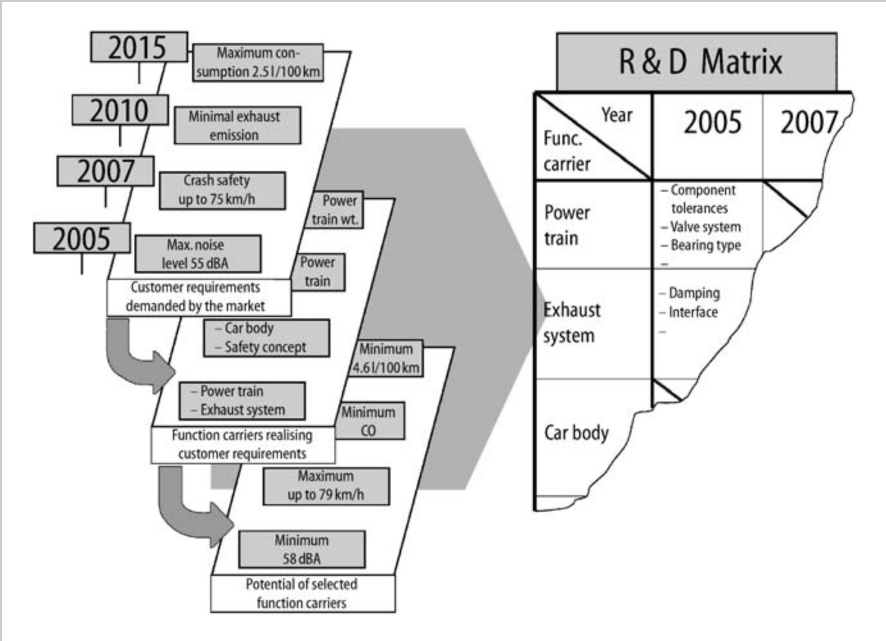


Figure 3.7. Product goals derived from customer requirements

arise for which no function carriers are yet available. As a result, this analysis can also reveal research and development needs regarding new and further developments of components, assemblies and products. It is useful to weight and prioritise the identified future requirements relating to client benefits. This will also rank the research and development themes. The results of these processes are the research and development goals that are used to plan the timing of research and development tasks. The product goals are also obtained. These goals provide the sequence in which new products, using the newly developed assemblies and components, are to be introduced into the market. Figure 3.7 illustrates this process.

For a medium- and long-term view of the future, scenario planning can be used to identify needs and trends, as well as profitable areas for the future [3.20, 3.21].

Considering Company Aims

Table 3.1 lists the goals and strengths of the company, which must be used to select a search field. The matrix in Figure 3.6 also emphasises the importance of the strengths and competences of the company in the selection of a worthwhile search field.

Determining Search Fields

The previously described steps of this product planning stage should lead, after a selection process, to a limited number of search fields (about 3–5 according to [3.22]) on which to concentrate the search for products.

4. Finding Product Ideas

The preferred search fields are now investigated in more detail using known search methods such as those that are used in product development (see Sections 3.2 and 6.4). These include: considering functions; intuitive methods such as brainstorming (see the so-called "idea-finding workshops" in [3.22]); and discursive methods such as ordering schemes, morphological charts and systematic combination.

When working out the search fields, a directed search for product ideas may be encouraged by the general relationships in technical products and their particular level of concretisation (see Section 2.1). Depending on the degree of novelty, the starting points for new products can be new product functions; other working principles; new embodiments; and rearrangements of an existing or new system structure. For a company producing measuring instruments, for example (see Figures 3.3 and 3.6), worthwhile product ideas can emerge from: new measuring functions; new physical effects (e.g. laser effect) used to fulfil known functions; or new embodiment goals (e.g. miniaturisation, better ergonomics and improved aesthetics).

The considerations follow the known interrelationship between function, working principle and embodiment:

Function:

- Which functions are required by the client?
- Which functions do we already fulfil?
- What complements existing functions?
- Which functions represent a generalisation of the existing ones?

For example, until now our company has only transported unit loads overland.

- What can we do in the future?
- Should we also use waterways?
- Should we start transporting very large, heavy items?
- Should we also transport bulk goods?
- Should we try to solve transport problems in general?

Working principle:

Existing products are based on a specific working principle. Would a change of working principle lead to better products?

Characteristics to look for are the types of energy and physical effects. For example, should a temperature-dependent flow-rate controller be based on the principle of fluid expansion, the bimetallic effect or the use of microprocessor-controlled temperature probes?

Embodiment:

- Is the space used still appropriate?
- Should we focus on miniaturisation?

- Is the shape still appealing?
- Could the ergonomics be better?

For example, is it still appropriate to use laces in shoes? Would Velcro or hooks be more appealing and more comfortable?

The answers to these questions determine the novelty of the product idea and therefore the developmental risks.

5. Selecting Product Ideas

The product ideas generated are first subjected to a selection procedure (see Section 3.3.1). For this initial selection, the criteria linked to the company's goals are sufficient in so far as they can be determined (see Table 3.1). At the very least, high turnover, large market share and functional advantages for the customer should be taken into account. A more detailed selection involves the other criteria. To identify promising product ideas, it is often sufficient, in the sense of an efficient application of selection procedures, to work only with binary values (yes/no).

6. Definiting Products

In this step, product ideas that seem promising are elaborated more concretely and in more detail. It is useful to consider the characteristics of requirements lists used in product development (see Section 5.2). During this step, at the latest, sales, marketing, research, development and design should work actively together. This can be encouraged by involving these groups in the evaluation and selection of product ideas.

Product ideas, after elaboration, are then subjected to an evaluation in which all of the criteria listed in Table 3.1, as far as they are known, are used.

Often some criteria, such as investment needs or sourcing problems, cannot be assessed because they are solution dependent. In these cases they will not be considered during this step. The best product definitions are given to the product development department as a product proposal together with a preliminary requirements list. The product development department then develops the actual product, using, for example, the systematic approach we propose.

The product proposal should:

- Describe the intended functions.
- Contain a preliminary requirements list that should have been compiled as far as possible using the characteristics used later to clarify the task and finalise the requirements list.
- Formulate all requirements in a solution-neutral way. The working principle should only be determined in so far as it is really necessary from the point of view of the overall functionality. For example, the same working principle

will be specified when an existing product range is being extended. Suggestions for working principles, however, should always be indicated, in particular when suitable solution principles have emerged during the idea-finding step. These should not prejudice product development (see also the solution-neutral formulation of requirements).

- Indicate a cost target or a budget linked to the company's goals which clarifies future intentions such as production volume, extensions to the product range, new suppliers, etc.

This concludes the product planning phase. By using the listed decision criteria, only those proposals that are likely to fit the company's goals and strengths, and that match the macro- and microeconomic situations, should enter the development stage. The development of the requirements list using the same method that will be applied in product development ensures an easy and seamless transition from product planning to product development.

For successful product planning and development, it is important that both groups work together using the same methods and similar evaluation and decision criteria. At the latest, product development should be actively involved when product ideas are selected and the product is defined. Together they should also develop the requirements list in a format suitable for product development (see Section 5.2).

7. Product Planning in Practice

Because of strong competition, new products have to meet market needs closely, be produced at a competitive cost and be economical to use. In addition, requirements relating to disposal and recycling, and to low environmental impact during production and use, are becoming increasingly important. Products with such complex requirements need to be planned systematically to meet these demands. Just relying on spontaneous ideas or incremental developments to existing products will not, in general, fulfil these demands. Systematic product planning often uses the same methods as concept development, and staff can usefully be exchanged between the two departments.

The following guidelines are important:

- The size of the company determines whether or not it is possible to set up interdisciplinary project groups or departments. In smaller companies it might be necessary to involve external consultants to supply expertise that is missing in the company.

- To use company expertise, however, can involve less risk and often increases client confidence.

- If product planning focuses on existing product lines, in other words further development or systematic variation, the development department responsible for the product line can monitor the new product, or this can be done by a special planning group that includes members from that department.

- When product planning takes place outside an existing product line, in other words the focus is on completely new products or diversification of the product programme, it is better to set up a new planning group. This group works on "innovative planning" and can either be set up as a permanent department or as a temporary working group.
- More elaborate analysis and conscious thought is required when planning for new markets than when dealing with known sales channels and existing client circles.
- When the starting situation is complex, it can be useful to undertake product planning and development using a stepwise and iterative approach. Acquisition of information and the decision making steps should be scheduled such that the anticipated effort and success can be reviewed and planned.
- Even when product ideas have been generated intuitively, a situation analysis and a feasibility study using the search strategies should still be performed.
- To identify customer problems, it is useful to have intensive collaboration with a few leading clients, referred to as "lead users" [3.22]. QFD methods can be used here too [3.11, 3.38].
- When new products are introduced, technical failures and weaknesses can have a far-reaching impact on the reputation of such products. Part of a careful product planning process, therefore, should include sufficient time for testing and the calculation of risks (see Section 7.5.12).
- Entry into the market later than announced can also have a negative effect on reputation because it suggests technical problems.
- During the planning and introduction of new products, it is useful to have a powerful product champion, e.g. a board member who identifies personally with the new product. This helps overcome a potential lack of interest and conventional resistance [3.22].
- Scenario planning (see [3.20, 3.22]) is particularly suitable for long-term forecasts. The effort required for scenario preparation, scenario field analysis, scenario forecasts and scenario building, however, is only worthwhile for business areas that are important to the company and its survival.

Finally, it should be stated that the procedure shown in Figure 3.2 does not represent a straight path with sequential steps, but a guideline for obtaining an essentially purposeful approach. The practical application of this approach will require an iterative procedure in which forward and backward steps at higher levels of information are necessary. This is quite normal in successful product finding.

3.2 Solution Finding Methods

The main advantage of the systematic approach is that designers do not have to rely on coming up with a good idea at the right moment. Solutions can be systematically elaborated using the relevant methods. These methods are the subject of this chapter.

An optimal solution:

- fulfils all demands in the requirements list as well as most of the wishes
- can be realised by the company within the constraints of budget (target costing), time-to-market, production facilities, etc.

Several steps are required to realise such a solution.

First, a range of possible solutions for the given task has to be generated. The basis for this is the function structure (see Section 2.1.3) that is used to divide the overall task into manageable subtasks. The function structure also provides the functional interrelationship between the subtasks, by describing the relationship between the inputs and outputs of each subfunction with respect to the flows of material, energy and signals.

In a second step, one or more possible physical effects are assigned to each of these solution-neutral subfunctions in order to realise them. This is done in accordance with the task-specific requirements. To realise a certain force, for example, a physical effect with the appropriate capability needs to be selected.

The approach described thus far typifies the traditional approach of an engineer. A solution space is created because variants are generated while developing the function structure and when selecting physical effects.

The use of a combination of solution-finding methods can be used to extend the solution space.

Often a subfunction can only be realised through a combination of several physical effects. This is another reason to use several solution finding methods. Those that are proposed or described in the following sections originate from, among others, the area of creativity techniques with its generally recurring methods that are described in Section 2.2.5. Others are based on analogical or logical reasoning.

The methods described here are mainly intended for the design and development of new products. However, they can be very helpful when existing patents of a competitor have to be circumvented or when existing products or components have to be optimised. The methods have to be selected for, adapted to and used in accordance with the context of the problem.

3.2.1 Conventional Methods

1. Information Gathering

For designers, access to state-of-the-art information is essential. As a first step, designers use a variety of collection techniques [3.45]. Information and data repositories, along with systems used to search and process the data, assist the active search for and the passive discovery of solutions. The internet enables a more effective and efficient application of the following conventional techniques:

- searching the literature
- analysing trade publications

- surveying the presentations from exhibitions and fairs
- assessing catalogues of competitors
- exploring patents, etc.

2. Analysis of Natural Systems

The study of natural forms, structures, organisms and processes can lead to very useful and novel technical solutions. The connections between biology and technology are investigated by bionics and biomechanics. Nature can stimulate the creative imagination of designers in a host of different ways [3.6, 3.29, 3.31, 3.35].

Technical applications of the design principles of natural forms include lightweight structures employing honeycombs, tubes and rods, the profiles of aircraft and ships, and the take-off and flying characteristics of aircraft. Lightweight structures in the form of thin stems are very important (see Figure 3.8). Another technical application is sandwich construction, and Figure 3.9 shows a few derivations of this natural principle that have proved useful in aircraft construction.

The hooks of a burr provided a solution that was incorporated into the Velcro fastener (see Figure 3.10). Further examples are given in Figure 3.11.

Fibre composites can be used to optimise the stiffness and deformation of structures that can equal or exceed those in found in nature. Carbon, glass and plastic fibres are aligned according to the principal stress directions and embedded in a predominantly polymer matrix of polyester, epoxy and other resins. This construction method requires an in-depth stress analysis along with a laying-up technique for the fibres adapted to that analysis, as well as extensive knowledge of plastics to select the fibre matrix composite. The basic relationships and ideas for the correct design of fibre composites and numerous literature references are provided by Flemming et al. [3.16].

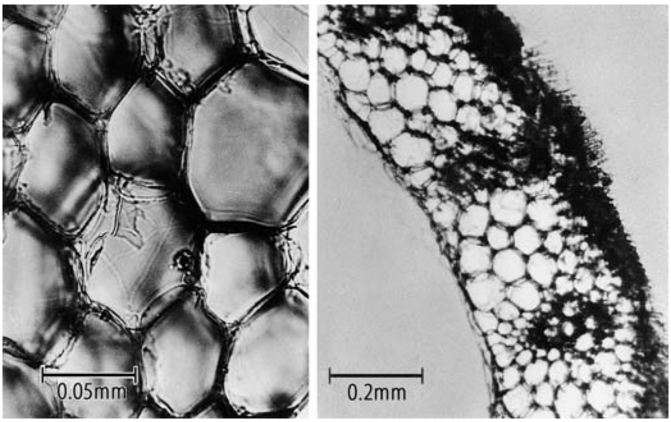


Figure 3.8. Wall of a wheat stem [3.29]

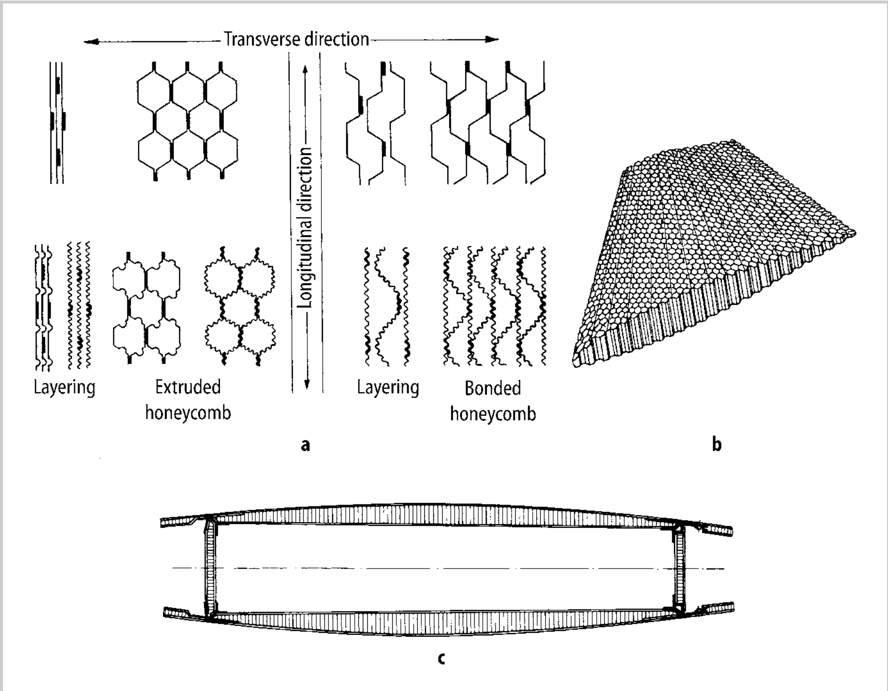


Figure 3.9. Sandwich construction for lightweight structures [3.30]. **a** A few honeycomb structures. **b** Completed honeycomb structure. **c** Sandwich box girder

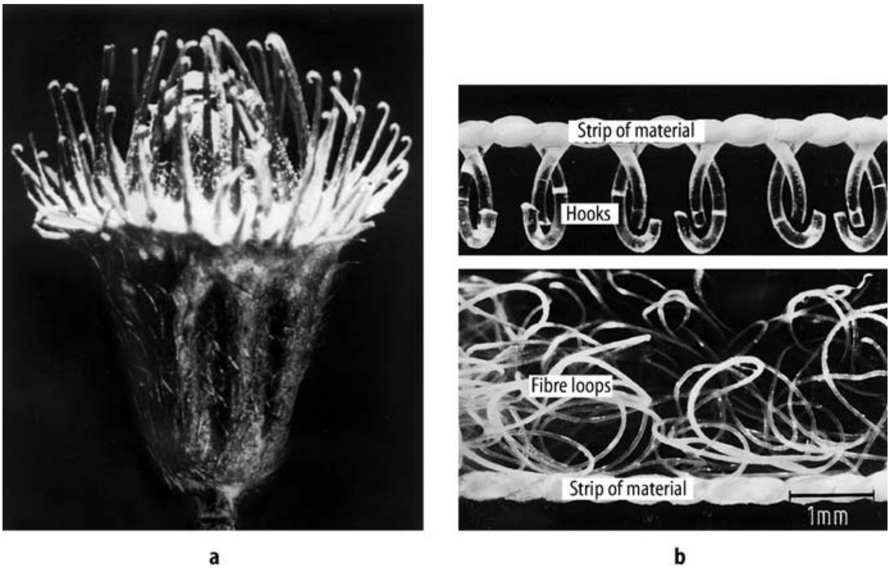


Figure 3.10. **a** Hooks of a burr. **b** Velcro fastener. After [3.29]

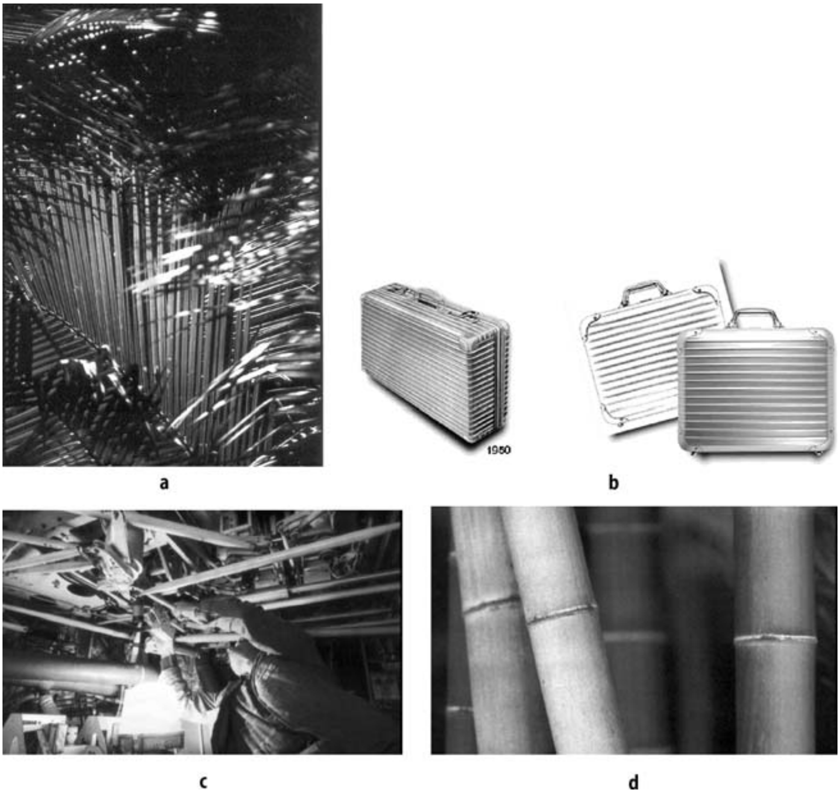


Figure 3.11. **a** Palm leaves (Lufthansa publication 2/96). **b** Aluminium suitcase (Rimowa Kofferfabrik 10/01). **c** Tubular structure in an aircraft. **d** Bamboo stems (Lufthansa publication 5/96)

3. Analysis of Existing Technical Systems

The analysis of existing technical systems is one of the most important means of generating new or improved solution variants in a step-by-step manner.

This analysis involves the mental or even physical dissection of finished products. It may be considered a form of structure analysis (see Subsection 1 in Section 2.2.5) aimed at the discovery of related logical, physical and embodiment design features. Figure 6.10 shows an example of this type of analysis. Here, subfunctions were derived from the existing configuration. From them, further analysis led to the identification of the physical effects involved which, in turn, might have suggested new solution principles for corresponding subfunctions. It is also possible to adopt solution principles discovered during the analysis.

Existing systems used for analysis might include:

- products or production methods from competing companies
- older products and production methods from one's own company
- similar products or assemblies in which some subfunctions or parts of the function structure correspond to those for which a solution is being sought.

Because the only systems to be analysed are those that have some bearing on the new problem as a whole or on parts of it, we could call this way of collecting information the systematic exploitation of proven ideas, or of experience. It proves particularly helpful for finding a first solution concept as a starting point for further variations. It must, however, be said that this approach carries the danger of causing designers to stick with known solutions instead of pursuing new paths.

4. Analogies

In the search for solutions and in the analysis of system properties, it is often useful to substitute an analogous problem (or system) for the one under consideration, and to treat it as a model. In technical systems, analogies may be obtained, for instance, by changing the type of energy used [3.3, 3.64]. Analogies chosen from the nontechnical sphere may prove very useful as well.

Besides helping in the search for solutions, analogies are also helpful in the study of the behaviour of a system during the early stages of its development by means of simulation and model techniques, and in the subsequent identification of essential new subsolutions and the introduction of early optimisations.

If the model is to be applied to systems of markedly different dimensions and conditions, a supportive similarity (dimensional) analysis should be undertaken (see Section 9.1.1).

5. Measurements and Model Tests

Measurements on existing systems, model tests supported by similarity analyses and other experimental studies are among the most important sources of information. Rodenacker [3.59] in particular stresses the importance of experimental studies, arguing that design can be interpreted as the reversal of physical experiment.

In the precision engineering and mass production industries, including those where micromechanisms and electronic products are developed, experimental investigations are an important and established means of arriving at solutions. This approach has organisational repercussions since, in the creation of such products, experimental development is often incorporated within the design activity (see Figure 1.3).

In a similar way, the testing and subsequent modification of software solutions belong to this empirically based group of methods.

3.2.2 Intuitive Methods

Designers often seek and discover solutions for difficult problems by intuition—that is, solutions come to them in a flash after a period of search and reflection. These solutions suddenly appear as conscious thoughts and often their origins cannot be traced. As Galtung of the International Peace Research Institute in Oslo has put it: “The good idea is not discovered or undiscovered; it comes, it happens”.

It is then developed, modified and amended, until such time as it leads to the solution of the problem.

Good ideas are always scrutinised by the subconscious or preconscious in the light of expert knowledge, experience and the task in hand, and often the simple impetus resulting from the association of ideas suffices to force them into consciousness. That impetus can also come from apparently unconnected external events or discussions. Frequently, a sudden idea will hit the bull's eye, so that all that needs to be done is to make changes or adaptations that lead straight to a final solution. If that is indeed the case and a successful product is created, then this represents the optimum procedure. Very many good solutions are born in that way and developed successfully. A good design method, far from trying to eliminate this process, should serve to back it up.

An industrial concern should nevertheless beware of exclusive reliance on the intuition of its designers, nor should designers themselves leave everything to chance or rare inspiration. Purely intuitive methods have the following disadvantages:

- The right idea does not always come at the right time, since it cannot be forced.
- Current conventions and personal prejudices may inhibit original developments.
- Because of inadequate information, new technologies or procedures may fail to reach the consciousness of the designer.

These dangers increase with specialisation, the division of tasks and with time pressure.

There are several methods of encouraging intuition and opening new paths by the association of ideas. The simplest and most common of these involves critical discussions with colleagues. Provided that such discussions are not allowed to stray too far and are based on the general methods of persistent questions, negation, forward steps, etc. (see Section 2.2.5), they can be very helpful and effective.

Methods with an intuitive bias such as Brainstorming, Synectics, Gallery Method, Method 635 and many others involve group dynamics that are used to generate the widest possible range of ideas. One of the effects of group dynamics is the uninhibited exchange of associated ideas between the members.

Most of these techniques were originally devised for the solution of nontechnical problems. They are, however, applicable to any field that demands new, unconventional ideas.

1. Brainstorming

Brainstorming can be described as a method of generating a flood of new ideas. It was originally suggested by Osborn [3.51] and provides conditions in which a group of open-minded people from as many different spheres of life as possible bring up, without prejudice, any thoughts that occur to them and thus trigger off new ideas in the minds of the other participants [3.74]. Brainstorming relies strongly on stimulation of the memory and on the association of ideas that have never been considered in the current context or have never been allowed to reach consciousness.

For maximum effect, brainstorming sessions should be run along the following lines:

Composition of the Group

- The group should have a leader and consist of a minimum of five and a maximum of 15 people. Fewer than five constitute a spectrum of opinion and experience that is too small, and hence produce too few stimuli. With more than 15, close collaboration may decline because of individual passivity and withdrawal.
- The group must not be confined to experts. It is important that as many fields and activities as possible are represented, the involvement of nontechnical members adding a rich new dimension.
- The group should not be hierarchically structured but, if possible, made up of equals in order to prevent the censoring of such thoughts as might give offence to superiors or subordinates.

Leadership of the Group

- The leader of the group should only take the initiative when dealing with organisational problems (invitation, composition, duration and evaluation). Before the actual brainstorming session, the leader must outline the problem and, during the session, must see to it that the rules are observed and, in particular, that the atmosphere remains free and easy. To that end the leader should start the session by expressing a few absurd ideas, or mentioning an example from another brainstorming session, but should never lead in the expression of ideas. On the other hand, the flow of new ideas should be encouraged whenever the productivity of the group slackens. The leader must ensure that no one criticises the ideas of other participants, and should appoint one or two members to take minutes.

Procedure

- All participants must try to shed their intellectual inhibitions; that is, they should avoid rejecting as absurd, false, embarrassing, stupid, well-known or redundant any ideas expressed spontaneously by themselves or by other members of the group.
- No participant should criticise any ideas that are brought up, and everyone must refrain from using such killer phrases as “we’ve heard it all before”, “it can’t be done”, “it will never work” and “this has nothing to do with the problem”.
- New ideas will be taken up by the other participants, who may change and develop them at will. It is also useful to combine several ideas into new proposals.
- All ideas should be written down, sketched out, or recorded.
- All suggestions should be concrete enough to allow the emergence of specific solution ideas.
- The practicability of the suggestions should be ignored at first.

- A session should not generally last for more than 30 to 45 minutes. Experience has shown that longer sessions produce nothing new and lead to unnecessary repetitions. It is better to make a fresh start with new ideas or with other participants later.

Evaluation

- The results should be reviewed by experts to find potential solution elements. If possible, these should be classified and graded in order of feasibility and then developed further.
- The final result should be reviewed with the entire group to avoid possible misunderstandings or one-sided interpretations on the part of the experts. New and more advanced ideas may well be expressed or developed during such a review session.

Brainstorming is indicated [3.56] whenever:

- No practical solution principle has been discovered.
- The physical process underlying a possible solution has not yet been identified.
- There is a general feeling that deadlock has been reached.
- A radical departure from the conventional approach is required.

Brainstorming is even useful in the solution of subproblems arising in known or existing systems. Moreover, it has a beneficial side-effect: all of the participants are supplied with new data, or at least with fresh ideas on possible procedures, applications, materials, combinations, etc., because the group represents a broad spectrum of opinion and expertise (for instance, designers, production engineers, sales persons, materials experts and buyers). It is astonishing what a profusion and range of ideas such a group can generate. The designers will remember the ideas brought up during brainstorming sessions on many future occasions. Brainstorming triggers off new lines of thought, stimulates interest and represents a break in the normal routine.

It should, however, be stressed that no miracles must be expected from brainstorming sessions. Most of the ideas expressed will not be technically or economically feasible, and those that are will often be familiar to the experts. Brainstorming is meant first of all to trigger off new ideas, but it cannot be expected to produce ready-made solutions because problems are generally too complex and too difficult to be solved by spontaneous ideas alone. However, if a session should produce one or two useful new ideas, or even some hints in what direction to go looking for the solution, it will have achieved a great deal.

An example of a solution obtained by Brainstorming can be found in Section 6.6, which also shows how the resulting ideas were evaluated and how classifying criteria for the subsequent search for solutions were derived from them.

2. Method 635

Brainstorming has been developed into Method 635 by Rohrbach [3.60]. After familiarising themselves with the task, and after careful analysis, each of six participants is asked to write down three rough solutions in the form of keywords. After some time, the solutions are handed to each participant's neighbour who, after reading the previous suggestions, enters three further solutions or developments. This process is continued until each original set of three solutions has been completed or developed through association by the five other participants, hence the name of the method.

Method 635 has the following advantages over Brainstorming:

- A good idea can be developed more systematically.
- It is possible to follow the development of an idea and to determine more or less reliably who originated the successful solution principle, which might prove advisable for legal reasons.
- The problem of group leadership rarely arises.

The method has the following disadvantage:

- Reduced creativity by the individual participants owing to isolation, and lack of stimulation in the absence of overt group activity.

3. Gallery Method

The Gallery Method developed by Hellfritz [3.27] combines individual work with group work, and is particularly suitable for any stage of the design process where solution proposals can be expressed in the form of sketches or drawings. The organisation and team building are similar to Brainstorming. The method consists of the following steps.

Introduction Step: The group leader presents the problem and explains the context.

Idea Generation Step 1: For 15 minutes the individual group members create solutions intuitively and without prejudice using sketches supported, where necessary, by text.

Association Step: The results from idea generation step 1 are hung on a wall as in an art gallery so that all group members can see and discuss them. The purpose of this 15-minute association step is to find new ideas or to identify complementary or improved proposals through negation and reappraisal.

Idea Generation Step 2: The ideas and insights from the association step are further developed individually by each of the group members.

Selection Step: All ideas generated are reviewed, classified and, if necessary, finalised. Promising solutions are then selected (see Section 3.3.1). It is also possible to identify potential solution characteristics that can be developed later using a discursive method (see Section 3.2.3).

The Gallery Method has the following advantages:

- Intuitive group working takes place without unduly lengthy discussions.
- An effective exchange of ideas using sketches is possible.
- Individual contributions can be identified.
- Documentary records are easily assessed and stored.

4. Delphi Method

In this method, experts in a particular field are asked for written opinions [3.7].

The requests take the following form:

First Round: What starting points for solving the given problem do you suggest? Please make spontaneous suggestions.

Second Round: Here is a list of various starting points for solving the given problem. Please go through this list and make what further suggestions occur to you.

Third Round: Here is the final evaluation of the first two rounds. Please go through the list and write down what suggestions you consider most practicable.

This elaborate procedure must be planned very carefully and is usually confined to general problems bearing on fundamental questions or on company policy. In the field of engineering design, the Delphi Method should be reserved for fundamental studies of long-term developments.

5. Synectics

Synectics is a word derived from Greek and it refers to the activity of combining various and apparently independent concepts. Synectics is comparable to Brainstorming, with the difference that its aim is to trigger off fruitful ideas with the help of analogies from nontechnical or semi-technical fields.

The method was first proposed by Gordon [3.25]. It is more systematic than Brainstorming, with its arbitrary flow of ideas. However, both methods call for complete frankness and lack of inhibition or criticism.

A synectics group should consist of no more than seven members, otherwise the ideas expressed will run away with themselves. The leader of the group has the additional task of helping the group to develop the proposed analogies by guiding them through the following steps:

- Presentation of the problem.
- Familiarisation with the problem (analysis).
- Grasping the problem.
- Rejection of familiar assumptions with the help of analogies drawn from other spheres.
- Analysis of one of the analogies.
- Comparison of the analogy with the existing problem.
- Development of a new idea from that comparison.
- Development of a possible solution.

If the result is unsatisfactory, the process may have to be repeated with a different analogy.

An example may help to illustrate this method. In a seminar set up for the purpose of discovering the best method of removing urinary calculi from the human body, several mechanical devices for gripping, holding and extracting these stones were mentioned. The device would have to stretch and open up inside the urethra. The keywords "stretch" and "open up" suggested the idea of an umbrella to one of the participants (see Figure 3.12).

Question: How can the umbrella analogy—(a) in Figure 3.12—be applied?

Possible answer 1: By (b) drilling through the stone, pushing the umbrella through the hole and opening it up. Not very feasible.

Possible answer 2: By (c) pushing a tube through the hole and blowing it up (balloon) behind the stone. Drilling of hole not feasible.

Possible answer 3: By (d) pushing the tube past the stone. When the tube is withdrawn the resistance may seriously damage the urethra.

Possible answer 4: By (e) adding a second balloon as a guide and by (f) embedding the stone in a gel between the two balloons and then pulling it out? This was found to be the best solution.

This example shows the association with a semi-technical analogy (umbrella) from which a solution was developed that took into account the special constraints that existed in this case. The solution shown here is not the final solution resulting from the seminar but represents an example of how the method was used.

Characteristic of this approach is the unrestricted use of analogies which, in the case of technical problems, are selected from nontechnical or semi-technical spheres. Such analogies will generally suggest themselves quite spontaneously at the first attempt but, during subsequent development and analysis, they will generally be derived more systematically.

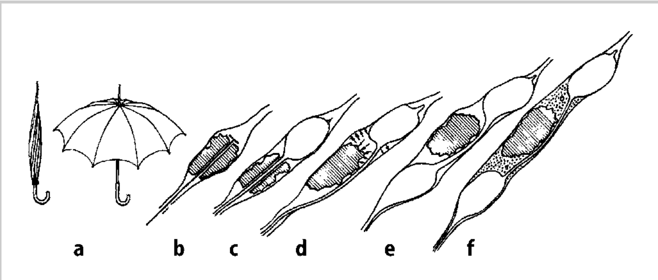


Figure 3.12. Step-by-step development of a solution principle for the removal of urinary calculi based on analogy and stepwise improvement

6. Combination of Methods

Any one of these methods taken by itself may not lead to the required goal. Experience has shown that:

- The group leader of, or another participant in, a brainstorming session may, when the flow of ideas dries up, introduce synectic procedures—deriving analogies, rejection of familiar assumptions, etc.—to release a new flood of ideas.

- A new idea or an analogy may radically change the approach and ideas of the group.
- A summary of what has been agreed so far may lead to new ideas.
- The explicit use of the methods of negation and reappraisal and of forward steps (see Section 2.2.5) can enrich and extend the variety of ideas.

In the seminar we mentioned, the presentation of the idea "destroy stone" produced a host of new suggestions, such as drilling, smashing, hammering, ultrasonic disintegration and so on. When the flow of ideas eventually dried up, the group leader asked, "How does nature destroy?", which immediately evoked a number of new suggestions, including weathering, heating and cooling, decay, putrefaction, bacterial action, ice expansion and chemical decomposition. A combination of the two principles "clasp stone" and "destroy stone" provoked the question, "What else?" This produced the answer "contact stone rather than clasp", which in turn threw up such new ideas as sucking, gluing, and applying various contact forces.

The different methods should be combined so as to best address particular cases. A pragmatic approach ensures the best results.

3.2.3 Discursive Methods

Methods with a discursive bias provide solutions in a deliberate step-by-step approach that can be influenced and communicated. Discursive methods do not exclude intuition, which can make its influence felt during individual steps and in the solution of individual problems, but not in the direct implementation of the overall task.

1. Systematic Study of Physical Processes

If the solution of a problem involves a known physical (chemical, biological) effect represented by an equation, and especially when several physical variables are involved, various solutions can be derived from the analysis of their interrelationships, that is, of the *relationship* between a dependent and an independent variable, all other quantities being kept constant. Thus, if we have an equation in the form $y = f(u, v, w)$, then, according to this method, we investigate solution variants for the relationships $y_1 = f(u, \underline{v}, \underline{w})$, $y_2 = f(\underline{u}, v, \underline{w})$ and $y_3 = f(\underline{u}, \underline{v}, w)$, the underlined quantities being kept constant.

Rodenacker has given several examples of this procedure, one of which concerns the development of a capillary viscometer [3.59]. Four solution variants can be derived from the well-known law of capillary action $\eta \sim \Delta p \cdot r^4/(\dot{V} \cdot l)$. They are shown schematically in Figure 3.13.

1. A solution in which the differential pressure Δp serves as a measure of the viscosity: $\Delta p \sim \eta$ ($\dot{V}$, r and l = constant).
2. A solution based on changes in radius of the capillary tube: $\Delta r \sim \eta$ ($\dot{V}$, Δp and l = constant).

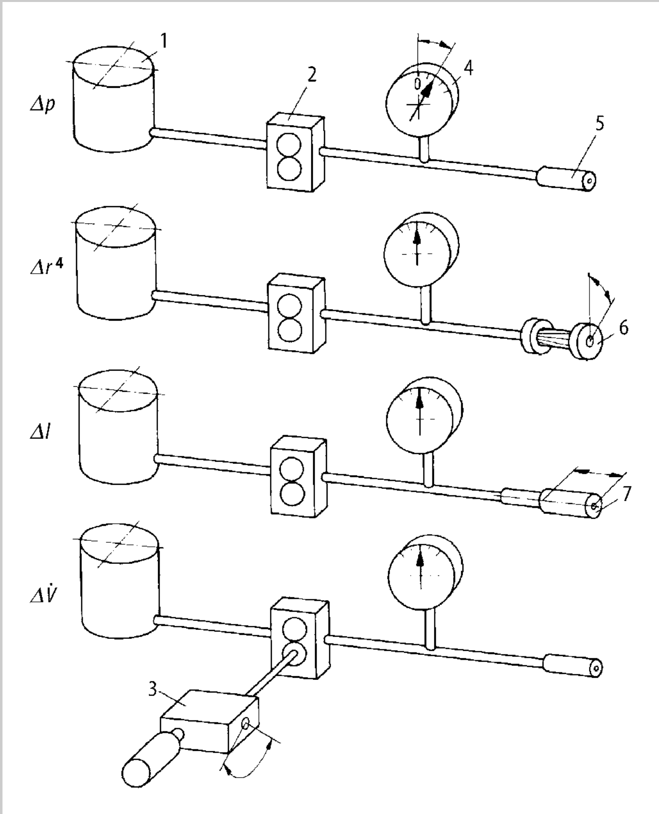


Figure 3.13. Schematic representation of four viscometers, after [3.59]. *1*, container; *2*, gear pump; *3*, variable drive; *4*, pressure gauge; *5*, fixed capillary tube; *6*, capillary tube with variable diameter; *7*, capillary tube with variable length

3. A solution based on changes in the length of the capillary tube: $\Delta l \sim \eta$ (Δp, $\dot{V}$ and r = constant).
4. A solution based on changes in the volume flow rate: $\Delta \dot{V} \sim \eta$ (Δp, r and l = constant).

Another way of obtaining new or improved solutions by the analysis of physical equations is the resolution of known physical effects into their individual components. Rodenacker [3.59], in particular, has used this approach in the design of novel devices and the development of new applications for existing ones.

By way of example, let us look at the development of a frictional thread locking device, based on the analysis of the equation governing the torque needed to release a threaded fastener:

$$T = P[(d/2)\tan(\phi_v - \beta) + (D/2)\mu_f] \tag{3.1}$$

The torque given by Equation (3.1) is made up of the following components:

Frictional torque in the thread:

$$T_t \sim P(d/2)\tan\phi_v = P(d/2)\mu_v \tag{3.2}$$

where

$$\tan\phi_v = \mu_t/\cos(\alpha/2) = \mu_v$$

Frictional torque on the bolt head or nut face:

$$T_f = P(D/2)\tan\phi_f = P(D/2)\mu_f \tag{3.3}$$

Release torque of the thread due to pre-load and thread pitch:

$$T_r \sim P(d/2)\tan(-\beta) = -P \cdot \frac{P}{2\pi} \tag{3.4}$$

(where p = thread pitch, β = helix angle, d = mean thread (t) diameter, P = pre-load, D = mean face (f) diameter, μ_v = virtual (v) coefficient of friction in the thread, μ_t = actual coefficient of friction in the thread, μ_f = coefficient of friction on the head or nut face, α = flank angle, ϕ = angle of friction).

To discover solution principles for the improvement of the locking properties of a threaded fastener, we must analyse the physical relationships further so as to identify the physical effects involved. The individual effects involved in Equations (3.2) and (3.3) are:

- the friction effect (Coulomb friction)

$$F_t = \mu_v P \quad \text{and} \quad F_f = \mu_f P$$

- the lever effect

$$T_t = F_t\, d/2 \quad \text{and} \quad T_f = F_f\, D/2$$

- the wedge effect

$$\mu_v = \mu_t/\cos(\alpha/2)$$

The individual effects in Equation (3.4) are:

- the wedge effect

$$F_r \sim P\tan(-\beta)$$

- the lever effect

$$T_r = F_r\, d/2$$

An examination of the individual physical effects will yield the following solution principles for the improvement of the locking properties of the fastener:

- Use of the wedge effect to reduce the tendency to loosen by decreasing the helix angle β.

- Use of the lever effect to increase the frictional moment on the head or nut face by increasing the mean face diameter D.
- Use of the friction effect to increase the frictional force by increasing the coefficient of friction μ.
- Use of the wedge effect to increase the frictional force on the face by means of conical surfaces ($P\mu_f/\sin\gamma$ with cone angle $= 2\gamma$). This method is used with automobile wheel attachment nuts.
- Increase of the flank angle α to increase the virtual coefficient of friction in the thread.

2. Systematic Search with the Help of Classification Schemes

In Section 2.2.5 we showed that the systematic presentation of information and data is helpful in two respects. On the one hand it stimulates the search for further solutions in various directions; on the other hand it facilitates the identification and combination of essential solution characteristics. Because of these advantages, a number of classification schemes have been drawn up, all with a similar basic structure. Dreibholz [3.10] has published a comprehensive survey of the possible applications of such classification schemes.

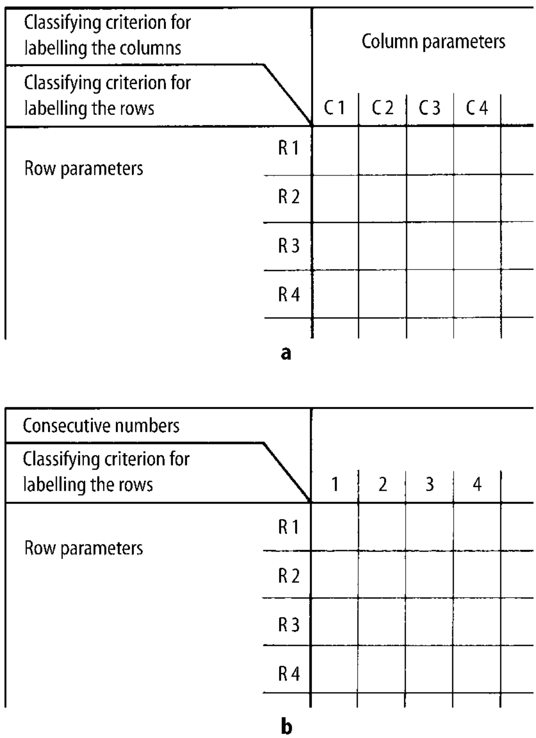


Figure 3.14. General structure of classification schemes. After [3.10]

The usual two-dimensional scheme consists of rows and columns of parameters used as classifying criteria. Figure 3.14 illustrates the general structure of classification schemes: (a) when parameters are provided for both the rows and the columns; and (b) when parameters are provided for the rows only, because the columns cannot be arranged in any apparent order. If necessary, the classifying criteria can be extended by a further breakdown of the parameters or characteristics (see Figure 3.15); this, however, often tends to confuse the general picture. By allocating the column parameters to the rows it is possible to trans-

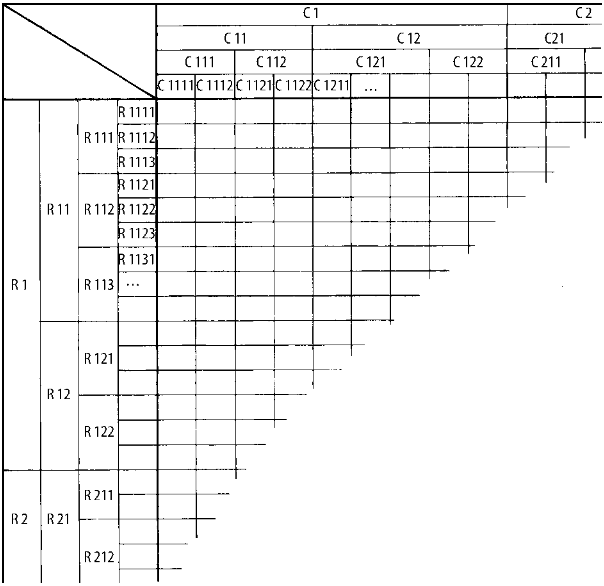


Figure 3.15. Classification scheme with further subdivision of parameters. After [3.10]

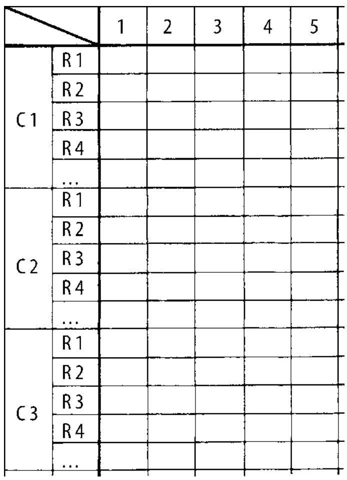


Figure 3.16. Modified classification scheme. After [3.10]

form every classification scheme based on row and column into a scheme in which only the row parameters are retained, and the columns are merely numbered (see Figure 3.16).

Such classification schemes help the design process in a great many ways. In particular, they can serve as design catalogues during all phases of the search for a solution, and they can also help in the combination of subsolutions into overall solutions (see Section 3.2.4). Zwicky [3.77] has referred to them as "morphological matrices".

The choice of classifying criteria or their parameters is of crucial importance. In establishing a classification scheme it is best to use the following step-by-step procedure:

Step 1: Solution proposals are entered in the rows in random order.

Step 2: These proposals are analysed in the light of the main headings (characteristics), such as type of energy, working geometry, working motion, etc.

Step 3: They are classified in accordance with these headings.

The criteria and their parameters can also be obtained from an earlier use of intuitive methods to analyse known solutions or solution ideas.

This procedure not only helps with the identification of compatible combinations but, more importantly, encourages the opening up of the widest possible solution

Classifiing criteria:
Types of energy, physical effects and manifestations

Headings	*Examples*
Mechanical	Gravitation, inertia, centripetal force
Hydraulic	Hydrostatic, hydrodynamic
Pneumatic	Aerostatic, aerodynamic
Electrical	Electrostatic, electrodynamic, inductive, capacitative, piezo-electric, transformation, rectification
Magnetic	Ferromagnetic, electromagnetic
Optical	Reflection, refraction, diffraction, interference, polarisation, infra-red, visible, ultra-violet
Thermal	Expansion, bimetal effect, heat storage, heat transfer, heat conduction, heat insulation
Chemical	Combustion, oxidation, reduction, dissolution, combination, transformation, electrolysis, exothermic and endothermic reactions
Nuclear	Radiation, isotopes, source of energy
Biological	Fermentation, putrefaction, decomposition

Figure 3.17. Classifying criteria and headings (characteristics) for variation in the physical search area

fields. The classifying criteria and characteristics listed in Figures 3.17 and 3.18 can be useful when searching systematically for solutions and the variation of solution ideas for technical systems. They refer to types of energy, physical effects, manifestations, as well as the characteristics of the working geometry, working motions, and the basic material properties (see Section 2.1.4).

Figure 3.19 provides a simple example of searching for a solution to satisfy a subfunction. Here the answer was obtained by varying the type of energy against a number of working principles.

Classifying criteria

Working geometry, working motions and basic material properties

Working geometry

Headings	*Examples*
Type	Point, line, surface, body
Shape	Curve, circle, ellipse, hyperbola, parabola Triangle, square, rectangle, pentagon, hexagon, octagon Cylinder, cone, rhomb, cube, sphere Symmetrical, asymmetrical
Position	Axial, radial, tangential, vertical, horizontal Parallel, sequential
Size	Small, large, narrow, broad, tall, low
Number	Undivided, divided Simple, double, multiple

Working motions

Headings	*Examples*
Type	Stationary, translational, rotational
Nature	Uniform, non-uniform, oscillating Plane or three-dimensional
Direction	In x,y,z direction and/or about x,y,z axis
Magnitude	Velocity
Number	One, several, composite movements

Basic material properties

Headings	*Examples*
State	Solid, liquid, gaseous
Behaviour	Rigid, elastic, plastic, viscous
Form	Solid body, grains, powder, dust

Figure 3.18. Classifying criteria and headings (characteristics) for variation in the form design search area

Type of energy / Working principle	mechanical	hydraulic	electrical	thermal
1	m, h Pot. energy	h Liquid reservoir (pot. energy)	Battery V	Mass m s $\Delta\vartheta$
2	V m Moving mass (transl.)	Flowing liquid	Capacitor (electr. field) C	Heated liquid
3	J ω Flywheel (rot.)			Superheated steam
4	J v ω Wheel on inclined plane (rot. + transl. + pot.)			
5	Metal spring d F F	Other springs (compression of fluid + gas) $\Delta p; \Delta V$		
6		Hydraulic reservoir a. Bladder b. Piston c. Membrane (Pressure energy)		

Figure 3.19. Different working principles that satisfy the function "store energy" obtained by varying the type of energy

Figure 3.20 is an example of variation based on working motions.

Figure 3.21 shows the variation in the working geometry in the design of shaft–hub connections. Thanks to such arrangements, the multiplicity of solutions obtained, for instance by the method of forward steps (see Section 2.2.5 and Figure 2.21), can be put into order and completed.

To sum up, the following recommendations are given:

- Classification schemes should be built up step-by-step and as comprehensively as possible. Incompatibilities should be discarded, and only the most promising solution proposals pursued. In so doing, designers should try to determine which classifying criteria contribute to the discovery of a solution, and to examine further variations by modifying the parameters.
- The most promising solutions should be chosen and labelled using a special selection procedure (see Section 3.3.1).
- If possible, the most comprehensive classification schemes should be drawn up (those schemes intended for repeated use), but systems should never be built for the sake of systematics alone.

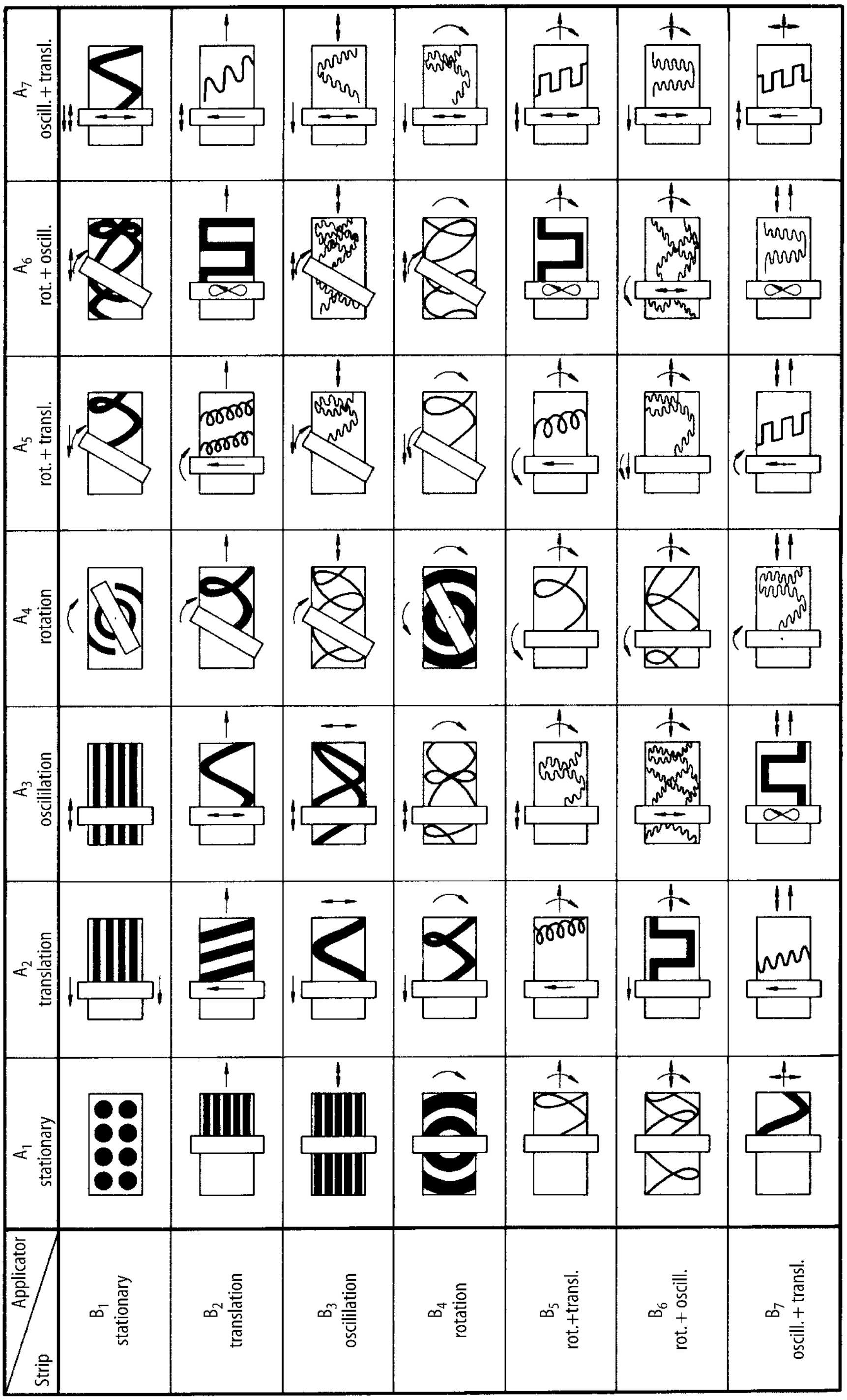


Figure 3.20. Means of coating the backs of carpets by combining the motions of the carpet (strip) and those of the applicator

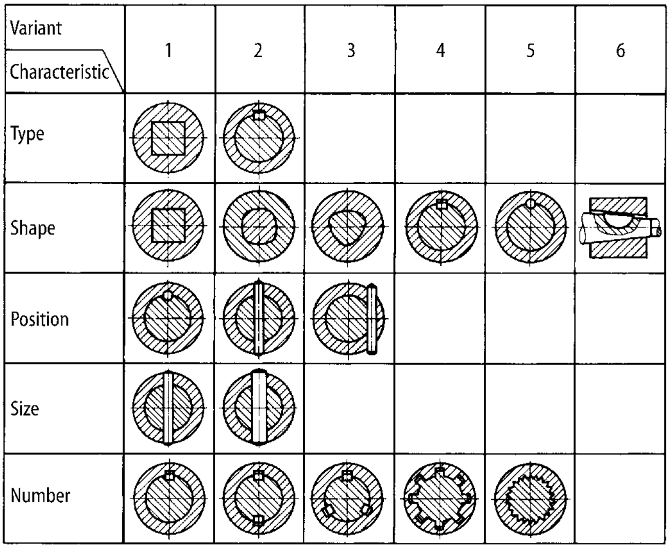


Figure 3.21. Variations in the working geometry for shaft–hub connections

3. Use of Design Catalogues

Design catalogues are collections of known and proven solutions to design problems. They contain data of various types and solutions at distinct levels of embodiment. Thus they may cover physical effects, working principles, principle solutions, machine elements, standard parts, materials, bought-out components, etc. In the past, such data were usually found in textbooks and handbooks, company catalogues, brochures and standards. Some of these contained, apart from purely objective data and suggested solutions, examples of calculations, solution methods and other design procedures. It is also possible to imagine catalogue-like collections for methods and procedures.

Design catalogues should provide:

- quicker, more problem-oriented access to the accumulated solutions or data
- the most comprehensive range of solutions possible, or, at the very least, the most essential ones, which can be extended later
- the greatest possible range of interdisciplinary applications
- data for conventional design procedures as well as for computer-aided methods.

The construction of design catalogues has been studied, above all, by Roth and collaborators [3.62]. Roth suggests that a design catalogue of the type shown in Figure 3.22 is most likely to satisfy all of the demands listed above.

The classifying criteria determine the structure of the catalogue. They influence the ease with which catalogues can be handled and reflect the level of complexity of particular solutions, as well as their degree of embodiment. In the conceptual design phase, for instance, it is advisable to select as classifying criteria the

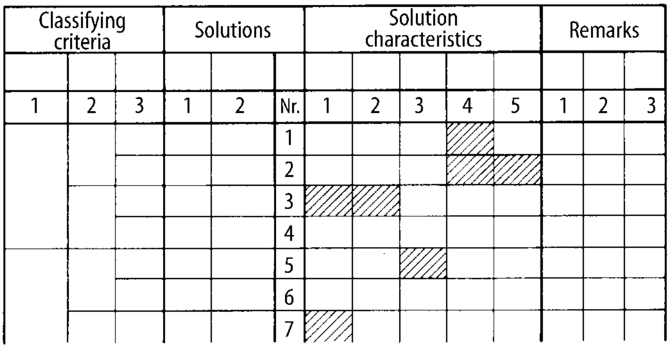


Figure 3.22. Basic structure of a design catalogue. After [3.62]

functions to be fulfilled by the solutions. This is because the conceptual design is based on the underlying subfunctions. When classifying characteristics it is best to choose generally valid functions (see Section 2.1.3), which help to elicit the most product-independent solutions.

Further classifying criteria might include the types and characteristics of energy (mechanical, electrical, optical, etc.), of material or signals, of working geometries, of working motions and of basic material properties. In the case of design catalogues intended for the embodiment design phase, useful classifying criteria include the properties of materials and the characteristics of particular machine elements, such as types of coupling.

The solution column is the main part of the catalogue and contains the solutions. Depending on the level of abstraction, the solutions are represented as sketches, with or without physical equations, or as more or less complete drawings or illustrations. The type and completeness of the information given once again depends on the intended application. It is important that all data is of the same level of abstraction and omits side issues.

The column covering the solution characteristics is important for the choice of solutions.

The remarks column can be used for information about the origin of the data and for additional comments.

The characteristics used for selection may involve a great variety of properties—for instance typical dimensions, reliability, response, number of elements, etc. They help designers in the preliminary selection and evaluation of solutions and, in the case of computer-based catalogues, they can also be used in the final selection and evaluation.

Another important requirement of design catalogues is that they should have uniform and clear definitions and symbols.

The more concrete and detailed the stored information, the more direct but also the more limited the application of a catalogue. With increasing degree of embodiment, data for a given solution become more comprehensive. However, the chances of arriving at a complete solution field decreases because the number of details, for example embodiment variants, increases rapidly. Thus, it may be

Table 3.2. Available design catalogues

Application	Object	Author and reference
General	Construction of catalogues	Roth [3.62]
	List of available catalogues and solutions	Roth [3.62]
Principle solutions	Physical effects	Roth [3.62]
	Solutions to functions	Koller [3.39]
Connections	Types of connections	Roth [3.62]
	Connections	Ewald [3.14]
	Fixed connections	Roth [3.62]
	Wedded joints for steel profiles	Wölse and Kastner [3.75]
	Riveted joints	Roth [3.62], Kopowski [3.41], Grandt [3.26]
	Adhesive joints	Fuhrmann and Hinterwalder [3.18]
	Clamping elements	Ersoy [3.13]
	Principles of threaded joints	Kopowski [3.41]
	Threaded fasteners	Kopowski [3.41]
	Elimination of backlash in threaded joints	Ewald [3.14]
	Elastic joints	Gießner [3.24]
	Shaft–hub connections	Roth [3.62], Diekhöner and Lohkamp [3.9], Kollmann [3.40]
Guides and bearings	Linear guides	Roth [3.62]
	Rotational guides	Roth [3.62]
	Plain and roller bearings	Diekhöner [3.8]
	Bearings and guides	Ewald [3.14]
Power generation, power transmission	Electric motors (small)	Jung and Schneider [3.32]
	Drives (general)	Schneider [3.65]
	Power generators (mechanical)	Ewald [3.14]
	Effects to generate power	Roth [3.62]
	Single-stage power multiplication	Roth [3.62], VDI 2222 [3.70]
	Lifting mechanisms	Raab and Schneider [3.57]
	Screw drives	Kopowski [3.41]
	Friction systems	Roth [3.62]
Kinematics, mechanisms	Solving motion problems using mechanisms	VDI 2727, part 2 [3.72]
	Chain drives and mechanisms	Roth [3.62]
	4-bar mechanisms	VDI 2222, part 2 [3.70]
	Logical inverse mechanisms	Roth [3.62]
	Logical conjunctive and disjunctive mechanisms	Roth [3.62]
	Mechanical flip-flops	Roth [3.62]
	Mechanical non-return safety devices	Roth [3.62], VDI 2222, part 2 [3.70]
	Lifting mechanisms	Raab and Schneider [3.57]
	Uniform-motion transmissions	Roth [3.62]
	Handling devices	VDI 2740 [3.73]
Gearboxes	Spur gears	VDI 2222, part 2 [3.70], Ewald [3.14]
	Mechanical single-stage gearboxes with constant gear ratio	Diekhoner and Lohkamp [3.9]
	Elimination of backlash in spur gears	Ewald [3.14]
Safety technology	Danger situations	Neudorfer [3.52]
	Protective barriers	Neudorfer [3.53]
Ergonomics	Indicators, controls	Neudorfer [3.51]
Production processes	Casting	Ersoy [3.13]
	Drop forging	Roth [3.62]
	Press forging	Roth [3.62]

Function	Input	Output	Physical effects						
$E_{mech} \rightarrow E_{mech}$	Force, pressure, torque	Length, angle	Hooke (Tension/ compression/ bending)	Shear, torsion	Upthrust Poisson´s effect	Boyle-Mariotte	Coulomb I and II	...	...
		Speed	Energy Law	Conservation of momentum	Conservation of angular momentum	...	...	...	...
		Acceleration	Newton´s Law	...	...	...	...	...	...
	Length, angle	Force, pressure, torque	Hooke	Shear, torsion	Gravity	Upthrust	Boyle-Mariotte	Capillary	
			Coulomb I and II	...	...	...	...	...	...
	Speed		Coriolis force	Conservation of momentum	Magnus-effect	Energy law	Centrifugal force	Eddy current	
	Acceleration		Newton´s Law	...	...	...	...	...	...
$E_{mech} \rightarrow E_{hyd}$	Force, length, speed, pressure	Speed, pressure	Bernoulli	Viscosity (Newton)	Torricelli	Gravitational pressure	Boyle-Mariotte	Conservation of momentum	...
$E_{hyd} \rightarrow E_{mech}$	Speed	Force, length	Profile lift	Turbulence	Magnus-effect	Flow resistance	Back pressure	Reaction principle	...
$E_{mech} \rightarrow E_{therm}$	Force, speed	Temperature, quantity of heat	Friction (Coulomb)	1st law	Thomson-Joule	Hysteresis (damping)	Plastic deformation	...	...
$E_{therm} \rightarrow E_{mech}$	Temperature, heat	Force, pressure, lenght	Thermal expansion	Steam pressure	Gas Law	Osmotic pressure	...	...	...
$E_{elektr} \rightarrow E_{mech}$	Voltage, current, magn. field	Force, speed, pressure	Biot-Savart-effect	Electro-kinetic effect	Coulomb I	Capacitance effect	Johnsen-Rhabeck-effect	Piezoeffect	...
$E_{mech} \rightarrow E_{elektr}$	Force, length, speed, pressure	Voltage, current	Induction	Electro-kinetics	Electro-dynamic effect	Piezoeffect	Frictional electricity	Capacitance effect	...
$E_{elektr} \rightarrow E_{therm}$	Voltage, current	Temperature, heat	Joule heating	Peltier-effect	Electric arc	Eddy current	...	...	...
$E_{therm} \rightarrow E_{elektr}$	Temperature, heat	Voltage, current	Electr. conduction	Thermo-effect	Thermionic emission	Pyroelectricity	Noise-effect	Semiconductor, Super-conductor	...
$E_{mech} \rightarrow E_{mech}$	Force, length, pressure, speed	Force, length, pressure, speed	Lever	Wedge	Poisson´s effect	Friction	Crank	Hydraulic effect	...
$E_{hyd} \rightarrow E_{hyd}$	Pressure, speed	Pressure, speed	Continuity	Bernoulli	...	...	...	...	...
$E_{therm} \rightarrow E_{therm}$	Temperature, heat	Temperature, heat	Heat conduction	Convection	Radiation	Condensation	Evaporation	Freezing	...
$E_{elektr} \rightarrow E_{elektr}$	Voltage, current	Voltage, current	Transformer	Valve	Transistor	Transducer	Thermogalvanometer	Ohm´s law	...
...	...	...	...	...	...	...	...	...	...

Figure 3.23. Design catalogue of physical effects based on [3.39, 3.48] for the generally applicable functions "change energy" and "vary energy component". Also applicable to flow of signals

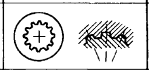
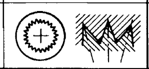
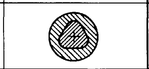
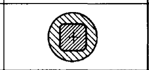
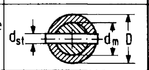
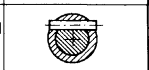
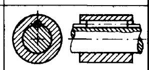
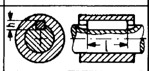
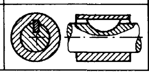
Classifying criteria: Type of interface	Classifying criteria: Type of force transmission	Solutions: Equation	Solutions: Name	Solutions: Configuration	Nr.	Trans-ferable torque	Torque transmis-sion de-pending on	Axial forces	Stress concentration	Appli-cable for	Beha-viour at over-load	Center-ing possible	Unba-lanced force	Axial displace-ment of hub	Hub move-able	Joint adjus-table	Shaft diameter (mm)	Material	Manu-factur-ing effort	Assem-bly effort	Stan-dard (DIN)	Applica-tion examples	Remarks
1	2	1	2	3		1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17
Normal (form fit)	Direct	$T \le K \cdot \frac{d}{2} \cdot A_s \cdot \tau_{max}$ or $T \le K \cdot \frac{d}{2} \cdot A_p \sigma_{max}$	spline shaft		1	large	h i l shaft diameter,(form) factor, centering factor, material	—	large	pulsa-ting or alterna-ting	fracture	yes	no	clearance fit	yes	no	10 – 150	shaft: 37 Cr 4 41 Cr 4 42 CrMo	high	small	5461/63 5471/72	toothed wheels	exterior, flank, interior centering possible short hub possible
			involute spline shaft		2			—													5480, 5482		
			serrated shaft		3			—	medium								150 – 500				5481		
			3-sided polygon-shaft		4		e i l	—		pulsa-ting or alterna-ting		self-cente-ring	no	clea-rance fit without load		yes for taper	10 – 100		small, special machi-nery neces-sary		—		used for short and thin hubs, conical shaft end possible, broaching or grinding necessary
			4-sided polygon-shaft		5			—									10 – 100				—		
	Indirect		transverse pin		6	small	$\frac{d_p}{D}$	are supported	large	—		yes	yes	—		yes for taper pin	0.5 – 50	pin: 4D, 5S 6S, 8G 9S, 20K St 50 K St 70 St 60	medium	medium	1,7 1470 – 77 1481, 6324, 7346	power stretcher, machine tools, vehicles	taper and groo-ved pin possible
			tangential pin		7					—				—	no								
			in line pin		8		$\frac{d_p}{l}$	—	medium	—				clearance fit						small			
			key joint		9		h l b	—	large	—						no	5 – 500	spring St 60			6885		
			Woodruff key		10			—		—								shaft, hub: GG,GS ST			6888		

Figure 3.24. Extract of a catalogue for shaft–hub connections. After [3.62]

possible to provide a full list of physical effects fulfilling the function "channel", but it would hardly be possible to list all of the potential embodiments of bearings (channelling a force from a rotating to a stationary system).

Table 3.2 lists the currently available design catalogues that satisfy the requirements and structure described above. Therefore, in what follows we include just a few examples of, or extracts from, available design catalogues.

Figure 3.23 shows a catalogue of physical effects associated with the functions "change energy" and "vary energy component". It is based on Koller [3.39] and Krumhauer [3.48]. The catalogue makes it possible to derive these effects from the classifying criteria, that is, the "inputs and outputs" of the functions. The characteristics on which the selection is based must be derived from the technical literature.

Figure 3.24 shows an extract of a catalogue for shaft–hub connections based on [3.62]. In this, unlike the previous catalogue, the solutions are concrete enough, thanks to the specification of the form design features, for the embodiment design phase to start with a scale layout drawing.

Computer-based systems are used to facilitate searching through catalogues, company brochures, supplier information and other documents. Hypermedia software provides a way of structuring, storing and retrieving the contents of such documents. It allows the flexible manipulation of chunks of information, and the representation and linking of objects and procedures in a specific knowledge domain, using different representation principles. This is called navigating in a hypermedia system [3.58]. To use distributed sources of information, a global network is required, such as the internet (www). Using the internet, so-called "virtual markets" or "virtual supply chains" can be created with which designers can communicate from their work places [3.4].

3.2.4 Methods for Combining Solutions

As described in Sections 2.1.3 and 2.2.5, it is often useful to divide problems, tasks and functions into subproblems, subtasks and subfunctions and to solve these individually (factorisation method) (see also Section 6.3). Once the solutions for subproblems, subtasks or subfunctions are available, they have to be combined in order to arrive at an overall solution.

The methods we have been describing, particularly those with an intuitive bias, may have led to the discovery of suitable combinations. However, there are special methods for arriving at such syntheses more directly. In principle, they must permit a clear combination of solution principles with the help of the associated physical and other quantities and the appropriate geometrical and material characteristics. When analysing combinations that involve software elements, it is important to identify and use appropriate solution characteristics.

The main problem with such combinations is ensuring the physical and geometrical compatibility of the solution principles to be combined, which in turn ensures the smooth flow of energy, material and signals, and avoids geometrical interference in mechanical systems. For information systems, the main problem is the compatibility requirements of the information flow.

A further problem is the selection of technically and economically favourable combinations of principles from the large field of theoretically possible combinations. This aspect will be discussed at greater length in Section 3.3.1.

1. Systematic Combination

For the purpose of systematic combination, the classification scheme to which Zwicky [3.77] refers as the "morphological matrix" (see Figure 3.25) is particularly useful. Here, the subfunctions, usually limited to the main functions, and appropriate solutions (solution principles) are entered in the rows of the scheme.

If this scheme is to be used for the elaboration of overall solutions, then at least one solution principle must be chosen for every subfunction (that is, for every row). To provide the overall solution, these principles (subsolutions) must then be combined systematically into an overall solution. If there are m_1 solution principles for the subfunction F_1, m_2 for the subfunction F_2, and so on, then after complete combination we have $N = m_1 \cdot m_2 \cdot m_3 \cdots m_n$ theoretically possible overall solution variants.

The main problem with this method of combination is to decide which solution principles are compatible; that is, to narrow down the theoretically possible search field to the practically possible search field.

The identification of compatible subsolutions is facilitated if:

- the subfunctions are listed in the order in which they occur in the function structure, if necessary separated according to flow of energy, material and signals
- the solution principles are suitably arranged with the help of additional column parameters, for example the types of energy
- the solution principles are not merely expressed in words but also in rough sketches

Subfunctions \ Solutions		1	2	…	j	…	m
1	F_1	S_{11}	S_{12}		S_{1j}		S_{1m}
2	F_2	S_{21}	S_{22}		S_{2j}		S_{2m}
⋮		⋮	⋮		⋮		⋮
i	F_1	S_{i1}	S_{i2}		S_{ij}		S_{im}
⋮		⋮	⋮		⋮		⋮
n	F_n	S_{n1}	S_{n2}		S_{nj}		S_{nm}

2 1 **Combinations of principles**

Figure 3.25. Combining solution principles into combinations of principles: Combination 1: $S_{11} + S_{22} + \ldots S_{n2}$; Combination 2: $S_{11} + S_{21} \ldots S_{n1}$

- the most important characteristics and properties of the solution principles are recorded as well.

The verification of compatibilities, too, is facilitated by classification schemes. If two subfunctions to be combined—for instance, "change energy" and "vary mechanical energy component"—are entered respectively in the column and row headings of a matrix with their characteristics in the appropriate cells, then the compatibility of the subsolutions can be verified more easily than it could be if such examinations were to be confined to the designer's head. Figure 3.26 illustrates this type of compatibility matrix. Further examples of this method of combination will be found in Section 6.4.2 (Figures 6.15 and 6.19).

To sum up:

- Combine only compatible subfunctions.
- Pursue only such solutions as meet the demands of the requirements list and fall within the available resources (see selection procedures in Section 3.3.1).
- Concentrate on promising combinations and establish why these should be preferred above the rest.

In conclusion, it must be emphasised that what we have been discussing is a generally valid method of combining subsolutions into overall solutions. The method can be used for the combination of working principles during the conceptual phase, and of subsolutions or even of components and assemblies during the embodiment phase. Because it is essentially a method of information processing, it

Vary mechan. energy component \ Change energy		Electric motor	Oscillating solenoid	Bimetal spiral in hot water	Oscillating hydraulic piston	...
		1	2	3	4	...
Four-bar linkage	A	if A capable of rotating	slow motion	yes	additional lever linkage but only for low piston speeds	...
Chain drive Spur gear drive	B	yes	slow rotation only through additional elements (free wheeling etc.), difficult to reverse direction	gear segments suffice, depending on angle of rotation	with a rack and swivel, but only for low piston speeds	...
Maltese drive	C	yes look out for shock loads	see B2	yes (when angle of rotation is small lever with sliding block)	lever with sliding block, but only for low piston speeds	...
Friction wheel drive	D	yes	see B2	large forces because of torque during slow movement, imprecise positioning	see D3	...
...	...	...	...	...	...	...

☒ very difficult to apply (do not pursue further)

☒ can only be applied under certain circumstances (defer)

Figure 3.26. Compatibility matrix for combination possibilities of the subfunctions "change energy" and "vary mechanical energy component". After [3.10]

is not confined to technical problems but can also be used in the development of management systems and in other fields.

2. Combining With the Help of Mathematical Methods

Mathematical methods and computers should only be used for the combination of solution principles if real advantages can be expected from them. Thus, at the relatively abstract conceptual phase, when the nature of the solution is not yet fully understood, a quantitative elaboration—that is, a mathematical combination along with an optimisation—is quite out of place and can be misleading. The exceptions are combinations of known elements and assemblies, for instance in variant or circuit design. In the case of purely logical functions, combinations can be performed with the help of Boolean algebra [3.17, 3.59] in, say, the layout of safety systems or the optimisation of electronic or hydraulic circuits.

In principle, the combination of subsolutions into overall solutions with the help of mathematical methods calls for knowledge of the characteristics or properties of the subsolutions that are expected to correspond with the relevant properties of the neighbouring subsolutions. These properties must be unambiguous and quantifiable. In the formation of principle solutions (for example working structures), data about the physical relationships may be insufficient, since the geometrical relationships may have a limiting effect and hence may, in certain circumstances, lead to incompatibilities. In that case, physical equations and geometrical structure must first be matched mathematically, and this is not generally possible except for systems of low complexity. For systems of higher complexity, in contrast, such correlations often become ambiguous, so that designers must once again choose between variants. We may, accordingly, speak of dialogue systems in which the process of combination consists of mathematical and creative steps.

This makes it clear that, with increasing physical realisation or embodiment of a solution, it becomes simpler to establish quantitative combination rules. However, the number of properties increases and with them the number of constraints and optimisation criteria, so that the mathematical effort becomes very great and requires computer support.

3.3 Selection and Evaluation Methods

3.3.1 Selecting Solution Variants

For the systematic approach, the solution field should be as wide as possible. By considering all possible classifying criteria and characteristics, designers are often led to a larger number of possible solutions. This profusion constitutes the strength and also the weakness of the systematic approach. The very great theoretically admissible, but practically unattainable, number of solutions must be reduced at the earliest possible moment. On the other hand, care must be taken not to eliminate valuable working principles, because it is often only through their combination with others that an advantageous working structure will emerge. While there is no absolutely safe procedure, the use of a systematic and verifiable selection procedure greatly facilitates the choice of promising solutions from a wealth of proposals [3.55].

This selection procedure involves two steps, namely *elimination* and *preference*.

First, all totally unsuitable proposals are eliminated. If too many possible solutions still remain, those that are patently better than the rest must be given preference. Only these solutions are evaluated at the end of the conceptual design phase.

If faced with a large number of solution proposals, the designer should compile a selection chart (see Figure 3.27). In principle, after every step—that is, even after establishing function structures—the only solution proposals pursued should:

- be compatible with the overall task and with one another (Criterion A)
- fulfil the demands of the requirements list (Criterion B)
- be realisable in respect of performance, layout, etc. (Criterion C)
- be expected to be within permissible costs (Criterion D).

Unsuitable solutions are eliminated in accordance with these four criteria applied in the above sequence. Criteria A and B are suitable for yes/no decisions and their application poses relatively few problems. Criteria C and D often need a more quantitative approach, which should only be used once Criteria A and B have been satisfied.

Since Criteria C and D involve quantitative considerations, they may lead not only to the elimination of proposed solutions that fail to meet the requirements, but also of those that exceed the requirements by an unnecessary margin.

A preference is justified if, among the very large number of possible solutions, there are some that:

- incorporate direct safety measures or introduce favourable ergonomic conditions (Criterion E)
- are preferred by the designer's company; that is, can be readily developed with the usual know-how, materials, procedures and under favourable patent conditions (Criterion F).

Additional selection criteria can be used if they help decisions to be made.

It must be stressed that selection based on preferential criteria is only advisable when there are so many variants that a full evaluation would involve too much time and effort.

If, in the suggested sequence, one criterion leads to the elimination of a proposal, then the other criteria need not be applied to it there and then. At first, only the solution variants that satisfy all of the criteria should be pursued. Sometimes, however, it is impossible to settle the issue because of lack of information. In the case of promising variants that satisfy Criteria A and B, the gap will have to be filled by a reevaluation of the proposal, which will ensure that no good solutions are passed over.

TH Darmstadt	SELECTION CHART for *Fuel gauge*	Page: *1*

Solution variants (Sv) evaluated by

SELECTION CRITERIA
- (+) Yes
- (–) No
- (?) Lack of information
- (!) Check requirements list

DECISION

Mark solution variants (Sv)
- (+) Pursue solution
- (–) Eliminate solution
- (?) Collect information (re-evaluate solution)
- (!) Check requirements list for changes

Enter solution variant (Sv):

- A: Compatibility assured
- B: Fulfils demands of requirements list
- C: Realisable in principle
- D: Within permissible costs
- E: Incorporates direct safety measures
- F: Preferred by designer's company
- G: Adequate information

Sv		A	B	C	D	E	F	G	Remarks (Indications, Reasons)	DECISION
1	1	+	+	+	?				Number of measuring positions	?
2	2	+	–						Storing the mass	–
3	3	–							Radioactivity	–
4	4	+	+	+	+		(+)		(Further development of existing solutions)	+
5	5	+	+	+	+					+
6	6	–							Fluid not conducting	–
7	7	+	+	+	+					+
8	8	+	+	+	+				see Sv 7	+
	9									
	10									
	11									
	12									
	13									
	14									
	15									
	16									
	17									
	18									
	19									
	20									

Date: *9.85* Initials: *La*

Figure 3.27. Systematic selection chart: 1, 2, 3, etc. are solution variants of the proposals made in Table 3.3. The column reserved for remarks lists reasons for lack of information or elimination

Table 3.3. Extract from a list of solutions for a fuel gauge

No.	Solution principle	Signal
	1. Measuring the quantity of fluid	
	1.1. Mechanical, static	
1.	Fix container at three points. Measure vertical forces (weight). (Measuring at one support may be sufficient)	Force
2.	Mutual attraction. The force is proportional to the masses and therefore to the fluid mass	Force
	1.2. Atomic	
3.	Distribution of radioactive material in the fluid	Concentration of radiation intensity
	2. Measuring the fluid level	
	2.1. Mechanical, static	
4.	Float with or without lever effect. Lever output: linear or angular displacement Potentiometer resistance represents fluid level within the container	Displacement
	2.2. Electrical	
5.	Resistance wire: hot in air, cold in fluid. Level of fluid determines: overall resistance, volume (dependent on temperature and length of wire)	Ohmic resistance
6.	Fluid as ohmic resistance (level-dependent). Changing the level of the (conducting) fluid changes the resistance	Ohmic resistance
	2.3. Optical	
7.	Photocells in the container. Fluid covers a certain number of photocells. The number of light signals is a measure of the fluid level	Light signal (discrete)
8.	Light transmission or light reflection. Transmission in the presence of fluid. Total reflection in presence of air	Light signal (discrete)

The criteria are listed in the order shown above as a labour-saving device, and not in order of importance.

The selection procedure has been systematised for easier implementation and verification (see Figure 3.27). Here, the criteria are applied in sequence and the reasons for eliminating any solution proposal is recorded. Experience has shown that the selection procedure we have described can be applied very quickly, that it gives a good picture of the reasons for selection, and that it provides suitable documentation in the form of a selection chart.

If the number of solution proposals is small, elimination may be based on the same criteria, but less formally recorded.

The example we have chosen concerns solution proposals for a fuel gauge in accordance with the requirements in Figure 6.4. An extract from the list of proposals is given in Table 3.3.

Further examples of selection charts can be found in Section 6.4.3 (see Figure 6.17) and Section 6.6.2 (see Figure 6.48).

3.3.2 Evaluating Solution Variants

The promising solutions that result from the selection procedure usually have to be firmed up before a final evaluation is made using criteria that are more detailed and possibly quantified. This evaluation involves an assessment of technical, safety, environmental and economic values. For this purpose, evaluation procedures have been developed that can be used to evaluate technical and nontechnical systems, and that can be applied in all phases of product development. Evaluation procedures are by their very nature more elaborate than selection procedures (see Section 3.3.1) and are therefore only applied at the end of the main working steps to determine the current value of a solution. This occurs, in general, when preparing for a fundamental decision concerning the direction of a solution path, or at the end of the conceptual and embodiment phases [3.61].

1. Basic Principles

An evaluation is meant to determine the "value", "usefulness" or "strength" of a solution with respect to a given objective. An objective is indispensable since the value of a solution is not absolute, but must be gauged in terms of certain requirements. An evaluation involves a comparison of concept variants or, in the case of a comparison with an imaginary ideal solution, a "rating" or degree of approximation to that ideal.

The evaluation should not be based on individual aspects such as production cost, safety, ergonomics or environment, but should, in accordance with the overall aim (see Section 2.1.7), consider all aspects in an appropriate balance.

Hence there is a need for methods that allow a more comprehensive evaluation, or in other words cover a broad spectrum of objectives (task-specific requirements and general constraints). These methods are intended to elaborate not only the quantitative but also the qualitative properties of the variants, thus making it possible to apply them during the conceptual phase, with its low level of embodiment and correspondingly low state of information. The results must be reliable, cost-effective, easily understood and reproducible. The most important methods to date are Cost–Benefit Analysis based on the systems approach [3.76], and the combined technical and economic evaluation technique specified in Guideline VDI 2225 [3.71], which essentially originates from Kesselring [3.36].

In what follows, we shall outline a basic evaluation procedure incorporating the concepts of Cost–Benefit Analysis and of Guideline VDI 2225. At the end the similarities and differences between both methods will be discussed.

Identifying Evaluation Criteria

The first step in any evaluation is the drawing up of a set of objectives from which evaluation criteria can be derived. In the technical field, such objectives are mainly derived from the requirements list and from general constraints (see guidelines in Section 2.1.7), which are identified while working on a particular solution.

A set of objectives usually comprises several elements that not only introduce a variety of technical, economic and safety factors, but that also differ greatly in importance.

A range of objectives should satisfy as far as possible the following conditions:

- The objectives must cover the decision-relevant requirements and general constraints as completely as possible, so that no essential criteria are ignored.

- The individual objectives on which the evaluation must be based should be as independent of one another as possible; that is, provisions to increase the value of one variant with respect to one objective must not influence its values with respect to the other objectives.
- The properties of the system to be evaluated must, if possible, be expressed in concrete quantitative or at least qualitative (verbal) terms.

The tabulation of such objectives depends very much on the purpose of the particular evaluation, that is, on the design phase and the relative novelty of the product.

Evaluation criteria can be derived directly from the objectives. Because of the subsequent assignment of values, all criteria must be given a positive formulation, i.e. such that a higher value indicates better, for example:

- "low noise" not "loudness level"
- "high efficiency" not "magnitude of losses"
- "low maintenance" not "maintenance requirements".

Cost–Benefit Analysis systematises this step by means of an objectives tree, in which the individual objectives are arranged in hierarchical order. The subobjectives are arranged vertically into levels of decreasing complexity, and horizontally into objective areas—for instance, technical, economic—or even into major and minor objectives (see Figure 3.28). Because of their required independence, subobjectives of a higher level may only be connected with an objective of the next lowest level. This hierarchical order helps the designer to determine whether or not all decision-relevant subobjectives have been covered. Moreover, it simplifies the assessment of the relative importance of the subobjectives. The evaluation criteria (called objective criteria in Cost–Benefit Analysis) can then be derived from the subobjectives of the stage with the lowest complexity.

Guideline VDI 2225, on the contrary, introduces no hierarchical order for the evaluation criteria, but derives a list of them from minimum demands and wishes and also from general technical properties.

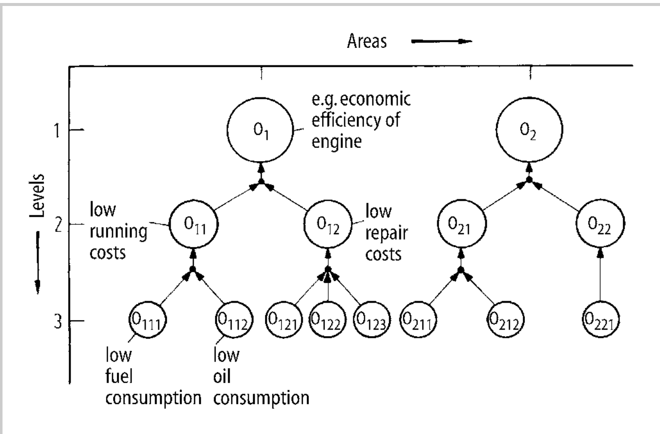


Figure 3.28. Structure of an objectives tree

Weighting Evaluation Criteria

To establish evaluation criteria, we must first assess their relative contribution (weighting) to the overall value of the solution, so that relatively unimportant criteria can be eliminated before the evaluation proper begins. The evaluation criteria retained are given "weighting factors" which must be taken into consideration during the subsequent evaluation step. A weighting factor is a real, positive number. It indicates the relative importance of a particular evaluation criterion (objective).

It has been suggested that such weightings should be assigned to the wishes when they are recorded in the requirements list [3.62, 3.63], but that is only possible if such wishes can be ranked in order of importance when the requirements list is first drawn up. That, however, rarely happens at this early stage—experience has shown that many evaluation criteria emerge during the development of the solution, and that their relative importance changes. It is nevertheless most helpful to include rough estimates of the importance of wishes when drawing up the requirements list, because, as a rule, all the persons concerned are available at that time (see Section 5.2.2).

In Cost–Benefit Analysis, weightings are based on factors ranging from 0 to 1 (or from 0 to 100). The sum of the factors of all evaluation criteria (subobjectives at the lowest level) must be equal to 1 (or 100) so that a percentage weighting can be attached to all of the subobjectives. The drawing up of an objectives tree greatly facilitates this process.

Figure 3.29 illustrates the procedure. Here the objectives have been set out on four levels of decreasing complexity and provided with weighting factors. The evaluation proceeds step-by-step from a level of higher complexity to the next lowest level. Thus the three subobjectives O_{11}, O_{12} and O_{13} of the second level are first weighted with respect to the objective O_1. In this particular case the

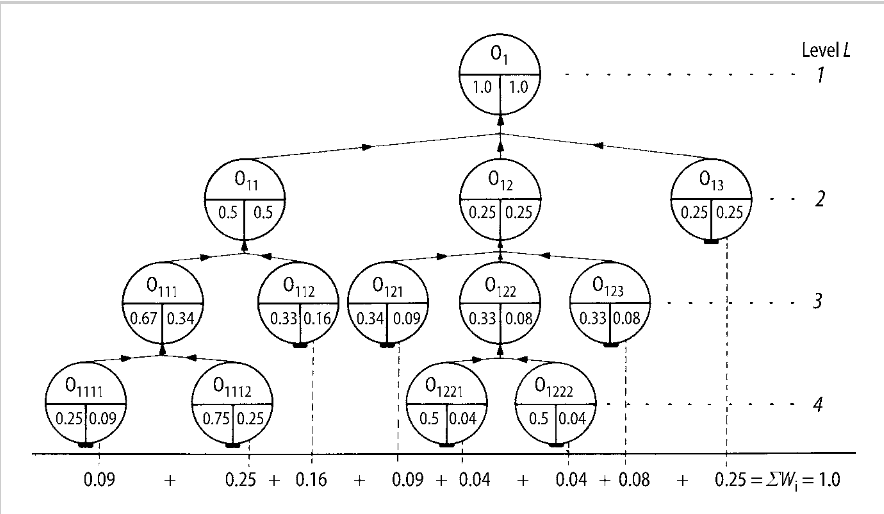


Figure 3.29. Objectives tree with weighting factors. After [3.76]

weightings are 0.5, 0.25 and 0.25. The sum of the weighting factors for any one level must always be equal to $\sum w_i = 1.0$. Next comes the weighting of the objectives of the third level with respect to the subobjectives of the second level. Thus the relative weights of O_{111} and O_{112} with respect to the higher objectives O_{11} were fixed at 0.67 and 0.33. The remaining objectives are treated in similar fashion. The relative weighting of an objective at a particular level with respect to the objective O_1 is found by multiplication of the weighting factor of the given objective level by the weighting factors of the higher objective levels. Thus the subobjective O_{1111}, which has a weighting of 0.25 with respect to the subobjective O_{111} of the next higher level, has a weighting of $0.25 \times 0.67 \times 0.5 \times 1 = 0.09$ with respect to O_1.

Such step-by-step weighting generally produces a realistic ranking because it is much easier to weight two or three subobjectives with respect to an objective on a higher level than to confine the weighting to one particular level only, especially the lowest. Figure 6.33 gives a concrete example of the recommended procedure.

Guideline VDI 2225 tries to dispense with weightings and relies instead on evaluation criteria of approximately equal importance. Weighting factors ($2\times, 3\times$) are, however, used for pronounced differences. Kesselring [3.36], Lowka [3.50] and Stahl [3.68] have examined the influences of such weighting factors on the overall value of the solution. Their conclusion was that they exert a significant influence whenever the variants to be evaluated have very distinct properties, and whenever the corresponding evaluation criteria have great importance.

Compiling Parameters

The setting up of evaluation criteria and the determination of their importance is followed, in the next step, by the assignment to them of known (or analytically determined) parameters. These parameters should either be quantifiable or, if that is impossible, be expressed by statements framed as concretely as possible. It has proved very useful to assign such parameters to the evaluation criteria in an evaluation chart before proceeding to the actual evaluation. Figure 3.30 shows an example of such a chart for an internal combustion engine, with appropriate magnitudes entered in the relevant variant columns. The reader will see that the verbal formulation of the evaluation criteria strongly resembles that of the parameters.

In Cost–Benefit Analysis these parameters are referred to as objective parameters (objective criteria) that are compiled with evaluation criteria in a chart. A concrete example is given in Figure 6.55.

In Guideline VDI 2225, in contrast, evaluation follows immediately upon the setting up of evaluation criteria (see Figure 6.41).

Assessing Values

The next step is the assessment of values and hence the actual evaluation. These "values" derive from a consideration of the relative scale of the previously determined parameters, and are thus more or less subjective in character.

The values are expressed by points. Cost–Benefit Analysis employs a range from 0 to 10; Guideline VDI 2225 a range from 0 to 4 (see Figure 3.31). The advantage of the wider range is that, as experience has shown, classification and evaluation

Evaluation criteria			Objective Parameters		Variant V_1 (e.g. Eng.$_1$)			Variant V_2 (e.g. Eng.$_2$)			…	Variant V_j			…	Variant V_m		
No.		Wt.		Unit	Magn. m_{i1}	Value v_{i1}	Weighted value WV_{i1}	Magn. m_{i2}	Value v_{i2}	Weighted value WV_{i2}		Magn. m_{ij}	Value v_{ij}	Weighted value WV_{ij}		Magn. m_{im}	Value v_{im}	Weighted value WV_{im}
1	Low fuel consumption	0.3	Fuel consumption	$\frac{g}{kWh}$	240			300			…	m_{1j}			…	m_{1m}		
2	Light weight construction	0.15	Mass per unit power	$\frac{kg}{kW}$	1.7			2.7			…	m_{2j}			…	m_{2m}		
3	Simple production	0.1	Simplicity of components	–	low			average			…	m_{3j}			…	m_{3m}		
4	Long service life	0.2	Service life	km	80 000			150 000			…	m_{4j}			…	$m4_m$		
⋮	⋮	⋮	⋮	⋮	⋮			⋮				⋮				⋮		
i		W_i			m_{i1}			m_{i2}			…	m_{ij}			…	m_{im}		
⋮	⋮	⋮	⋮	⋮	⋮			⋮				⋮				⋮		
n		W_n			m_{n1}			m_{n2}			…	m_{nj}			…	m_{nm}		
		$\sum_{i=1}^{n} W_i = 1$																

Figure 3.30. Correlation of evaluation criteria and parameters in an evaluation chart

are greatly facilitated by the use of a decimal system that reflects percentages. The advantage of the smaller range is that, in dealing with what are so often no more than inadequately known characteristics of the variants, rough evaluations are sufficient and, indeed, may be the only meaningful approach. They involve the following assessments:

- far below average
- below average
- average
- above average
- far above average.

It is useful to begin with a search for variants with extremely good and bad qualities for a particular criterion and to assign appropriate points to them. Points 0 and 4 (or 10) should only be awarded if the characteristics are really extreme, that is, unsatisfactory or very good (ideal). Once these extreme points have been assigned, the remaining variants are relatively easy to fit in.

Before points can be assigned to the parameters of the variants, the evaluator must at least be clear about the assessment range and the shape of the so-called "value function" (see Figure 3.32). A value function connects values and parameter

<table>
<tr><th colspan="4">Value scale</th></tr>
<tr><th colspan="2">Use-value analysis</th><th colspan="2">Guideline VDI 2225</th></tr>
<tr><th>Pts.</th><th>Meaning</th><th>Pts.</th><th>Meaning</th></tr>
<tr><td>0</td><td>absolutely useless solution</td><td rowspan="2">0</td><td rowspan="2">unsatisfactory</td></tr>
<tr><td>1</td><td>very inadequate solution</td></tr>
<tr><td>2</td><td>weak solution</td><td rowspan="2">1</td><td rowspan="2">just tolerable</td></tr>
<tr><td>3</td><td>tolerable solution</td></tr>
<tr><td>4</td><td>adequate solution</td><td rowspan="2">2</td><td rowspan="2">adequate</td></tr>
<tr><td>5</td><td>satisfactory solution</td></tr>
<tr><td>6</td><td>good solution with few drawbacks</td><td rowspan="2">3</td><td rowspan="2">good</td></tr>
<tr><td>7</td><td>good solution</td></tr>
<tr><td>8</td><td>very good solution</td><td rowspan="3">4</td><td rowspan="3">very good (ideal)</td></tr>
<tr><td>9</td><td>solution exceeding the requirement</td></tr>
<tr><td>10</td><td>ideal solution</td></tr>
</table>

Figure 3.31. Points awarded in use-value analysis and guideline VDI 2225

magnitudes, and its characteristic shape is determined either with the help of the known mathematical relationship between the value and the parameter or, more frequently, by means of estimates [3.28].

It is useful to draw up a chart in which the parameter magnitudes are correlated step-by-step with the value scale. Figure 3.33 shows such a scheme, incorporating the point systems of Cost–Benefit Analysis and VDI 2225.

All in all, therefore, the assignment of a value, the selection of a value function and the setting up of an assessment scheme may involve strong subjective influences. Cases with a clear, or even experimentally verified, correlation between the values and the parameters are few and far between. One such exception is the evaluation of machine noise, where the correlation between the value (that is, the protection of the human ear) and the parameter (noise level in dB) is clearly defined by ergonomics.

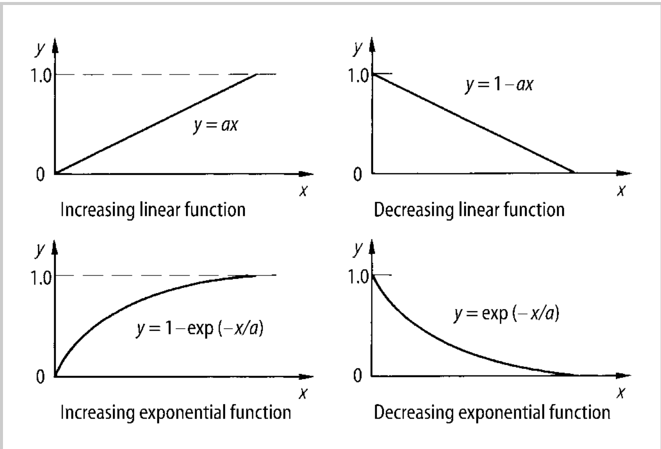


Figure 3.32. Common value functions, after [3.76]; $x \mathrel{\hat{=}} m_{ij}, y \mathrel{\hat{=}} v_{ij}$

Value Scale		Parameter magnitudes			
Use-value analysis Pts	VDI 2225 Pts	Fuel consumption g/kWh	Mass per unit power kg/kW	Simplicity of components	Service life
0	0	400	3.5	extremely complicated	$20 \cdot 10^3$
1		380	3.3		30
2	1	360	3.1	complicated	40
3		340	2.9		60
4	2	320	2.7	average	80
5		300	2.5		100
6	3	280	2.3	simple	120
7		260	2.1		140
8	4	240	1.9	extremely simple	200
9		220	1.7		300
10		200	1.5		$500 \cdot 10^3$

Figure 3.33. Chart correlating parameter magnitudes with value scales

Evaluation criteria			Parameters		Variant V_1 (e.g. *Eng.*$_1$)			Variant V_2 (e.g. *Eng.*$_2$)			…	Variant V_j			…	Variant V_m		
No.		Wt.		Unit	Magn. m_{i1}	Value v_{i1}	Weighted value WV_{i1}	Magn. m_{i2}	Value v_{ij}	Weighted value WV_{ij}		Magn. m_{ij}	Value v_{ij}	Weighted value WV_{ij}		Magn. m_{im}	Value V_{im}	Weighted value WV_{im}
1	Low fuel consumption	0.3	Fuel consumption	$\frac{g}{kWh}$	240	8	2.4	300	5	1,5	…	m_{1j}	V_{1j}	WV_{1j}	…	m_{1m}	V_{1m}	WV_{1m}
2	Lightweight construction	0.15	Mass per unit power	$\frac{kg}{kW}$	1.7	9	1.35	2.7	4	0,6	…	m_{2j}	V_{2j}	WV_{2j}	…	m_{2m}	V_{2m}	WV_{2m}
3	Simple production	0.1	Simplicity of components	-	compli-cated	2	0.2	average	5	0,5	…	m_{3j}	V_{3j}	WV_{3j}	…	m_{3m}	V_{3m}	WV_{3m}
4	Long service life	0.2	Service life	km	80 000	4	0.8	150 000	7	1,4	…	m_{4j}	V_{4j}	WV_{4j}	…	$m4_m$	V_{4m}	WV_{4m}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮		⋮	⋮	⋮
i		W_i			m_{i1}	V_{i1}	WV_{i1}	m_{i2}	V_{i2}	WV_{i2}	…	m_{ij}	V_{ij}	WV_{ij}	…	m_{im}	V_{im}	WV_{im}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮		⋮	⋮	⋮
n		W_n			m_{n1}	V_{n1}	WV_{n1}	m_{n2}	V_{n2}	WV_{n2}	…	m_{nj}	V_{nj}	WV_{nj}	…	m_{nm}	V_{nm}	WV_{nm}
		$\sum_{i=1}^{n} W_i = 1$				OV_1 R_1	OWV_1 WR_1		OV_2 R_2	OWV_2 WR_2			OV_j R_j	OWV_j WR_j			OV_m R_m	OWV_m WR_m

Figure 3.34. Completed evaluation chart with values (see Figure 3.30)

The values v_{ij} of every solution variant established in respect to every evaluation criterion are added to the list shown in Figure 3.30 in order to produce Figure 3.34.

Whenever the evaluation criteria have a different importance to the overall value of a solution, the weighting factors determined during the second step must also be taken into consideration. To that end, subvalue v_{ij} is multiplied by the weighting factor w_i ($wv_{ij} = w_i \cdot v_{ij}$). Figure 6.55 gives a practical example. The Cost–Benefit Analysis refers to the unweighted values as objective values and the weighted ones as benefit values.

Determining Overall Value

When the subvalues for every variant have been determined, the overall value must now be calculated.

In the evaluation of technical products, the summation of subvalues has become the usual method of calculation but can only be considered accurate if the evaluation criteria are independent. However, even when this condition is only satisfied approximately, the assumption that the overall value has an additive structure seems to be justified.

The overall value of a variant j can then be determined as follows:

$$\text{Unweighted: } OV_j = \sum_{i=1}^{n} v_{ij}$$

$$\text{Weighted: } OWV_j = \sum_{i=1}^{n} w_i \cdot v_{ij} = \sum_{i=1}^{n} wv_{ij}$$

Comparing Concept Variants

On the basis of the summation rule it is possible to assess variants in several ways.

Determining the maximum overall value: In this procedure the variant is judged to be the best if it has the largest overall value:

$$OV_j \rightarrow \max \quad \text{or} \quad OWV_j \rightarrow \max$$

What we have here is a relative comparison of the variants. This fact is made use of in Cost–Benefit Analysis.

Determining the rating: If a relative comparison of the variants is considered to be insufficient and the absolute rating of a variant has to be established, then the overall value must be referred to an imaginary ideal value which results from the maximum possible value as follows:

$$\text{Unweighted: } R_j = \frac{OV_j}{v_{\max} \cdot n} = \frac{\sum_{i=1}^{n} v_{ij}}{v_{\max} \cdot n}$$

$$\text{Weighted: } WR_j = \frac{OWV_j}{v_{\max} \cdot \sum_{i=1}^{n} w_i} = \frac{\sum_{i=1}^{n} w_i \cdot v_{ij}}{v_{\max} \cdot \sum_{i=1}^{n} w_i}$$

If the available information about all the concept variants allows cost estimates, then it is advisable to proceed to a separate determination of the *technical rating* R_t and the *economic rating* R_e. The technical rating is calculated in accordance with the rule we have given—that is, by division of the technical overall value of the given variant by the ideal value—and the economic rating is calculated similarly, but by reference to comparative costs. The latter procedure is suggested in VDI 2225, which relates the manufacturing costs determined for a variant to the comparative manufacturing costs C_o. In that case, the economic rating becomes $R_e = (C_o/C_{variant})$. It is possible to put, say, $C_o = 0.7 \times C_{admissible}$ or $C_o = 0.7 \times C_{minimum}$ for the cheapest variant. If the technical and economic ratings have been determined separately, then the determination of the "overall rating" of a particular variant may prove interesting. For that purpose, Guideline VDI 2225 suggests a so-called s-diagram (strength diagram) with the technical rating R_t as the abscissa and the economic rating R_e as the ordinate (see Figure 3.35). Such diagrams are particularly useful in the appraisal of variants during further developments, because they show up the effects of design decisions very clearly.

In some cases it is useful to derive the overall rating from these partial ratings and to express it in numerical form, for instance for computer processing. To that end, Baatz [3.1] has proposed two procedures, namely:

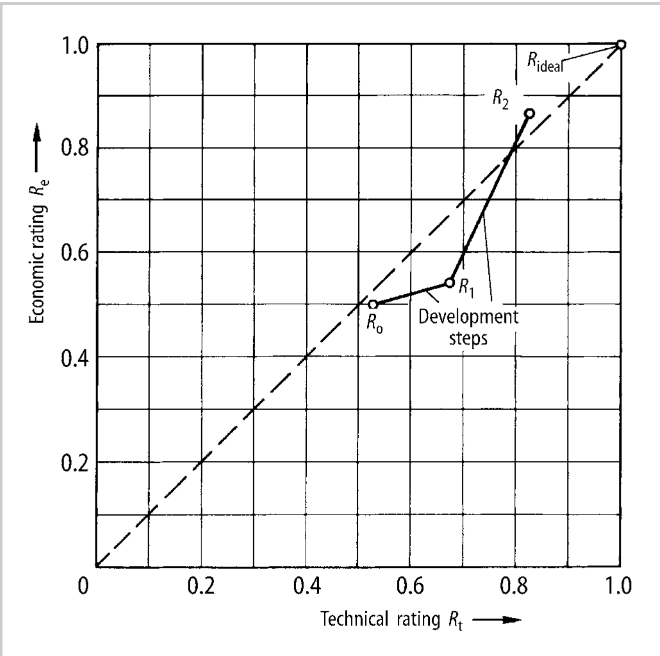


Figure 3.35. Rating diagram. After [3.36, 3.71]

- the straight-line method, based on the arithmetic mean:

$$R = \frac{R_t + R_e}{2} \tag{3.5}$$

  and

- the hyperbolic method, which involves multiplying both ratings and then reducing to values between 0 and 1:

$$R = \sqrt{R_t \times R_e} \tag{3.6}$$

  The two methods have been combined in Figure 3.36.

Where there are large differences between the technical and economic ratings, the straight-line method might compute a higher overall rating than is the case with lower but balanced partial ratings. Because balanced solutions should be preferred, however, the hyperbolic method is the better of the two; it helps to balance large differences in rating by its progressive reduction effect. The greater the imbalance, the greater the reduction effect on the overall value.

Rough comparison of solution variants: The method we have described relies on differentiated value scales. It is useful whenever the "objective" parameters can be stated with some accuracy and whenever clear values can be assigned to

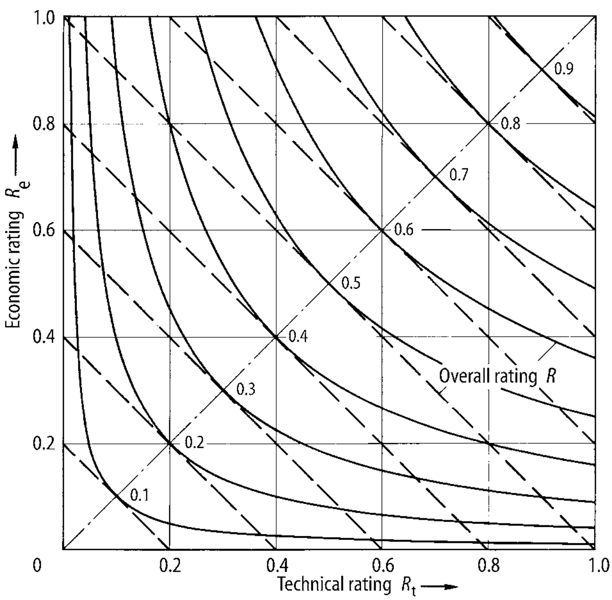


Figure 3.36. Determining the overall rating by the straight-line and hyperbolic methods. After [3.1]

In comparison with Variant	Variant 1	2	3	4	5	6	7
1	-	1	0	1	0	1	0
2	0	-	0	1	0	0	0
3	1	1	-	1	0	1	0
4	0	0	0	-	0	0	0
5	1	1	1	1	-	1	1
6	0	1	0	1	0	-	0
7	1	1	1	1	0	1	-
Sum	3	5	2	6	0	4	1
Rank	4	2	5	1	7	3	6

1 ≙ better   0 ≙ not better

Figure 3.37. Binary evaluation of solution variants. After [3.15]

them. If these conditions cannot be satisfied, relatively fine evaluations based on a differentiated value scale constitute a questionable and expensive method. The alternative here is a rough evaluation involving the application of a particular evaluation criterion to two variants at a time and the selection of the best in each case. The results are entered into a so-called *dominance matrix* [3.15] (see Figure 3.37). From the sum of the columns it is possible to establish a ranking order. If such matrices of individual criteria are combined into an overall matrix, an overall ranking order can be established, either by addition of the preference frequencies or by addition of all the column sums. While this method is comparatively easy and quick, it is not nearly as informative as the other procedures we have discussed.

Estimating Evaluation Uncertainties

The possible errors or uncertainties of the proposed evaluation methods fall into two main groups, namely subjective errors and procedure-inherent shortcomings.

Subjective errors can arise through:

- Abandonment of the neutral position, that is, through bias and partiality. The bias may be hidden from designers, for instance when they compare their own designs with those of others. Hence an evaluation by several persons, if possible from various departments, is always advisable. It is equally important to refer to the different variants in neutral terms, for instance as A, B, C rather than as "Smith's Proposal", etc., since otherwise unnecessary identifications and emotional overtones may be introduced. Systematisation of the procedure also helps to reduce subjective influences.

- Comparison of variants by application of (the same) evaluation criteria not equally suited to all the variants. Such mistakes arise even during the determination of the parameters and their association with the evaluation criteria. If it is impossible to determine the parameter magnitudes of individual variants for certain evaluation criteria, then these criteria must be reformulated or dropped in case they lead to mistaken evaluations of the individual variants.
- Evaluation of variants in isolation instead of successively by application of the established evaluation criteria. Each criterion must be applied to all the variants in turn (row-by-row in the evaluation chart) to eliminate any bias in favour of a particular variant.
- Pronounced interdependence of the evaluation criteria.
- Choice of unsuitable value functions.
- Incompleteness of evaluation criteria. This defect can be minimised if one of the checklists for design evaluation appropriate to the relevant design phase is followed (see Figures 6.22 and 7.148).

Procedure-inherent shortcomings of the recommended evaluation methods are the result of the almost inevitable "prognostic uncertainty" arising from the fact that the predicted parameter magnitudes and also the values are not precise, but subject to uncertainty and to random variation. These mistakes can be greatly reduced by estimates of the mean error.

With regard to prognostic uncertainty, it is therefore advisable not to express the parameters in figures unless this can be done with some accuracy. It is preferable to use verbal estimates (for instance high, average, low) which do not claim to be precise. Numerical values, by contrast, are dangerous because they introduce a false sense of certainty.

Uncertainties in the evaluation are not only caused by prognostic uncertainty, but also through uncertainties in the formulation of requirements and solution descriptions. To be able to process such vague information in a quantitative way, fuzzy logic, and its extension into fuzzy-MADM (multi-attribute decision making), can be used [3.49]. These procedures use so-called fuzzy sets to describe these imprecise numbers and ranges and calculate their combined averages. The result is a fuzzy overall value for every solution variant.

A more detailed analysis of evaluation procedures for the purpose of judging their reliability and also for comparative purposes has been carried out by Feldmann [3.15] and Stabe [3.67]. The latter also provides an extensive bibliography. If there is an adequate number of evaluation criteria, and if the subvalues of a particular variant are fairly balanced, then the overall value will be subject to a balancing statistical effect, and partly too optimistic and partly too pessimistic individual values will more or less balance out.

Searching for Weak Spots

Weak spots can be identified from below average values for individual evaluation criteria. Careful attention must be paid to them, particularly in the case of promising variants with good overall values, and they ought if possible to be eliminated during further development. The identification of weak spots may be facilitated by graphs of the subvalues—for instance, by the so-called value profiles illustrated in Figure 3.38. In it, the lengths of the bars correspond to the values and the thicknesses to the weightings. The areas of the bars then indicate the weighted subvalues, and the cross-hatched area the overall weighted value of a solution variant. It is clear that, in order to improve a solution, it is essential to improve those subvalues that provide a greater contribution to the overall value than the rest. This is the case with the evaluation criteria that have an above average bar thickness (great importance) but a below average bar length. Apart from a high overall value, it is important to obtain a balanced value profile, with no serious weak spots. Thus, in Figure 3.38, variant 2 is better than variant 1, although both have the same overall weighted value.

There are also cases in which a minimum permissible value is stipulated for all sub-values; that is, any variant that does not fulfil this condition has to be rejected, and all variants that do fulfil it are developed further. In the literature this procedure is described as the "determination of satisfactory solutions" [3.76].

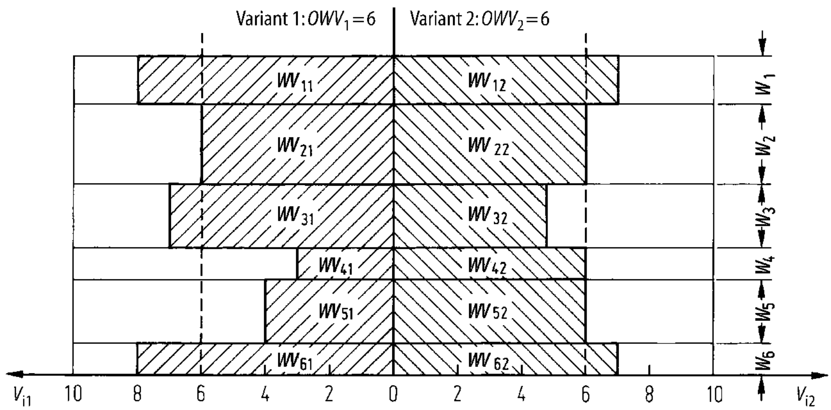


Figure 3.38. Value profiles for the comparison of two variants ($\sum w_i = 1$)

2. Comparison of Evaluation Procedures

Table 3.4 lists the individual steps in the evaluation procedures we have described and also the similarities and differences between Cost–Benefit Analysis and Guideline VDI 2225, which are based on similar principles.

Table 3.4. Individual steps in evaluation, and comparison between use-value analysis and Guideline VDI 2225

Step		Cost–Benefit Analysis	VDI Guideline 2225
1	*Identification of objectives* or *evaluation criteria* for the evaluation of concept variants with the aid of the requirements list and a checklist	Construction of a hierarchically related system of design objectives (objectives tree) based on the requirements list and other general requirements	Compilation of important technical characteristics and also of the minimum demands and wishes of the requirements list
2	*Analysis of the evaluation criteria* for the purpose of determining their *weighting* to the overall value of the solution. If necessary, determination of weighting factors	Step-by-step weighting of the objective criteria (evaluation criteria) and if necessary elimination of unimportant criteria	Determination of weighting factors only if evaluation criteria differ markedly in importance
3	*Compilation of parameters* applicable to the concept variants	Construction of an objective parameter matrix	Not generally included
4	*Assessment of the parameter magnitudes* and assignment of values (0–10 or 0–4 points)	Construction of objective value matrix, with the help of a points system or value functions; 0–10 points	Assessment of characteristics by points (0–4 points)
5	*Determination of the overall value* of the individual concept variants, generally by reference to an ideal solution (rating)	Construction of a use-value matrix with due regard to the weightings; determination of overall values by summation	Determination of a technical rating by summation, with or without weightings based on an ideal solution. If necessary determination of an economic rating based on manufacturing costs
6	*Comparison of concept variants*	Comparison of overall use-values	Comparison of the technical and economic ratings. Construction of an s-(strength) diagram
7	*Estimation of evaluation uncertainties*	Estimation of objective parameter scatter and use–value distribution	Not explicitly included
8	*Search for weak spots* for the purpose of improving selected variants	Construction of use-value profiles	Identification of characteristics with a few points only

The individual steps of Cost–Benefit Analysis are more highly differentiated and more clear-cut but involve more work than those of Guideline VDI 2225. The latter is more suitable when there are relatively few and roughly equivalent evaluation criteria, which is frequently the case during the conceptual phase, and also for the evaluation of certain form design areas during the embodiment phase.

The essence of evaluation procedures has been described on the basis of existing evaluation methods. However, these methods have been consolidated and the terms clarified. Specific suggestions for the use of these methods during the conceptual phase are given in Section 6.5.2, and during the embodiment phase in Section 7.6.

4 Product Development Process

In the previous chapters we examined the fundamentals on which design work should be built to best advantage. They form the basis of a systematic approach which practising designers can follow, regardless of their speciality. The approach is not based on one method but applies known and less well known methods where they are most suitable and useful for specific tasks and working steps.

4.1 General Problem Solving Process

An essential part of our own problem solving method involves step-by-step *analysis* and *synthesis*. In it we proceed from the *qualitative* to the *quantitative*, each new step being more concrete than the last.

In the following sections we propose plans and procedures that should be regarded as mandatory for the general problem solving process of planning and designing technical products, and as guidance for the more concrete phases of the design process. These plans and procedures assist in identifying what, in principle, has to be done, but of course they must be adapted to specific problem situations.

All procedural plans proposed in this book have to be considered as *operational guidelines for action* based on the pattern of technical product development and the logic of stepwise problem solving. According to Müller [4.17], they are process models that are suitable for describing in a rational way the approach necessary to make complex processes comprehensible and transparent.

Thus, these procedural plans are not descriptions of *individual thinking processes* as described in Section 2.2.1, and are not determined by personal characteristics. In a practical application of these procedural plans, the operational guidelines for action blend with individual thinking processes. This results in a set of individual planning, acting and controlling activities based on general procedures, specific problem situations and individual experiences.

As discussed in Section 2.2.1, the suggested procedural plans are meant to be guidelines and not rigid prescriptions. However, they have to be regarded as essentially sequential because, for example, a solution cannot be evaluated before it has been found or elaborated. On the other hand, the procedural plans have to be adapted to specific situations in a flexible manner. It is, for example, possible to leave out certain steps or order them in another sequence. It may be necessary or useful to repeat certain steps at a higher information level. Furthermore, special procedures (adapted from the more general plans proposed here) may be appropriate in specific product domains.

Given the complexity of the product development process and the many methods that have to be applied, not adopting a procedural plan would leave designers with an unmanageable number of possible approaches. It is therefore necessary for designers to learn about the design process and the application of individual methods, as well as the working and decision making steps proposed in the procedural plans.

The activity of planning and designing was described in Section 2.2.3 as information processing. After each information output, it might become necessary to improve or increase the value of the result of the last working step. That is, to repeat the working step at a higher information level, or to execute other working steps until the necessary improvements have been achieved.

Repeating working steps is the process of *iteration* by which one approaches a solution step-by-step until the result seems satisfactory. The so-called iteration loop can also be observed in the basic thinking processes, for example in the TOTE model (see Section 2.2.1). Such iteration loops are almost always required and occur continuously within and between steps. The reasons for this are that the interrelationships are often so complex that the desired solution cannot be achieved in one step and that information is frequently needed from a subsequent step. The iteration arrows in procedural plans clearly indicate this fact. In subsequent chapters, strategies for reducing, or even avoiding, such iteration loops are presented. It is therefore important that the procedural plans proposed are not considered rigid and purely sequential.

A systematic approach aims to keep the iteration loops as small as possible in order to make design work effective and efficient. It would be a disaster, for example, if the design team had to start again at the beginning having reached the end of a product development. This would correspond to an iteration loop covering the whole of the product development process.

The division in working and decision making steps ensures necessary and permanent links between *objectives*, *planning*, *execution* (organisation) and *control* [4.3, 4.29]. With these links, we can, following Krick [4.15] and Penny [4.21], construct a basic scheme for the general problem solving process (see Figure 4.1).

Every task involves an initial *confrontation* of the problem, which involves elucidating what is known or not (yet) known. The intensity of this confrontation depends on the knowledge, ability and experience of the designers, and on the particular field in which they are engaged. In all cases, however, more detailed *information* about the task itself, about the constraints, about possible solution principles and about known solutions for similar problems is extremely useful since it clarifies the precise nature of the requirements. This information can also reduce confrontation and increase confidence that solutions can be found.

Next comes the *definition* phase, where the essential problems (the crux of the task) are defined on a more abstract plane, in order to set the objectives and main constraints. Such solution-neutral definitions open the way to an unconstrained

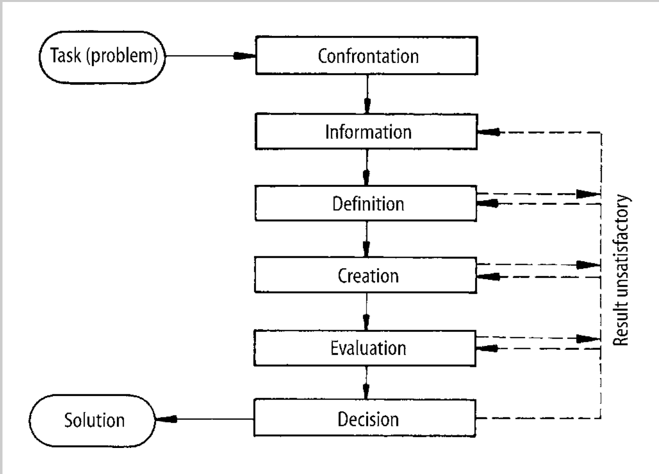


Figure 4.1. General problem solving process

search for solutions because this abstract definition encourages a search for more unconventional solutions.

The next step is *creation*, where solutions are developed by various means and then varied and combined using methodical guidelines. If the number of variants is large, there must also be an *evaluation* which is then used to select the best variant through a *decision*. Because each step of the design process must be evaluated, evaluation serves as a check on progress towards the overall objective.

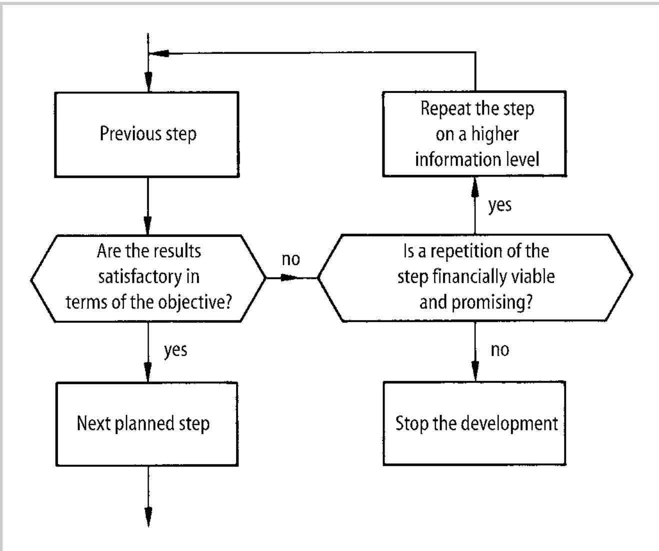


Figure 4.2. General decision making process

Decisions involve the following considerations (see Figure 4.2):

- If the result from the previous step meets the objective, the next step can be started.
- If the results are incompatible with the objective, the next step should not be taken.
- If resources permit repetition of the previous step (or if necessary several preceding steps), and good results can be expected, the step must be repeated on a higher information level.
- If the answer to the previous question is no, the development must be stopped.

Even if the results of a particular step do not meet the objectives, they might nevertheless prove interesting if the objectives are wholly or partly changed. In this case, there should be an investigation to see whether the objectives can be changed or if the results can be used for other applications. This whole process, leading from confrontation through creation to decision, must be repeated in each successive, increasingly concrete, phase of the design process.

4.2 Flow of Work During the Process of Designing

Today's conditions for product design and development demand careful planning of:

- the required activities for the proposed project
- the timing and scheduling of these activities
- the project and product costs.

The activities and their durations strongly depend on the type of task, in particular whether the task is for an original, adaptive or variant design.

4.2.1 Activity Planning

The flow of work during the process of designing has been described in both general terms as well as domain and product-specific terms in VDI Guidelines 2221 and 2222 [4.24, 4.25] (see Figure 1.9). In line with these guidelines, the next sections provide an extensive description of this flow of work, focused on mechanical engineering. The description is essentially based on the fundamentals of technical systems (see Section 2.1), the fundamentals of the systematic approach (see Section 2.2), and the general problem solving process (see Section 4.1). The aim is to adapt the general statements to the requirements of the mechanical engineering design process and to incorporate the specific working and decision making steps for this domain. In principle, the planning and design process proceeds from the planning and clarification of the task, through the identification of the required functions, the elaboration of principle solutions, the construction of modular structures, to the final documentation of the complete product [4.18].

In addition to the planning of the specific tasks described in the guidelines mentioned above, it is useful and common to divide the planning and design process into the following *main phases*:

- Planning and task clarification: specification of information
- Conceptual design: specification of principle solution (concept)
- Embodiment design: specification of layout (construction)
- Detail design: specification of production.

As we will see later on, it is not always possible to draw a clear borderline between these main phases. For example, aspects of the layout might have to be addressed during conceptual design, or it might be necessary to determine some production processes in detail during the embodiment phase. Neither is it possible to avoid backtracking, for example during embodiment design when new auxiliary functions may be discovered for which principle solutions have to be found. Nevertheless, the division of the planning and control of a development process into main phases is always helpful.

The working steps proposed for each of the main phases are termed the *main working steps* (see Figure 4.3). The results of these main working steps provide the basis for the subsequent working steps. Many lower level working steps are required to realise these results, such as collecting information, searching for solutions, calculating, drawing and evaluating. Each of these working steps is accompanied by indirect activities such as discussing, classifying and preparing. The *operational main working steps* listed in the procedural plans proposed in this chapter are considered to be the most useful strategic guidelines for a technical domain. Guidelines that are not listed include, for example, those related to basic problem solving, collecting information and verifying results. This is because they can usually only be recommended in relation to a specific problem and a particular designer. Recommendations for such elementary working steps will, where possible, be given in the sections describing individual methods and those dealing with practical applications.

After the main phases, and some of the more important main working steps, *decision making steps* are required. The decision making steps listed are the main ones—those that end a main phase or working step, which after an appropriate assessment of the results, allow the main flow of work to proceed. It is also possible, because the result of a decision making step was unsatisfactory, that certain steps will have to be repeated. The smallest possible iteration loop is desirable.

Again, the individual test and decision making steps (see for example the TOTE model in Section 2.2.1) that are required for every single action have not been listed separately. This would have been impossible because such decisions are determined by the approach of individual designers and by particular problem situations.

The decision to stop a development that ceases to be viable, as discussed in Section 4.1, is not mentioned explicitly in the individual decision making steps of the procedural plans. One should, however, always explicitly consider this possibility because an early and clear decision to halt a hopeless situation will, in the end, minimise disappointment and cost.

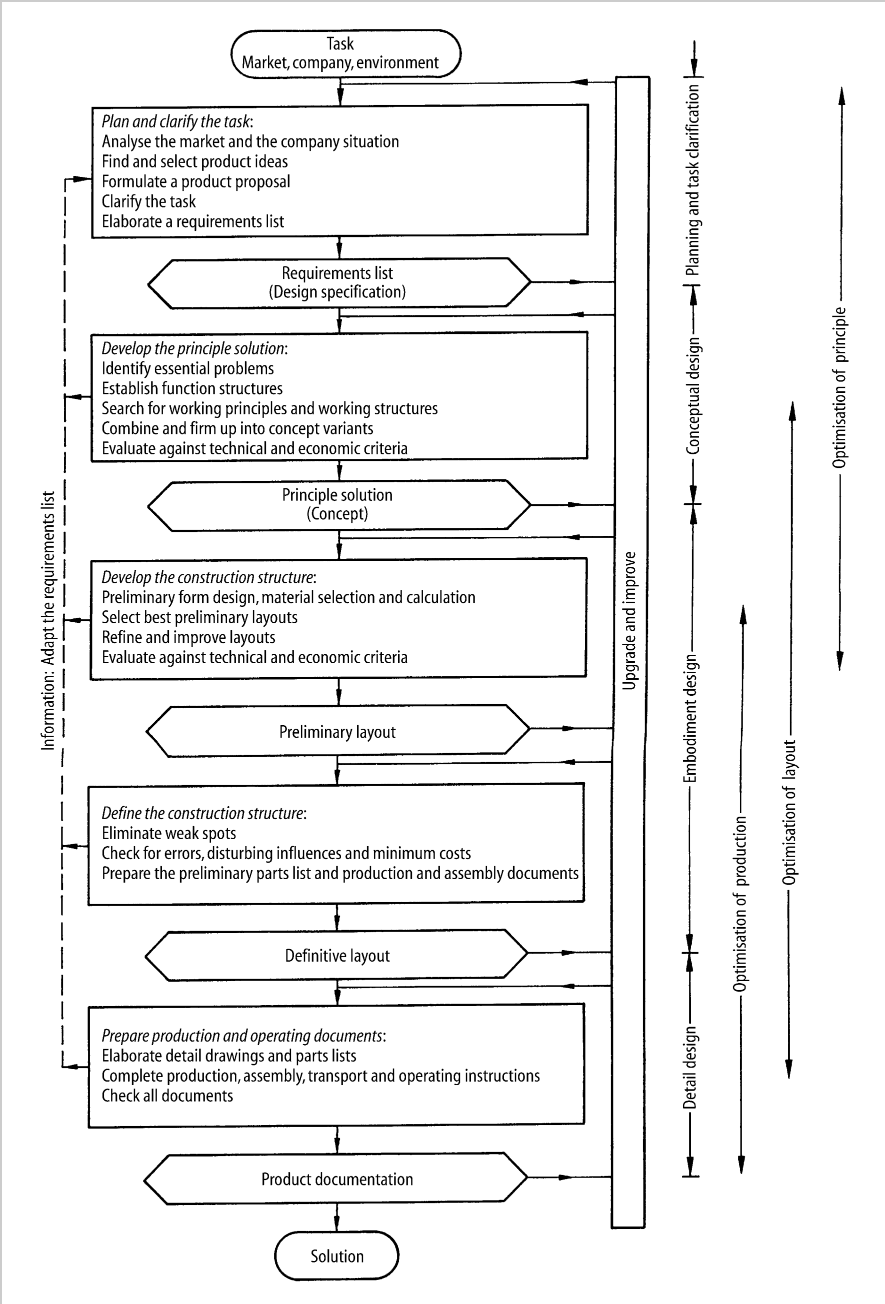


Figure 4.3. Steps in the planning and design process

In all cases procedural plans should be applied in a flexible manner and adapted to the particular problem situation. At the end of each main working and decision step, the overall approach should be assessed and adjusted if necessary.

The four main phases are outlined below.

1. Planning and Task Clarification

The product development task is given to the engineering department by the marketing department, or a special department responsible for product planning, see also Sections 3.1 and 5.1.

Irrespective of whether the task is based on a product proposal stemming from a *product planning* process or on a specific customer order, it is necessary to clarify the given task in more detail before starting product development. The purpose of this *task clarification* is to collect information about the requirements that have to be fulfilled by the product, and also about the existing constraints and their importance.

This activity results in the *specification of information* in the form of a *requirements list* that focuses on, and is tuned to, the interests of the design process and subsequent working steps (see Section 5.2). The conceptual design phase and subsequent phases should be based on this document, which must be updated continuously (this is indicated by the information feedback loop in Figure 4.3).

2. Conceptual Design

After completing the task clarification phase, the conceptual design phase determines the principle solution. This is achieved by abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining those principles into a working structure. Conceptual design results in the specification of a *principle solution* (concept).

Often, however, a working structure cannot be assessed until it is transformed into a more concrete representation. This concretisation involves selecting preliminary materials, producing a rough dimensional layout, and considering technological possibilities. Only then, in general, is it possible to assess the essential aspects of a solution principle and to review the objectives and constraints (see Section 2.1.7). It is possible that there will be several principle solution variants.

The representation of a principle solution can take many forms. For existing building blocks, a schematic representation in the form of a function structure, a circuit diagram or a flow chart may be sufficient. In other cases a line sketch might be more suitable, and sometimes a rough scale drawing is necessary.

The conceptual design phase consists of several steps (see Chapter 6), none of which should be skipped if the most promising principle solution is to be found. In the subsequent embodiment and detail design phases it is extremely difficult or impossible to correct fundamental shortcomings of the solution principle. A lasting and successful solution is more likely to spring from the choice of the most appropriate principles than from exaggerated concentration on technical details.

This claim does not conflict with the fact that problems may emerge during the detail design phase, even in the most promising solution principles or combinations of principles.

The solution variants that have been elaborated must now be evaluated. Variants that do not satisfy the demands of the requirements list have to be eliminated; the rest must be judged by the methodical application of specific criteria. During this phase, the chief criteria are of a technical nature, though rough economic criteria also begin to play a part (see Sections 3.3.2 and 6.5.2). Based on this evaluation, the best concept can now be selected.

It may be that several variants look equally promising, and that a final decision can only be reached on a more concrete level. Moreover, various form designs may satisfy one and the same concept. The design process now continues on a more concrete level referred to as embodiment design.

3. Embodiment Design

During this phase, designers, starting from a concept (working structure, principle solution), determine the construction structure (overall layout) of a technical system in line with technical and economic criteria. Embodiment design results in the specification of a *layout*.

It is often necessary to produce several *preliminary layouts* to scale simultaneously or successively in order to obtain more information about the advantages and disadvantages of the different variants.

After sufficient elaboration of the layouts, this design phase also ends with an evaluation against technical and economic criteria. This results in new knowledge on a higher information level. Frequently, the evaluation of individual variants may lead to the selection of one that looks particularly promising but which may nevertheless benefit from, and be further improved by, incorporating ideas and solutions from the others. By appropriate combination and the elimination of weak spots, the best layout can then be obtained.

This *definitive layout* provides a means to check function, strength, spatial compatibility, etc., and it is also at this stage (at the very latest) that the financial viability of the project must be assessed. Only then should work start on the detail design phase.

4. Detail Design

This is the phase of the design process in which the arrangement, forms, dimensions and surface properties of all of the individual parts are finally laid down, the materials specified, production possibilities assessed, costs estimated, and all the drawings and other production documents produced [4.28] (see also [4.26]). The detail design phase results in the *specification of information* in the form of *production documentation*.

It is important that designers should not relax their vigilance at this stage, otherwise their ideas and plans might change out of all recognition. It is a mistake to think that detail design poses subordinate problems lacking in importance or interest. As we said earlier, difficulties frequently arise from lack of attention to detail. Quite often corrections must be made during this phase and the preceding steps repeated, not so much with the overall solution in mind, as to improve assemblies and components as well as reduce costs.

5. Overall Design Process

In the flow diagram (see Figure 4.3), the main themes are:

- optimisation of principle
- optimisation of layout
- optimisation of production.

Clearly the description above is a generalisation of actual processes. In practice a clear distinction between the working steps and their results cannot always be made, nor is it necessary to do so. However, it is useful for designers to be aware of the main process flow and tasks described in order to plan their work and to avoid forgetting something.

Figure 4.3 does not include the production of models and prototypes because the information they supply may be needed at any point in the design process and so cannot be fitted into any particular slot. In many cases, it is even necessary to develop models and prototypes during the conceptual phase, particularly when they are intended to clarify fundamental questions in, say, the precision engineering, electronics and mass production industries. Due to the one-off nature of heavy and process engineering, the cost and time required to produce prototypes normally makes them uneconomic or infeasible. However, it is possible to test parts of the proposed plant or equipment by building partial prototypes within existing plant and equipment or by using specific test facilities. In batch production it is common to produce prototypes well before production starts and also to undertake a pre-production run to ensure that production will run smoothly. These pre-production products can still be sold.

Figure 4.3 also does not indicate when work has to be subcontracted, because this depends upon the type of product.

The execution of orders is usually part of product development, although in the case of size ranges and modular products it can take place quite late in the process.

If on receiving an order, only existing documents are used, and only production instructions, subcontractor orders, parts lists, etc., need to be compiled, no product development is required. So apart from tender drawings, layout drawings and assembly plans, no further design work is needed, and in many cases these drawings and plans can be generated automatically using variant design software.

Upon looking at Figure 4.3, and after reading about the methods described in the following chapters, practising designers may well object to the process on the basis that they lack the time to go through every one of the many steps. They should bear in mind that:

- Most of the steps are performed in any case—albeit unconsciously—although they are often carried out too quickly, leading to unforeseen consequences.

- This deliberate step-by-step procedure, on the other hand, ensures that nothing essential has been overlooked or ignored, and is therefore indispensable in the case of original designs.
- In the case of adaptive designs, it is possible to resort to time-tested approaches and to reserve the procedure described for where it offers special benefits; for example, when improving a specific detail, in which case the steps should be undertaken focusing on this detail.
- If designers are expected to produce better results, then they must be given the extra time the systematic approach demands, although experience has shown that only a little extra time is needed for a stepwise procedure.
- Scheduling becomes more accurate if the step-by-step method is followed rigorously.

4.2.2 Timing and Scheduling

Products will only be successful when they:

- satisfy the customer needs (requirements)
- reach the market at the right time
- are sold at the right price.

This section focuses on the second prerequisite, because designers often underestimate the importance of time-to-market and are not familiar with the methods and tools used for timing and scheduling. We only introduce the basic approaches. Details have to be obtained from the literature.

Two constraints determine the planning difficulty:

- the project or design result must be finished at a certain point in time, and intermediate results are required on specific dates
- not every task can be executed by every member of the team, i.e. there is a resource constraint.

Network planning is one of the most important planning tools [4.7, 4.8]. A network plan is used to estimate the overall project length and resource requirements. The graphical representation shows the logical links between the required project tasks and the resources assigned to these tasks.

Creating a network plan involves performing three main steps:

- Structure analysis to identify and describe the links and dependencies between the project tasks.
- Time analysis to identify the necessary duration for each task along with a feasible starting date for each of the main steps.
- Resource analysis to allocate the various tasks to individual team members. In the first instance this should be based on their competences, followed by their

Table 4.1. Procedure for creating a network plan

	Activity	Explanation
1.	Determine product structure	In general the structure of an existing similar product is adapted
2.	Determine the tasks necessary to create the individual product elements	For every product element and for the overall product, the tasks include the following to an appropriate level: ● solution finding ● investigation ● embodiment ● calculation
3.	Establish logical and temporal dependencies between individual tasks	Dependencies between tasks have to be identified and documented as unambiguous IF–THEN statements: e.g. IF the shaft diameter is determined, THEN the shaft–hub connection can be fixed
4.	Establish the duration of the tasks	● interview those with relevant experience ● compare with similar tasks ● document completed tasks ● estimate
5.	Fix milestones (these are used to check whether the work and schedule have been achieved; a milestone trend analysis allows the prediction of the success or failure of a project)	**Types of milestones:** **Event-driven:** The content of a milestone has to be defined precisely. A milestone is reached when the available working results meet the defined content of that milestone **Application:** Mostly used as the final milestone for the design of an assembly **Time-driven:** The milestone is reached at a certain point in time or after a certain time interval has elapsed **Application:** For large tasks when it is not possible to define clear intermediate results **Point of no return:** Event or point in time after which the results achieved must not be changed further **Application:** Securing intermediate results, e.g. against customers changing requirements **Review:** Point in time at which clearly defined results have to be explicitly signed off or released **Application:** The embodiment of expensive and complex assemblies or components is signed off by production or, in some cases, by the customer
6.	Determine necessary and possible float times for the tasks	Float times serve to manage risk in order to avoid endangering the project plan when delays occur and are applied, in particular, for novel tasks
7.	Create network plan (usually using special software tools: e.g. Microsoft Project, Super-Project-Expert)	A network plan shows in graphical and tabular form all of the dependencies between the tasks and milestones, and is used to determine the course of a project
8.	Create project calendar	The project calendar shows the exact number of working days available for the duration of the project
9.	Select resources and allocate them to tasks in the network plan	The selection is based on the required competencies and the availability of resources during the planned period of the project
10.	Create a resource calendar and allocate to the network plan	For every employee an individual calendar is created showing his or her available working time during the duration of the project: holidays, training days, etc. must be taken into account

Table 4.1. (continued)

	Activity	Explanation
11.	Run through the plan	After the resources and the individual calendars are allocated to the network plan, the first run-through is undertaken
12.	Evaluate the plan	• Can the project milestone be achieved? • What is the critical path? (i.e. the sequence of tasks with no float times that determines the overall duration of the project)
13.	Optimise the plan	The plan can be optimised and corrected by: • increasing the resources available • moving deadlines • reducing the number of tasks • changing the sequence of tasks • altering the content of the tasks
14.	Sign off the plan	The project plan is released through the signature of the manager responsible, and, where appropriate, by the customer
15.	Monitor the project	All project parameters, such as deadlines, costs and risks are continuously monitored and reported

availability, which can be limited because they may be absent due to training courses, illness, holidays, etc., or because they have been allocated to other projects.

In general the product structure is used as the basis for planning the task structure. The product structure determines the main assembly groups and components that have to be designed and, as a consequence, the majority of the tasks.

Table 4.1 shows the procedure for creating a network plan and the individual steps. Figure 4.4 shows part of a network plan, in this case a Gantt chart. The individual tasks are represented by bars. Their dependencies result from logical or possible working sequences, e.g. input/output requirements, where one task must have been completed before the next can be started.

A network plan not only shows project duration, resource requirements and allocation of team members to tasks, but also float times and the critical path of the project. The float times indicate how much the start or end of a task or series of tasks can be delayed without jeopardising the overall lead time of the project. The critical path contains those tasks that have no float times and therefore determine the overall duration of the project.

4.2.3 Planning Project and Product Costs

The cost price is the basis for determining the selling price and is therefore crucial to the success of the product. The cost price is influenced by the production costs and the associated project costs. Design and development are the costliest items contributing to the project cost, so engineering departments carry a great responsibility.

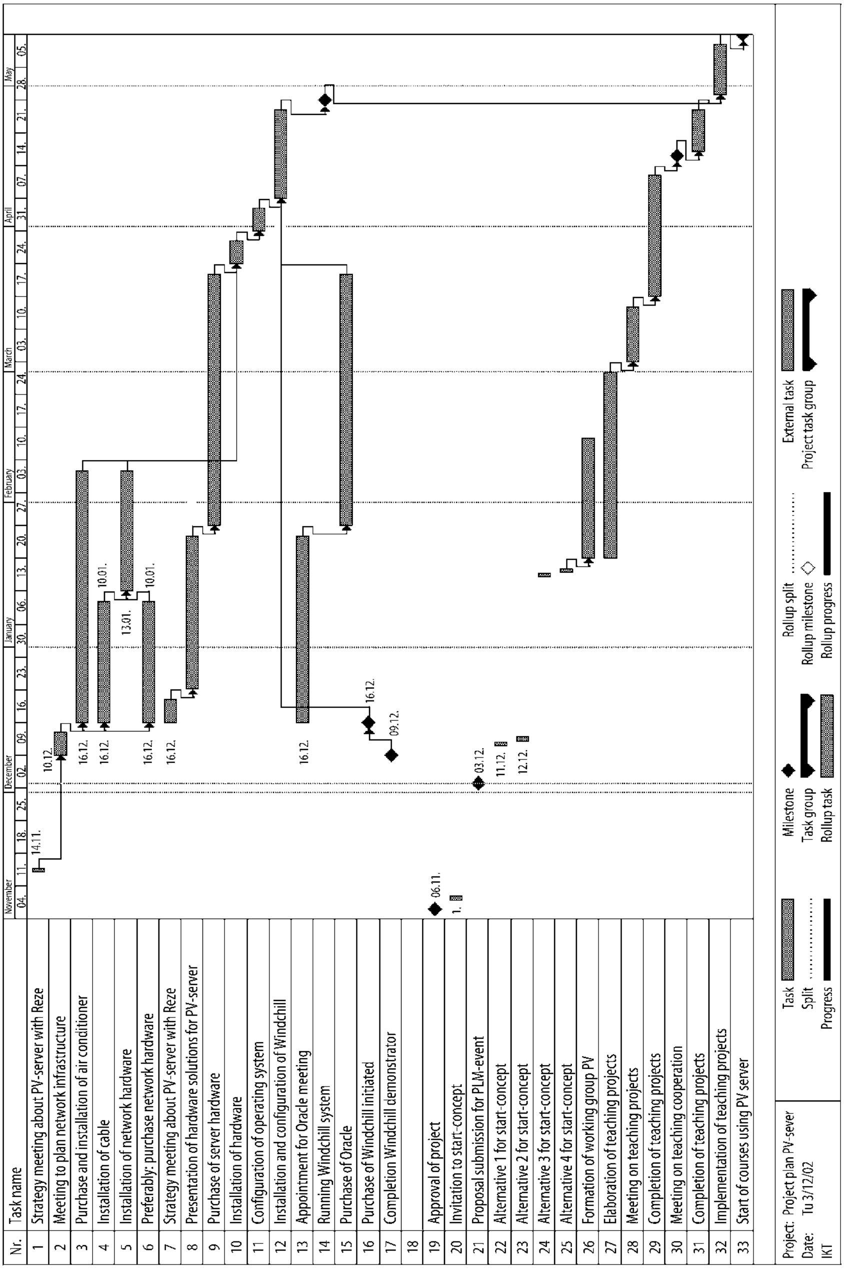


Figure 4.4. Example of a network plan

In order to meet the target cost price, engineering departments not only have to keep production costs to a minimum (see Chapter 11 for more details), but also the design and development costs. Depending on the batch size, the latter costs can represent a large share of the cost price.

To estimate the design and development costs, a network plan can also be used because the main costs incurred by engineering departments are staff costs. Support costs, such as facilities, CAD systems, external consultants, etc., are usually much lower. Using the network plan, costs can be assigned to the allocated resources using the appropriate hourly rate. The distribution of the costs with time can be represented by a cost plan [4.9], which is important when estimating the project budget.

4.3 Effective Organisation Structures

4.3.1 Interdisciplinary Cooperation

Designers cannot work independently of their environment—they depend on the results produced by others and others depend on their results. They are members of their departments, which in turn are parts of the company. Only the coordinated activities of all participants will lead to a satisfactory overall result [4.11, 4.22]. To achieve this, the responsibilities, tasks, etc., for every individual are specified by the organisational and operational structures:

- The *organisational structure* specifies the responsibilities and tasks for individuals, departments and standing committees, and relates these in a hierarchy.
- The *operational structure* specifies the various procedures.

The design and development process is made more efficient through the following actions:

- reducing inner iterations, i.e. repetition of the same activity within a working step
- reducing outer iterations, i.e. jumping back to a working step that has already been completed or even repeating a design phase
- omitting working steps
- executing working steps in parallel.

In particular, the last action has the potential to reduce the overall project time significantly. To achieve these four actions, the following prerequisites must be met:

- The product has to be structured in such a way that the properties of its systems, subsystems and system elements can be modelled precisely and unambiguously during every step of the process. Chapter 9 proposes some possible product structures.
- The interfaces between the process steps have to be defined precisely and unambiguously.
- The process steps have to be independent.

When these prerequisites have been met and interdisciplinary teams formed, then *Simultaneous or Concurrent Engineering* can be introduced. Simultaneous or Concurrent Engineering involves goal-oriented, interdisciplinary (interdepartmental) collaboration and parallel working throughout the development of the product, the production process and the sales strategy. It covers the total product life cycle and requires firm project management [4.1]. Experiences of its application in industry can be found in [4.12, 4.14]. Figure 1.4 highlights the intensive information flows that occur between departments. In a simultaneous engineering process the activities of the various departments run in parallel or at least have significant overlap. Intensive contacts with customers are encouraged, many suppliers are integrated in the process, see Figure 4.5 [4.5, 4.13, 4.23], and the product is monitored until the end of its working life.

For the duration of the project, a team is formed consisting not only of members of the design and development department but also those from other departments involved in the product creation process. This team, which is formed as early as possible, is led by a project manager, works independently, but has to report directly to the Board of Management or Head of Development. Departmental boundaries are thereby transcended. The team can operate as a virtual team; that is, without a visible organisational form. Characteristics of team structures and their importance can be found in [4.6, 4.27]. The objectives of this type of organisation and working procedure are:

- shorter development times
- faster product realisation
- reduction of product and product development costs
- improved quality.

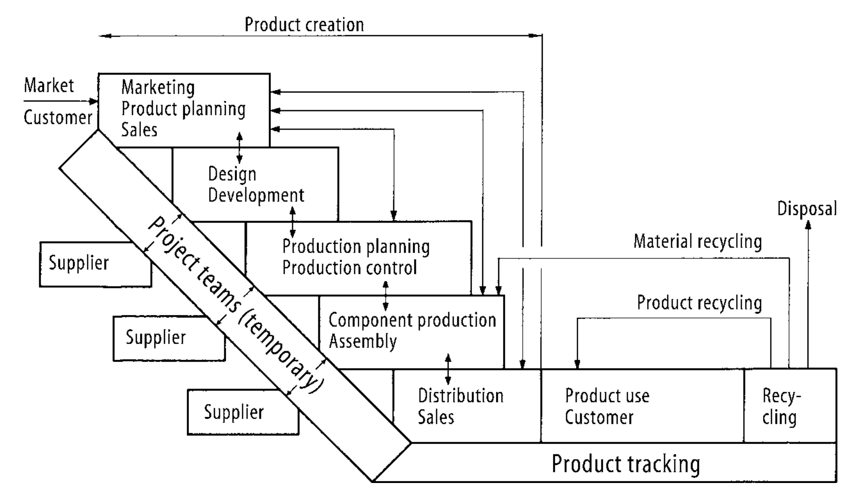


Figure 4.5. Product creation and tracking processes using Simultaneous Engineering, showing the overlapping activities of different disciplines, the formation of a project team and close contact with customers and suppliers

Simultaneous or Concurrent Engineering changes a designer's work as follows [4.20]:

- Working in an interdisciplinary team requires the adaptation of language and terminology.
- A closer, more direct exchange of information takes place through the early involvement of other departments and disciplines.
- More electronic information and communication technologies are used, e.g. data processing systems, CAD, multimedia, etc.
- A project management process with schedules and milestones is imposed so that design work has to be structured more systematically.
- Activities are run in parallel and therefore have to be coordinated accordingly.
- Individual responsibility for the assigned problems and tasks has to be accepted in line with team decisions.
- Contact with suppliers and customers becomes more intense.

It is useful to build a small core team with the experts who are responsible for design, production planning, marketing and sales. The composition of the team depends on the particular problem and type of product. This core team is complemented by experts from quality, assembly, electronics, software, recycling, etc., as and when needed and who may only participate for short periods of time. In such a team the knowledge and experience from neighbouring disciplines (see Figure 4.6) are more or less automatically incorporated into the project. This integration of a wide range of expertise significantly improves the realisation of the project goals and the ability to meet the constraints, as discussed in Section 2.1.7 and in accordance with Figure 2.15.

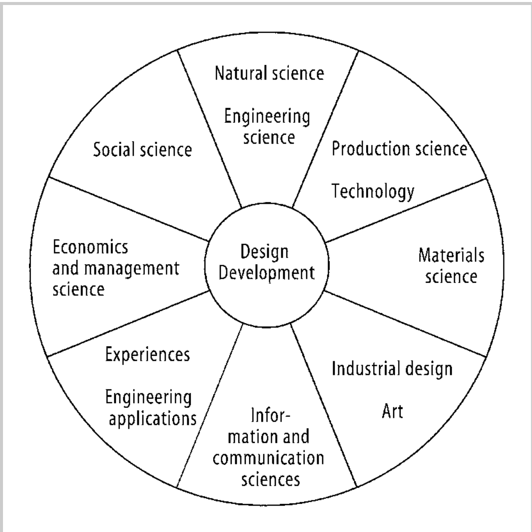


Figure 4.6. Related knowledge domains that support design and development

The advantages of an interdisciplinary team are:

- increased availability of knowledge and mutual stimulation
- better control of the product and the process—achieved by questioning issues and identifying contradictions
- increased motivation through direct participation and information sharing
- immediate responses to situations without the need to seek and wait for approval from higher levels in the hierarchy.

When the focus is on lean production, information and decision chains must become shorter. To facilitate this it is often necessary to build temporary project groups whose members are released from the departmental hierarchy for the duration of the project. The designer who previously worked within the confines of his discipline-based department, where he or she could easily call upon colleagues for advice and support, now has to work much more independently and within less familiar surroundings. To work in such project teams, a number of skills are required that go beyond the usual discipline-based ones [4.19,4.20] (see Figure 4.7). These issues must be taken into account when selecting the project leader.

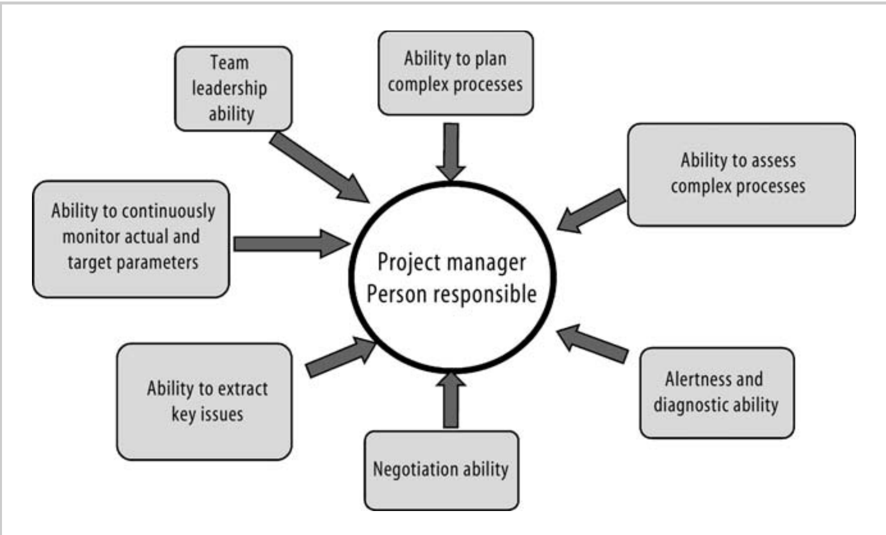


Figure 4.7. Abilities required of project managers

4.3.2 Leadership and Team Behaviour

Strong project leadership is necessary when developing new products in teams that are independent of departmental structures. Project leaders must have a good knowledge of the relevant technology and design methods as well as the characteristics of good problem solvers (see Section 2.2.2). Only then are they able to lead a team of experts from different fields to achieve the project goals and to cope with the tasks assigned to them [4.20].

Project leaders and their teams can use the systematic approach presented in this book as an effective means of support. They can use it to initiate and check their approach, to select suitable methods, define decision steps (milestones), and apply established design principles. Depending on the problem, project leaders and teams need to be willing to adapt their approaches and methods on the basis of importance and urgency. Project leaders must not be dogmatic in their leadership style, must utilise the manifold skills in the team, must provide every team member with individual freedom of action, and must demonstrate decisiveness when it matters. Leadership involves:

Providing timely information by:

- pointing out deviations from the project plan as early as possible
- managing information in a balanced and uniform manner.

Steering individual activities carefully in line with a systematic approach by:

- planning the main project parameters such as deadlines, costs and resources
- pursuing these project targets
- estimating the effort and consequences of any changes
- updating the project plan when necessary.

Representing the team effectively by:

- managing reporting and documentation
- taking personal responsibility for team presentations, etc.

Fostering team building and mutual trust by:

- making and encouraging decisions in difficult situations.

If project leaders cannot fulfil these requirements, then the simultaneous engineering approach will be difficult to adopt.

Team behaviour also plays an essential role. Teamwork benefits product development and individual team members (see Section 4.3.1), however it can also give rise to the following problems [4.2]:

- groups or teams that work together for a long time tend to oversimplify
- control of team effectiveness can decline
- teams begin to conform, which can lead to the protection of competences and the overestimation of capabilities
- groups who have worked together successfully for a long time develop a self-confidence that is not always justified
- within a team one may find opinionated individuals who dominate others and who need careful management
- some team members may sit back and not pull their weight.

In addition to adopting an understanding leadership style, these problems can be addressed specifically by creating small teams, encouraging an open dialogue, and, if necessary, removing or adding team members. Ideally, teams should be dissolved when their project goals have been achieved.

Dörner and Badke-Schaub [4.2, 4.10] have written about the effectiveness of groups and teams in comparison with individuals. Although general statements are difficult to make, it appears that group opinions settle at a relatively high level. This means that results are never as good as those of the best individuals, but also never as bad as those of the worst individuals. An idea or the work of an individual can stand out from that of the team, but can also be significantly worse.

This implies that surprising proposals from individuals should not be suppressed. On the contrary, these should be developed to a point where a clear comparison with the team result is possible. In a team one cannot rely on, or even expect, valuable individual original contributions to arise, so opportunities should be created to encourage them. Team building does not automatically guarantee good solutions. Company culture and leadership style remain fundamental for effective teamwork and successful individual work.

5 Task Clarification

5.1 Importance of Task Clarification

The design task is generally presented to the design and development department in one of the following forms:

- as a development order (from outside or from the product planning department in the form of a product proposal)
- as a definite order
- as a request based on, for instance, suggestions and criticism by sales, research, test or assembly staff, or originating in the design department itself.

The task description contains not only statements about the product, such as its functionality and performance, but also statements about deadlines and cost targets. The design and development department now faces the problem of identifying the requirements that determine the solution and embodiment and formulating and documenting these quantitatively as far as possible. In order to achieve this, the following questions need to be answered in close cooperation with the client or proposer:

- What are the objectives that the intended solution is expected to satisfy?
- What properties must it have?
- What properties must it not have?

The result or this process is a *requirements list*. This document thus represents the specification against which the success of the design project can be judged.

In so far as this has not already been done in product planning (see Section 3.1), the design and development department should undertake the situation analysis described in 3.1.4 in order to specify the product situation and to identify future developments.

A useful method used to support the preparation of the requirements list is *Quality Function Deployment* (QFD) (see Section 10.5). QFD helps to translate customer wishes into product requirements.

5.2 Setting Up a Requirements List (Design Specification)

The main working steps required to set up a requirements list are shown in Figure 5.1. The procedure involves two stages. In the first stage the obvious requirements are defined and recorded. In the second stage these requirements are refined and extended using special methods.

The following sections describe the contents and format of a requirements list, along with the individual working steps.

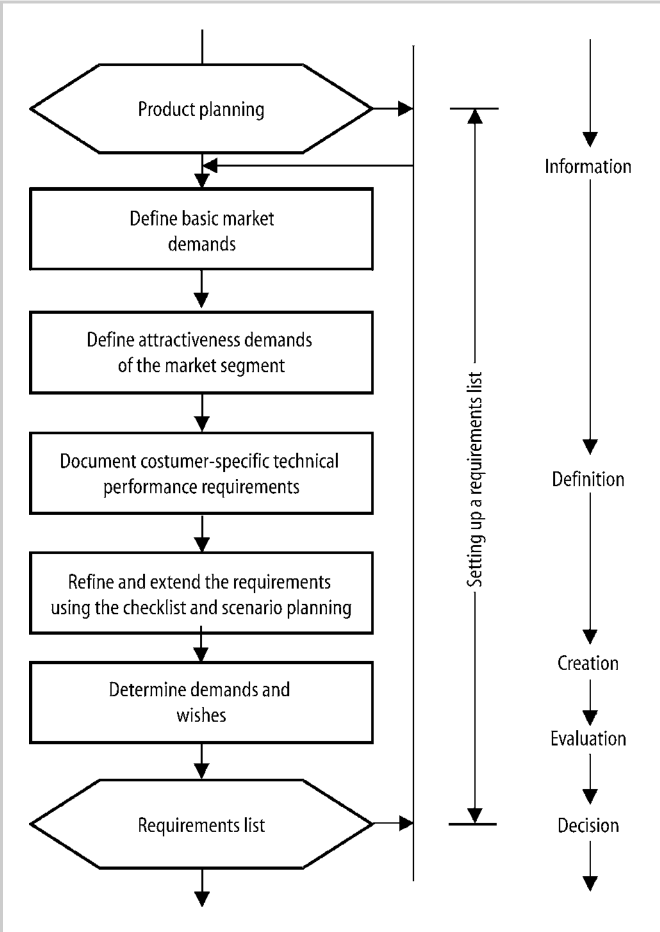


Figure 5.1. Main working steps required to set up a requirements list

5.2.1 Contents

When preparing a detailed requirements list it is essential to clearly elaborate the goals and the circumstances under which they have to be met. The resulting requirements must be identified either as demands or wishes.

Demands are requirements that must be met under all circumstances; in other words, if any of these requirements are not fulfilled the solution is unacceptable (for instance such qualitative demands as "suitable for tropical conditions", "splashproof", etc.). Minimum demands must be formulated as such (for example $P > 20$ kW; $L < 400$ mm).

Wishes are requirements that should be taken into consideration whenever possible, perhaps with the stipulation that they only warrant limited increases in cost, for example, central locking, less maintenance, etc. It is advisable to classify wishes as being of major, medium or minor importance [5.4].

The distinction between demands and wishes is also important at the evaluation stage, since selection (see Section 3.3.1) depends on the fulfilment of demands, while evaluation (see Section 3.3.2) is only performed on variants that already meet the demands.

Even before a certain solution is adopted, a list of demands and wishes should be set up and the quantitative and qualitative aspects tabulated. Only then will the resulting information be adequate:

- Quantity: All data involving numbers and magnitudes, such as number of items required, maximum weight, power output, throughput, volume flow rate, etc.
- Quality: All data involving permissible variations or special requirements, such as waterproof, corrosionproof, shockproof, etc.

Requirements should, if possible, be quantified and, in any case, defined in the clearest possible terms. Special indications of important influences, intentions or procedures may also be included in the requirements list, which is thus an internal digest of all the demands and wishes expressed in the language of the various departments involved in the design process. As a result, the requirements list not only reflects the initial position but, since it is continually reviewed, also serves as an up-to-date working document. In addition, it is a record that can, if necessary, be presented to the Management Board and the sales department so that they may make their objections known before the actual work is started.

5.2.2 Format

The requirements list should at least contain the following information in a structured format (see also Figure 5.2).

- user: company or department
- project or product name
- requirements labelled as demands or wishes
- person responsible for each requirement
- date of issue for the overall requirements list
- date of last change
- version number and/or index number
- page number.

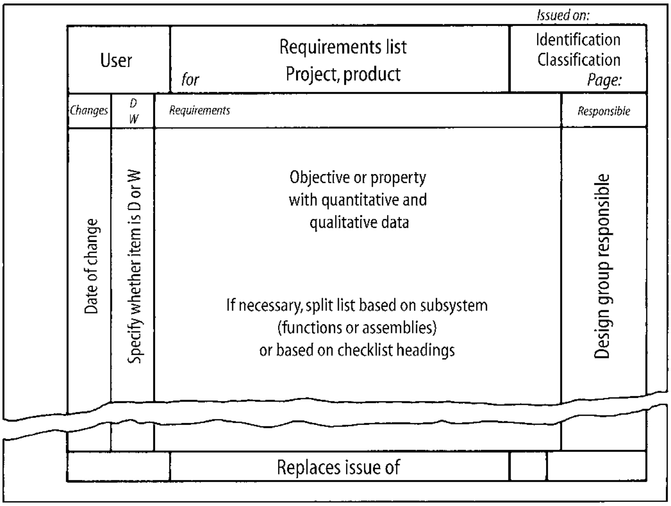


Figure 5.2. Layout of a requirements list

It is helpful if the format of the requirements list becomes a company standard so that it can be used, elaborated and adopted by as many departments as possible. Figure 5.2 is thus no more than a suggestion that can, of course, be modified at will.

It may prove useful to set up the requirements list based on subsystems (functions or assemblies) where these can be identified, or else based on checklist headings (see Figure 5.3). With established solutions, where the assemblies to be developed or improved are already determined, the requirements list must be arranged in accordance with these: special design groups are usually put in charge of the development of each assembly. With motor cars, for instance, the requirements list can be subdivided into engine, transmission and bodywork development.

It is extremely useful to *record the source* of demands and wishes. It is then possible to go back to the proposers of requirements and to enquire into their actual motives. This is particularly important when the question arises of whether or not the demands can be changed in the light of subsequent developments.

Any *changes in*, and *additions to*, the original task that may result from a better understanding of solution possibilities or from possible changes in emphasis must always be entered into the requirements list, which will then reflect the progress of the project at any particular time.

Responsibility for this work is placed on the chief designer. The updated requirements list should be circulated among all departments concerned with the development of the product (management, sales, accounts, research, etc.). The requirements list should only be changed or extended due to a decision of those in charge of the overall project and by following a formal change management procedure.

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, inertia 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 safety systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clarity 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.
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date

Figure 5.3. Checklist for setting up a requirements list

5.2.3 Identifying the Requirements

As a rule, the first requirements list undertaken is the most difficult to set up. Experience greatly facilitates the compilation of subsequent ones. After a relatively short period, several examples become available that can be used as the starting point for subsequent requirements lists.

The main issue associated with setting up a requirements list is the quantity and quality of the documents and data that are supplied with the design task. Depending on the branch of engineering, not all the expected product properties will have been defined and documented. The rest of them are expected by the customers but not made explicit, i.e. they are implicit requirements. The following questions therefore need to be answered:

- What is the problem really about?
- Which implicit wishes and expectations are involved?
- Do the specified constraints actually exist?
- What paths are open for development?

It is therefore important for the design and development department to understand the customers or the market segment involved. The basis of the requirements list is often a contract that has been signed with a customer. This contract usually includes the agreed product properties and performance data, product liability regulations, and the guidelines that have to be applied.

In a first exploratory step, the statements and requirements in the contract are translated into product-relevant parameters that designers and engineers can apply. This is relatively straightforward to do because the product specification in a contract involves explicit requirements. A bigger problem is how to deal with the implicit requirements; although they are not expressed they still have a very negative impact if they are not fulfilled. What effects, for example, do statements such as "simple maintenance" have on the embodiment of the product, and how can such statements be formulated as specific requirements? How difficult it is to formulate a requirements list depends on the type of customer and, in principle, two types can be distinguished:

- *anonymous customers:* these include a particular market segment, those identified by the sales department without a customer order, and those identified by the product planning department.
- *specific customers:* these not only include individual customers who place an order, but also market segments that are served by many companies with similar products in which requirements have become standardised, e.g. those for "compact cars" and "family cars". Although the actual customers in such cases are anonymous, they can, in effect, be treated as specific customers.

According to Kramer [5.3], some specific types of requirement can be formulated for each type of customer.

Basic requirements are always implicit requirements, i.e. they are not articulated by the customer. Their fulfilment is self-evident and vital for the customer. Success or failure of a product is determined by these requirements. For example, for a follow-on product the customer generally expects energy consumption and operating costs to be reduced. It is essential for the design and development department to recognise the importance of these implicit requirements. The sales department or product management must supply information about these requirements, along with the thoughts and expectations of the customers.

Technical performance requirements are explicit requirements. They are articulated by the customer and can usually be specified precisely. For example, a new engine may have to have 15 kW of power and weigh not more than 40 kg. Such concrete values are used by customers when comparing competing products. The importance of the individual parameters is determined by the customers themselves.

Attractiveness requirements are again implicit requirements. Customers are usually not aware of these; however, they are used to differentiate between competing products. In general customers are not willing to pay higher prices for these additional product properties. Consider an example from a motor car where the number of standard colours and the available combinations of external and internal colour schemes are such requirements.

5.2.4 Refining and Extending the Requirements

Two methods have been developed to refine and extend the requirements list defined thus far:

- follow a checklist
- create scenarios.

The checklist shown in Figure 5.3 is a generic one based on ideas described in Section 2.1.7. The items in this list are checked against the existing task and its requirements in order to obtain further requirements. A further checklist can be found in Ehrlenspiel's book [5.1].

When creating scenarios, the product life from production to disposal is considered and sketched out. For every stage, a scenario is developed and the following questions asked:

- What might happen to the product? Examples: What kind of state might it find itself in? How might it be treated and used? Who might use it or come into contact with it? Where might it be used?
- How should the product react? Examples: What level of tolerance to failure should be built in? How should dangerous situations be avoided?

The answers to these questions are used to formulate further product requirements. Most of these requirements will not be very specific, i.e. they cannot be translated into the product parameters that determine solutions or embodiments. For example, the previously mentioned statement "simple maintenance" needs to be specified in more detail. Kramer [5.3] proposes the following three-step procedure to achieve this.

First step (statement)

- Customer's need: simple maintenance.

Second step (development)

- Customer's requirements:
  1. Provide long maintenance interval

2. Enable simple maintenance
3. Make maintenance procedures easy to learn.

Third step (refinement)

- Provide long maintenance interval:
  1. Maintenance interval at least 5 000 operating hours
  2. Grease cams every 10 000 operating hours.
- Enable simple maintenance:
  1. Fit maintenance access covers with manual locks
  2. Fit cams with lubricating points that fit standard grease guns
  3. Leave space for oil drip tray
  4. Provide locating features to assist when refitting access covers.
- Make maintenance procedures easy to learn:
  1. Add a separate section in the operating manual describing maintenance procedures
  2. Provide labels indicating the locks that need to be undone for maintenance
  3. Indicate the directions of the maintenance operations with etched arrows.

The results of the third step are then added to the requirements list.

When clarifying the task, one should start by collecting the essential functions and the existing task-specific constraints with respect to the energy, material and signal transformations. When all of the information is available, it must be grouped, ordered and labelled.

In 5.2.1 we pointed out the essential differences between demands and wishes. In many cases it is clear from the outset whether a requirement is a demand or a wish. However, a definitive assignment is required before the requirements list is released. If necessary, further information should be collected. Wishes should be formulated such that their weighting can be established. Initially it is often useful to express such weightings qualitatively rather than quantitatively, because the estimates often change as the understanding of the task develops.

5.2.5 Compiling the Requirements List

In the light of arguments advanced in this chapter, the following general method of compiling a requirements list can now be recommended:

1. Identify the requirements:
   - Check the customer contract or the sales documents for technical requirements and define and document them.
   - Refer to the items of the checklist (Figure 5.3) and determine the quantitative and qualitative data.
   - Create scenarios that consider all stages in the product's life and thus derive further requirements.

- Refine by asking:
  - What objectives must the solution satisfy?
  - What properties must it have?
  - What properties must it not have?
- Collect further information.
- Specify demands and wishes clearly.
- If possible, rank wishes as being of major, medium or minor importance.

2. Arrange the requirements in a clear order:
   - Define the main objective and the main characteristics.
   - Split into identifiable subsystems, functions, assemblies, etc., or in accordance with the main headings of the checklist.
3. Enter the requirements list on standard forms and circulate among interested departments, licensees, directors, etc.
4. Examine objections and amendments and, if necessary, incorporate them into the requirements list.

Once the task has been adequately clarified, and the relevant departments are satisfied that the listed requirements are technically and economically attainable, the way is clear for the conceptual design phase.

5.2.6 Examples

Figure 5.4 shows a requirements list for a printed circuit board positioning machine, illustrating the main characteristics of the content and the format of requirements lists. It has been structured according to the main characteristics given in Figure 5.3. The requirements have been split into demands and wishes, and, where possible and necessary, quantified. Modifications and amendments with their dates are also shown. The latter were the result of an intensive discussion of a first draft of the requirements list (first version 21st April 1988).

Requirements lists based on the above recommendations are provided in Figures 6.4, 6.27 and 6.43 as further examples.

5.3 Using Requirements Lists

5.3.1 Updating

In principle, requirements lists should be binding and complete. However, initially a requirements list is always provisional because, as the design process proceeds, it grows and changes. Any attempt to formulate all possible requirements at the start of a project will fail and would cause considerable delays. Looking at the inputs

Siemens		Requirements list for a printed circuit board positioning machine	Issued on 27/04/88 Page: 1
Changes	D W	Requirements	Responsible
		1. Geometry: dimensions of the test sample	Langner's group
		Circuit board:	
	D	Length = 80 – 650 mm	
	D	Breadth = 50 – 570 mm	
	W	Height = 0.1 – 10 mm	
	D	Required hight = 1.6 – 2 mm	
	W	Clearance between basic grid boards ≤ 120 mm	
	D	'Clamping area' ≤ 2 mm (edges of the board)	
		2. Kinematics:	
27/04/88	D	Precise positioning of the test sample	
27/04/88	D	Minimum of 2 mm displacement of the test sample normal to the board	
27/04/88	D	Feedback to transfer position	
	W	separate stations for input and output	
	D	Design of clearance zone	
	W	Minimum handling time (as fast as possible)	
		3. Forces:	
	D	Weight of the test sample ≤ 1.7 kg	
27/04/88	W	Maximum weight of the test sample ≤ 2.5 kg	
		4. Energy:	
	D	Electrical and /or pneumatic (6 – 8 bar)	
		5. Material:	
	D	Free from rust	
	D	Isolation between test sample and testing device	
27/04/88	W	Thermal expansion of testing device adjusted to expansion of printed circuit	
27/04/88	D	Consideration of influence of temperature	
27/04/88	D	Temperature range: 15–40 °C	
27/04/88	D	Humidity: 65 %	
27/04/88	W	Circuit boards: epoxy-fiberglass sheet	
27/04/88	D	No condensation	
		6. Safety:	
27/04/88	D	Operator Safety	
		7. Production:	
		Consideration of tolerance build up	
		8. Operation:	
	D	No contamination inside the testing device	
	D	Destination: production line	
		9. Maintenance:	
	W	Maintenance intervall > 10^6 test operations	
		10. Schedule:	
	D	Embodiment finished by July 1988	
		Replaces issue of 21/04/88	

Figure 5.4. Requirements list for a printed circuit board positioning machine (Siemens AG)

and outputs of individual working steps in the design process, the reasons become clear. For example, in the final stages of designing a motor car, the thicknesses of all of the individual layers of body paint need to be known. However, to develop the concept, these data are not relevant. The paintwork requirements therefore do not have to be specified until much later in the process.

Thus, working with binding yet provisional requirements lists takes into account the fact that not all of the data and requirements are known or have to be known at the beginning of a design process. Only those requirements that are absolutely necessary in order to be able to proceed to the next working step need to be documented. At the start of a project, it is important to specify those parameters and properties that:

- define the particular concept
- influence the product structure
- determine the overall embodiment of the product.

The contents of a requirements list therefore depend on the state of the product design and the stage of the design process. The list has to be continuously amended and extended. Managing requirements lists in this way avoids having to deal with questions and requirements before they can be adequately answered and specified.

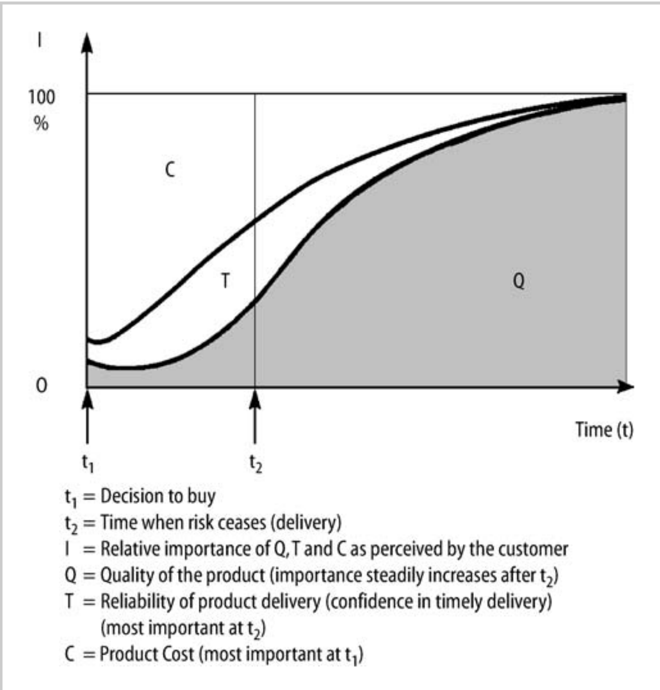


Figure 5.5. Changing appreciation of product quality by the customer

Product requirements frequently change with time, during both product creation and product use.

During Product Creation, customers often change their demands and wishes. This happens when customers gain new knowledge and understanding and when the planned application has been extended. This is typical of capital equipment because of its long development process. For railway rolling stock, for example, it is possible that during the development process the rail network has been extended with the consequence that specified powers and capacities are no longer sufficient.

During product use, customer appreciation of the product can change and, as a consequence, the requirements and their relative importance can also change. For example, the longer a product is in service, the more important quality issues such as long maintenance intervals and reliability become, see Figure 5.5 [5.3].

The fact that requirements can change must be considered when setting up a requirements list. A mutually satisfactory requirements management process is therefore essential in order to ensure good and lasting relations between a company and its customers.

5.3.2 Partial Requirements Lists

It is often beneficial for specialist areas or departments of a company to prepare so-called "partial requirements lists" documenting only their particular requirements. This removes the need for the design and development department to spend time collecting more information and data than are strictly relevant to them, see Figure 5.6 [5.2].

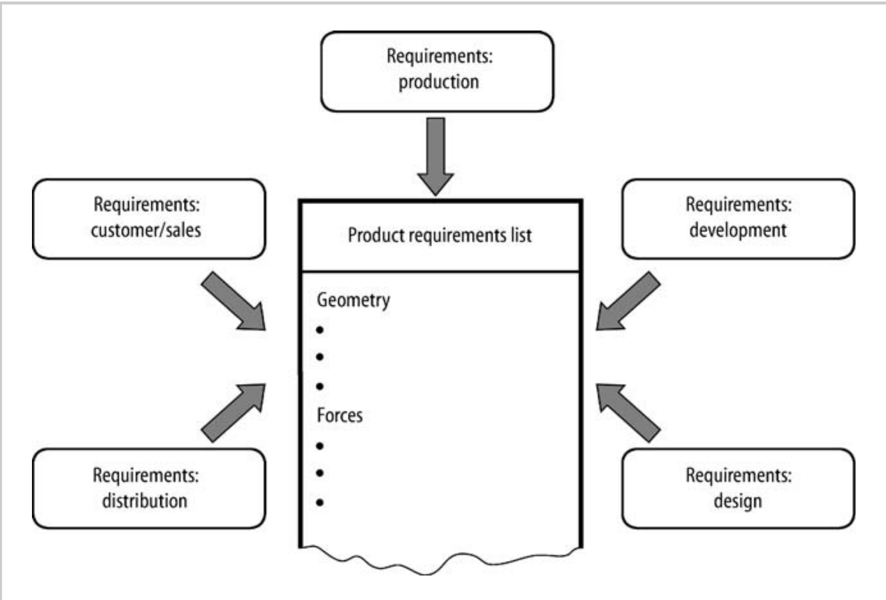


Figure 5.6. Product requirements list compiled from partial requirements lists

The product requirements list is a compilation of all of the partial requirements lists. An important role of project management is to ensure that the partial requirements lists cover all areas and are compatible with each other. Modern engineering data management systems [5.5] support their efficient administration and editing.

5.3.3 Further Uses

Even when the design is not original, and the solution principle and layout are fixed so that nothing more than *adaptations* or *dimensional changes* need to be made in a familiar area, orders should nevertheless be executed on the basis of requirements lists, which can then take the form of templates or questionnaires. These should be constructed in such a way that information for electronic data processing and quality control can be read off directly. As a result, requirements lists become sources of information for direct action.

Beyond that, requirements lists, once compiled, are an invaluable *source of information* about the required or desired properties of the product, and hence extremely helpful for further developments, negotiations with suppliers, etc. Setting up requirements lists for existing products can also provide a very valuable source of information for the subsequent development and rationalisation of those products.

The examination of a requirements list during project meetings or before assessing various designs is an extremely useful procedure. All of those involved are placed in possession of all of the available information and all salient evaluation criteria are brought home to them.

Requirements lists are an important basis for knowledge management systems. Stored in such systems, requirements lists provide a very valuable source of knowledge about previous projects that can often be reused.

5.4 Practical Application of Requirements Lists

In the last few years it has been shown that, at least for original designs, the formulation of a requirements list is a very efficient method for solution development and has been broadly adopted by industry. When used in practice, however, the following issues often arise:

- *Obvious requirements*, such as low-cost production, ease of assembly, are often not included in the requirements list. One should take care that these issues are both addressed and expressed precisely.
- In an early stage of the project it is not always possible to make *precise statements* in the requirements list. The statements have to be amended or corrected during the design and development process.
- A *stepwise development* of the requirements list is very useful when tasks are poorly defined. In these cases the requirements should be formulated more precisely as soon as possible.

- During the formulation of requirements lists or related discussions, *functions* or *solution ideas* are often mentioned. This is not wrong. They can encourage a clearer formulation of the requirements and even lead to the identification of new requirements. The solution ideas or proposals generated should be recorded so that they can be used later in the systematic search for solutions. However, they should not enter—and possibly bias—the requirements list.
- The identification of *deficiencies* and *failures* can initiate requirements that must then be formulated in a solution-neutral way. Failure analysis is often the starting point for a requirements list.
- For *adaptive* or *variant designs*, designers should still make requirements lists for themselves, even when the task is small.
- Setting up requirements lists should not be formalised too strictly. *Guidelines* and *forms* are only a *means* to prevent important issues from being forgotten and to provide a supporting structure. If one deviates from the recommendations in this book, one should a least consider the main characteristics and distinguish between demands and wishes.

6 Conceptual Design

Conceptual design is the part of the design process where—by identifying the essential problems through abstraction, establishing function structures, searching for appropriate working principles and combining these into a working structure—the basic solution path is laid down through the elaboration of a solution principle. Conceptual design *specifies the principle solution*.

From Figure 4.3 we can see that the conceptual phase is preceded by a decision. The purpose of this decision is to answer the following questions based on the requirements list agreed upon during task clarification:

- Has the task been clarified sufficiently to allow the development of a solution in the form of a design?
- Is a conceptual elaboration really needed, or do known solutions permit direct progress to the embodiment and detail design phases?
- If the conceptual stage is indispensable, how and to what extent should it be developed systematically?

6.1 Steps of Conceptual Design

According to the procedural plan outlined in Section 4.2, the conceptual design phase follows the clarification of the task. Figure 6.1 shows the steps involved, correlated in such a way as to satisfy the principles of the general problem solving process set out in Section 4.1.

The reasons for the individual steps have been examined in Section 4.2 and need not be discussed further here. It should, however, be mentioned that refinements of any one of the steps by reiteration on a higher information level should be made whenever necessary. The loops involved have been omitted from Figure 6.1 for the sake of greater clarity.

The individual steps and the appropriate working methods for the conceptual design phase will now be examined in detail.

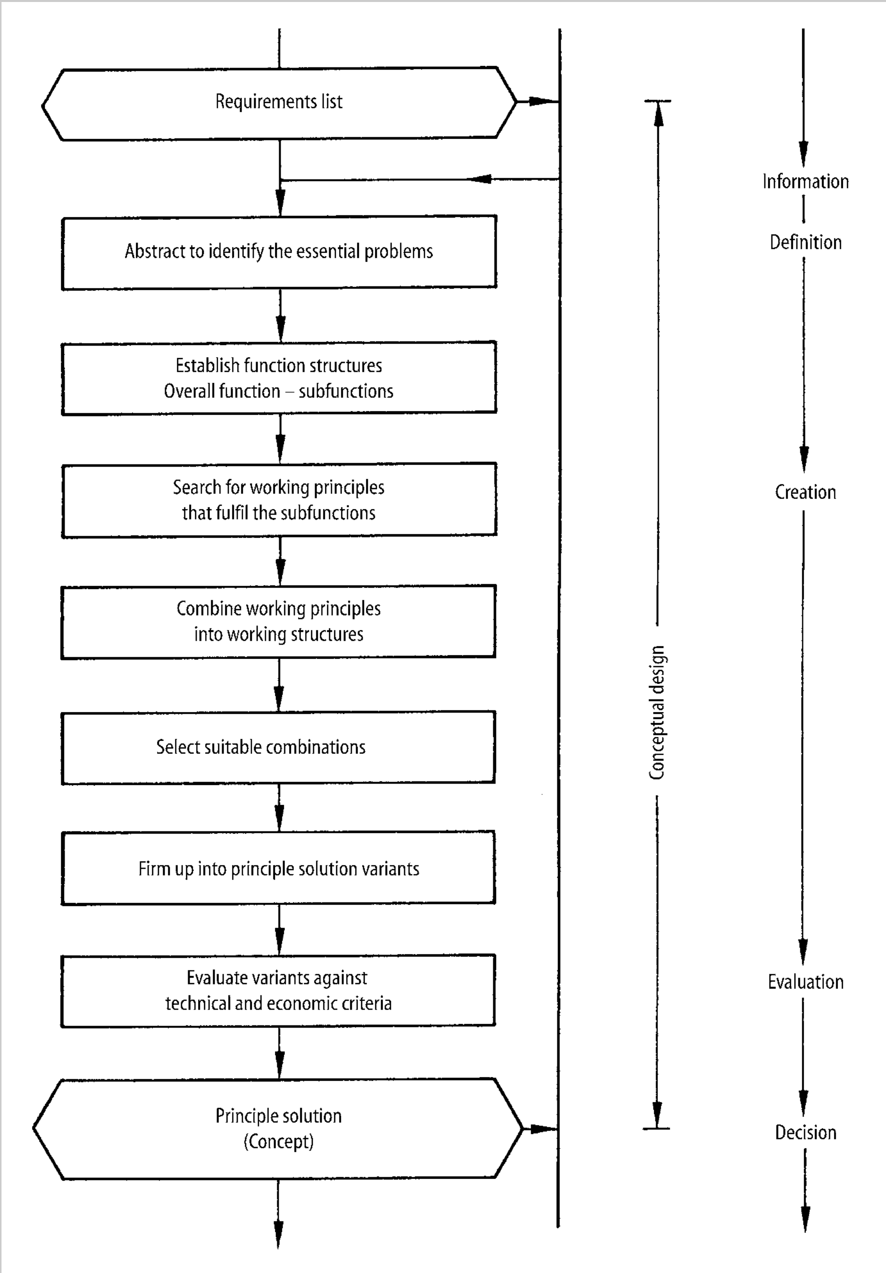


Figure 6.1. Steps of conceptual design

6.2 Abstracting to Identify the Essential Problems

6.2.1 Aim of Abstraction

Solution principles or designs based on traditional methods are unlikely to provide optimum answers when new technologies, procedures, materials, and also new scientific discoveries, possibly in new combinations, hold the key to better solutions.

Every industry and every design office is a store of experiences as well as of prejudices and conventions which, coupled to the wish to minimise risks, stand in the way of better and more economic but unconventional solutions. The client, customer or product planning group might have included specific proposals for a solution in the requirements list. It is also possible that during the discussion of individual requirements, ideas and suggestions for realising a solution will emerge. In the unconscious, at least, certain solutions might exist. Perhaps concrete ideas already exist, however these could be based on fixed ideas and fictitious constraints.

In their search for optimum solutions, designers, far from allowing themselves to be influenced by fixed or conventional ideas, must therefore examine very carefully whether novel and more suitable paths are open to them. In order to solve the problem of fixation and sticking with conventional ideas, *abstraction* is used. This means ignoring what is particular or incidental and emphasising what is general and essential. Such generalisation leads straight to the *crux of the task*. If it is properly formulated, then the overall function and the essential constraints become clear without prejudicing the choice of a particular solution in any way.

As an example, consider the improvement of a labyrinth seal in a high-speed turbine in accordance with a set of requirements. The task is described in detail by means of a requirements list and the formulation of the goal to be achieved. In the abstracting approach, the crux of the task would not so much be the design of a labyrinth seal as that of a shaft seal without physical contact, with due regard being paid to certain operating and spatial constraints, and also to cost limits and delivery times. Specifically, the designer should ask whether the crux is:

- to improve the technical functions, e.g. the sealing quality or safety
- to reduce weight or space
- to significantly lower costs
- to significantly shorten delivery times
- to improve production methods.

All of these questions might have to be satisfied by the overall solution, but their importance may differ from case to case. Nevertheless, due regard must be paid to each of them, since any one of them is likely to provide the impetus for the discovery of a new and better solution principle. New developments involving a proven solution principle, coupled to modifications in production methods, are often imposed by the need to lower costs and shorten delivery times.

Thus, if an improvement in the sealing properties were the crucial requirement in the example we have mentioned, new sealing systems would have to be found.

This would mean studying the flow of fluids in narrow passages and, from the knowledge acquired, providing for better sealing properties, while also satisfying the other subproblems we have mentioned.

If, on the other hand, cost reduction were the crucial point then, after an analysis of the cost structure, one would have to see whether the same physical effects could be produced through the use of cheaper materials, by reducing the number of components or by using a different production process. It is also possible to search for new concepts to achieve a better or at least similar sealing performance for lower cost.

It is the identification of the crux of the task with the functional connections and the task-specific constraints that throws up the essential problems for which solutions have to be found. Once the crux of the task has been clarified, it becomes much easier to formulate the overall task in terms of the essential subproblems as they emerge [6.2, 6.6, 6.13].

6.2.2 Broadening the Problem Formulation

This is the best point in the process to bring in those designers who are actually going to be responsible for the project. Having identified the crux of the task by correct problem formulation, a step-by-step enquiry is now initiated to discover if an extension of, or even a change in, the original task might lead to promising solutions.

An excellent illustration of this procedure has been given by Krick [6.5]. The task he used as an example was an improved method of filling, storing and loading bags of animal feed. An analysis gave the situation shown in Figure 6.2. It would have been a grave mistake to begin immediately by thinking of possible improvements to the existing situation. By proceeding in this way one is likely to ignore other, more useful and more economic solutions. Using abstraction and the systematic extension of what is already known about the task, the following problem formulations are possible, each representing a higher level of abstraction than the last:

1. Filling, weighing, closing and stacking bags of feed.
2. Transferring feed from the mixing silo to stacked bags in the warehouse.
3. Transferring feed from the mixing silo to bags on the delivery truck.
4. Transferring feed from the mixing silo to the delivery truck.
5. Transferring feed from the mixing silo to a delivery system.
6. Transferring feed from the mixing silo to the consumer's storage bins.
7. Transferring feed from ingredient containers to consumer's storage bins.
8. Transferring feed ingredients from their source to the consumer.

Krick has incorporated some of these formulations into a diagram (see Figure 6.3).

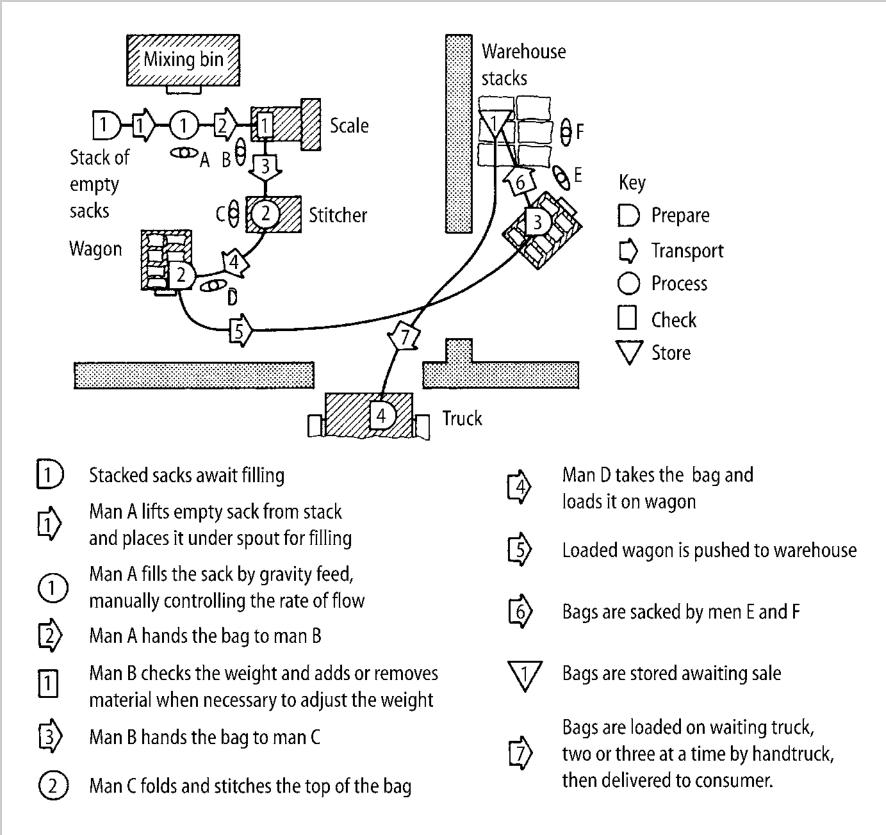


Figure 6.2. The present method of filling, storing and loading bags of feed. After [6.5]

It is characteristic of this approach that the problem formulation is made as broad as possible in successive steps. In other words, the current or obvious formulation is not accepted at face value but *broadened systematically*. Although this may conflict with decisions already taken, it opens up new perspectives. Thus, formulation 8 above is the broadest, the most general and the least circumscribed.

The crux of the task, in fact, is the transport of the correct quantity and quality of feed from the producer to the consumer and not, for instance, the best method of closing or stacking bags, or moving them into the warehouse. With a broader formulation, solutions may appear that render the filling of bags and storing them in the warehouse unnecessary.

How far this process of abstraction is continued depends on the constraints. In the case under consideration, Formulation 8 must be rejected on technical, seasonal and meteorological grounds: the consumption of feed is not confined to harvest time; for various reasons consumers will not want to store feed for a whole year; moreover, they may be reluctant to mix the required ingredients themselves. However, the transfer of feed on demand, for instance, with delivery trucks taking

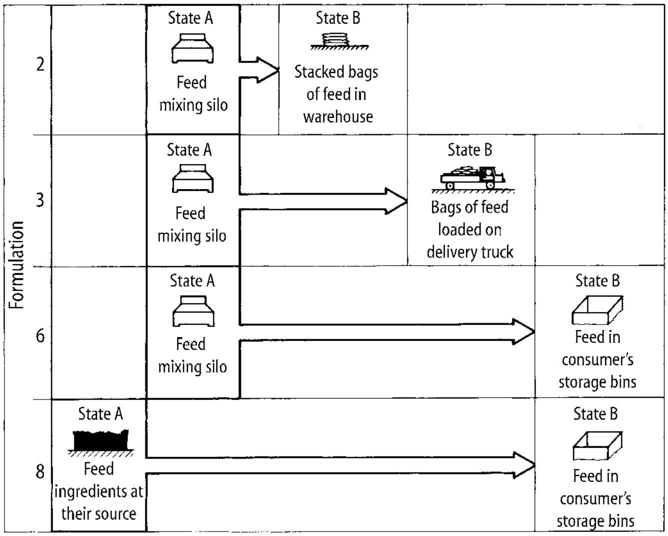


Figure 6.3. Alternative formulations of the feed distribution problem, illustrating progressively broader formulations of a problem. After [6.5]. A = initial state; B = final state

it directly from the mixing silo to consumers' storage bins (Formulation 6), is more economical than intermediate storage in a warehouse and the transport of smaller quantities in bags. In this connection, the reader might recall a development in a different field which culminated in the delivery of ready-mixed concrete direct to building sites in special vehicles.

We have tried to show how comprehensive problem formulation on an abstract plane opens the door to better solutions. This approach, furthermore, helps to raise the influence and responsibility of designers by giving them an overview of the problem and thus involving them in, for instance, environmental protection and recycling. It is useful to analyse the requirements list as set out in the next section.

6.2.3 Identifying the Essential Problems from the Requirements List

The clarification of the task with the help of a requirements list will have helped to focus attention on the problems involved and will have greatly increased the particular level of information (see Chapter 5). Elaborating the requirements list may thus be said to have prepared the way for following steps.

Here the task is to *analyse the requirements list* with respect to the required function and essential constraints in order to confirm and refine the crux of the problem. Roth [6.11] advises that the functional relationships contained in the requirements list should be formulated explicitly and arranged in order of their importance.

That analysis, coupled to the following step-by-step abstraction, will reveal the general aspects and essential problems of the task, as follows:

Step 1. Eliminate personal preferences.

Step 2. Omit requirements that have no direct bearing on the function and the essential constraints.

Step 3. Transform quantitative into qualitative data and reduce them to essential statements.

Step 4. As far as it is purposeful, generalise the results of the previous step.

Step 5. Formulate the problem in solution-neutral terms.

Depending on either the nature of the task or the size of the requirements list (or both), certain steps may be omitted.

Table 6.1 illustrates abstraction based on these steps using the requirements list for a motor vehicle fuel gauge shown in Figure 6.4. The general formulation makes it clear that, with respect to the functional relationships, the problem is the measurement of quantities of liquid, and that this is subject to the essential conditions that the quantity of liquid is changing continuously and that the liquid is in containers of unspecified size and shape.

This analysis thus leads to a definition of the objective on an abstract plane without laying down any particular solution.

In principle, all paths must be left open until such time as it becomes clear which solution principle is the best. Thus designers must question all the constraints they are given and work out with the client or proposer whether or not they should be retained as genuine restrictions. In addition, designers must learn to discard fictitious constraints that they themselves have come to accept, and to that end ask critical questions and test all their presuppositions. Abstraction helps to identify fictitious constraints and to eliminate all but genuine restrictions.

We shall conclude this section with a few examples of purposeful abstraction and problem formulation:

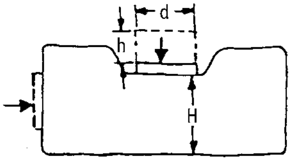
- Do not design a garage door, but look for means of securing a garage in such a way that a car is protected from thieves and the weather.
- Do not design a keyed shaft, but look for the best way of connecting a gear wheel and shaft.
- Do not design a packing machine, but look for the best way of despatching a product safely or, if specific constraints really exist, of packing a product safely, compactly and automatically.
- Do not design a clamping device, but look for a means of keeping a workpiece firmly fixed.

From the above formulations, and this is very helpful for the next step, the final formulation can be derived in a way that does not prejudice the solution, i.e. is *solution-neutral*, and at the same time turns it into a *function*:

- "Seal shaft without contact", not "Design a labyrinth seal".
- "Measure quantity of fluid continuously", not "Gauge height of liquid with a float".
- "Measure out feed", not "Weigh feed in sacks".

TH Darmstadt	Requirements list for fuel gauge	3rd issue 10/07/85 Page 1

Changes	D W	Requirements	Responsible
		• <u>Container</u>	
		<u>Geometry</u> H = 100 mm – 600 mm Volume: 20 – 160 litres	
	W	2 – 630 litres	
		Shape fixed but unspecified (rigid)	
	W	Container flexible or only partially rigid	
		<u>Material:</u> steel, plastic <u>Connection to container</u> Bayonet socket, clamped connections, top or side:	
	W	d = ∅71 mm, h = 20 mm	
		Tank not pressurised (ventilated) Pressure test for container 0.3 bar	
		<u>Contents, temperature range</u>	
	W	(see table below: Engine oil)	
	W	• <u>Display</u> System with electric input signal – Moving magnet instrument (catalogue) – Bimetallic instrument (catalogue) – Board computer	
		Availabel source of energy: DC at 12 V, 24 V Voltage variation – 10 % to + 25 % of nominal voltage Current consumption max. 300 mA	



Liquid	Operating Range °C	Storage enviroment °C
Petrol	– 25 to + 65	
Diesel	– 24 to + 65	– 40 to + 100
Engine oil	up to + 140	– 40 to + 100

	Replaces 2nd issue of 27/06/1973	

Figure 6.4. Requirements list: motor vehicle fuel gauge

TH Darmstadt	Requirements list for fuel gauge	3rd issue 10/07/85 Page 2

Changes	D W	Requirements	Responsible
		• <u>System to be developed</u>	
		<u>Geometry</u>	
		Consider connection constraints to container	
		<u>Kinematics</u>	
	W	No moving parts	
		<u>Energy (see display)</u>	
		<u>Material</u> (see container)	
		<u>Signal</u>	
		∘ <u>Input</u>	
		Minimum measurable content: 3 % of maximum value	
		Reserve tank contents by special signal	
	W	Signal unaffected by angle of liquid surface	
		Possibility of signal calibration	
	W	Possiblity of signal calibration with full container	
		∘ <u>Output</u>	
	W	Output of transmitter: electric signal	
		Output signal accuracy at max. value ±3%	
	W	±2%	
		(together with indicator error ±5%)	
		Under normal conditions, horizontal level, v=const.	
		Able to withstand shocks of normal driving	
		Response sensitivity: 1% of maximum output signal	
	W	0.5% of maximum output signal	
		∘ <u>Connection between input and output</u>	
		Distance container – display: ≠zero m;	
		3 m–4 m	
	W	1 m–20 m	
		Separate power possible	
		<u>Production</u>	
		large-scale production	

	Replaces 2nd issue of 27/06/1973	

Figure 6.4. (continued)

TH Darmstadt	Requirements list for fuel gauge	3rd issue 10/07/85 Page 3

Changes	D W	Requirements	Responsible
		<u>Test requirements</u>	
		<u>Operating conditions of vehicle</u>	
		Forward acceleration $\pm$ 10 m/s^2	
		Sideways acceleration $\pm$ 10 m/s^2	
		Upward acceleration (vibration), up to 30 m/s^2	
	W	Shocks in forward direction without damage, up to 30 m/s^2	
		Forward tilt up to $\pm 30°$	
		Sideways tilt max 45°	
		Salt spray tests for inside and outside components according to client's requirements (DIN 90905 to be considered)	
		Must conform with heavy vehicle regulations	
		<u>Operation, Maintenance</u>	
	W	Installation by non-specialist	
		Life expectancy 10^4 level changes (full/empty)	
		Minimum of 5 years service life	
		Fuel gauge replaceable	
		Fuel gauge maintenance-free	
	W	Fuel gauge simply modified to suite different container sizes	
		<u>Regulations</u>	
		No regulations relating to explosion safety	
		<u>Quantity</u>	
		10000/day of adjustable type	
		5000/day of the most popular type	
		Costs	
		Manufacturing costs $\leq$ DM 6.00 each (without display)	

	Replaces 2nd issue of 27/06/1973	

Figure 6.4. (continued)

Table 6.1. Procedure during abstraction: motor vehicle fuel gauge based on requirements list given in Figure 6.4

Result of Steps 1 and 2

- Volumes: 20 to 160 litres
- Shape of container: fixed or unspecified (rigid)
- Top or side connection
- Height of container: 100 mm to 600 mm
- Distance between container and indicator: $\neq 0$ m, 3 m to 4 m
- Petrol and diesel, temperature range: $-25\,°C$ to $65\,°C$
- Output of transmitter: unspecified signal
- External energy: DC at 12 V, 24 V. Variation -15% to $+25\%$
- Output signal accuracy at maximum $\pm 3\%$ (together with indicator error $\pm 5\%$)
- Response sensitivity: 1% of maximum signal output
- Possibility of signal calibration
- Minimum measurable content: 3% of maximum value

Result of Step 3

- Various volumes
- Various container shapes
- Various connections
- Various contents (liquid levels)
- Distance between container and indicator: $\neq 0$ m
- Quantity of liquid varies with time
- Unspecified signal
- (with outside energy)

Result of Step 4

- Various volumes
- Various container shapes
- Transmission over various distances
- Measure (continuously changing) quantities of liquid
- (with outside energy)

Result of Step 5 (Problem formulation)

- Measure continuously changing quantities of liquid in containers of unspecified size and shape and indicate the measurements at various distances from the containers.

6.3 Establishing Function Structures

6.3.1 Overall Function

According to Section 2.1.3, the requirements determine the function that represents the intended overall relationship between the inputs and the outputs of a plant, machine or assembly. In Section 6.2 we explained that problem formulation obtained by abstraction does much the same. Hence, once the crux of the overall problem has been formulated, it is possible to indicate an *overall function* that, based on the *flow of energy, material and signals* can, with the use of a *block diagram*, express the solution-neutral relationship between *inputs* and *outputs*. That relationship must be specified as precisely as possible (see Figure 2.3).

In our example of a fuel gauge (see Figure 6.4), quantities of liquid are introduced into and removed from a container, and the problem is to measure and indicate the quantity of liquid found in the container at any one time. The result, in the liquid system, is a flow of material with the function "store liquid" and, in the measuring system, a flow of signals with the function "measure and indicate quantity of liquid". The second is the overall function of the specific task under consideration, that is, the development of a fuel gauge (see Figure 6.5). That overall function can be broken down into subfunctions in a further step.

6.3.2 Breaking a Function Down into Subfunctions

Depending on the complexity of the problem, the resulting overall function will in turn be more or less complex. By complexity we mean that the transparency of the relationships between inputs and outputs is relatively poor, that the required physical processes are relatively intricate, and that the number of assemblies and components involved is relatively large.

Just as a technical system can be divided into subsystems and elements (see Section 2.1.3), so a complex or *overall function* can be broken down into *subfunctions* of lower complexity. The combination of individual subfunctions results in a *function structure* representing the overall function.

The aims of breaking down complex functions are to:

- determine subfunctions that facilitate the subsequent search for solutions
- combine these subfunctions into a simple and unambiguous function structure.

Let us return to the example of the fuel gauge (see Sections 6.2.3 and 6.3.1). The starting point is the problem formulation for the overall function given in Figure 6.5.

The flow of signals has been treated as the main flow. Associated subfunctions are developed in several steps. As a first step, the contents of the container have to be measured and the resulting signal received. This signal has to be channelled and

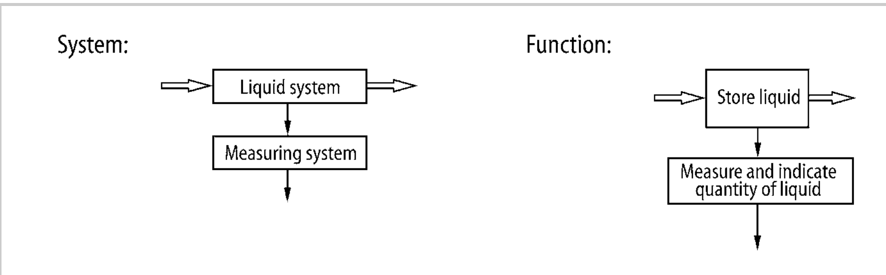


Figure 6.5. Overall functions of the systems involved in measuring the contents of a container. After Figure 6.4 and Table 6.1

finally displayed to the driver to indicate the contents of the container. Thus, three important direct main functions have been identified. Possibly the signal needs to be changed before it can be channelled. Figure 6.6 shows the development and variation of a function structure in accordance with the suggestions set out in this section.

Since the requirements list also provides for measurements in containers of different sizes holding varying initial quantities of liquid, an adjustment of the signal to the respective size of the container is expedient, and is accordingly introduced as an auxiliary function. Measurements in containers of various unspecified shapes will, in certain circumstances, demand the correction of the signal as another auxiliary function. The measuring operation may require a supply of external energy, which must then be introduced as a further flow. Finally, consider the system boundary. If existing indicating instruments are to be used, the device will have to emit an electric output signal. If they are not, then the subfunctions "channel signal" and "indicate signal" must be included in the search for solutions. In this way, a function structure with suitable subfunctions can be developed. The individual subfunctions are of a lower complexity than the overall function and, furthermore, it will become clear which subfunction provides the most useful starting point for the search for solutions.

In our example, this important solution-determining subfunction, that has the working principle upon which the others clearly depend, is "receive signal" (see Figure 6.6). The initial search for solutions should therefore focus on this subfunction. The solution selected for this will largely decide to what extent individual subfunctions can be changed round or omitted. It also allows for better judgement of whether to use existing channelling and display solutions or whether to seek a new solution for these subfunctions, i.e. an extension of the system boundary.

Further recommendations for identifying and formulating subfunctions are now described.

It is useful to start by determining the *main flow* in a technical system, if this is clear. The *auxiliary flows* should only be considered later. When a basic function structure, including the most important links, has been found, it is easier to undertake the next step; that is, to consider the auxiliary flows with their subfunctions and to achieve a further subdivision of complex subfunctions. For this step it is helpful to create a temporary working structure or a solution for the *basic function structure*, without, however, prejudicing the final solution.

The optimum method of breaking down an overall function—that is, the number of subfunction levels and also the number of subfunctions per level—is determined by the relative novelty of the problem and also by the method used to search for solutions. In the case of *original designs*, neither the individual subfunctions nor their relationships are generally known. In that case, the search for and establishment of an optimum function structure constitute some of the most important steps of the conceptual design phase. In the case of *adaptive designs*, on the other hand, the general structure with its assemblies and components is much more well-known, so that a function structure can be obtained by analysing the existing product. Depending on the special demands of the requirements list, that function

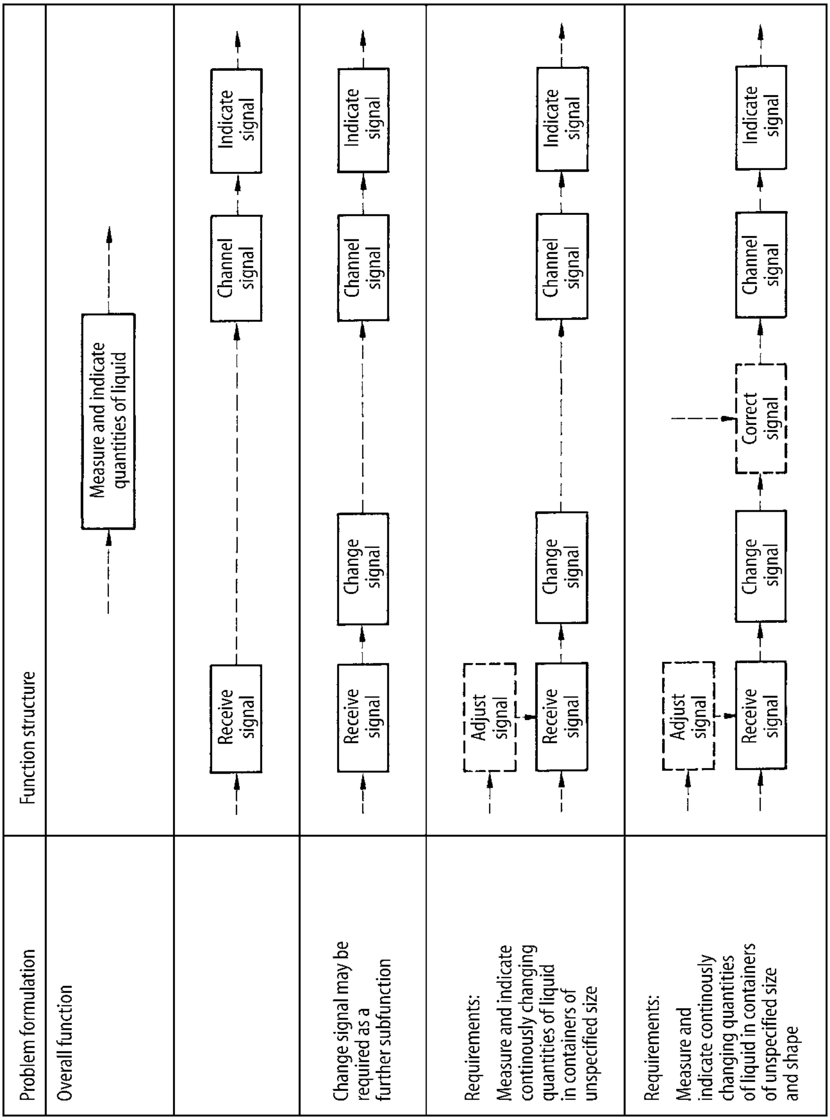


Figure 6.6. Development of a function structure for a fuel gauge

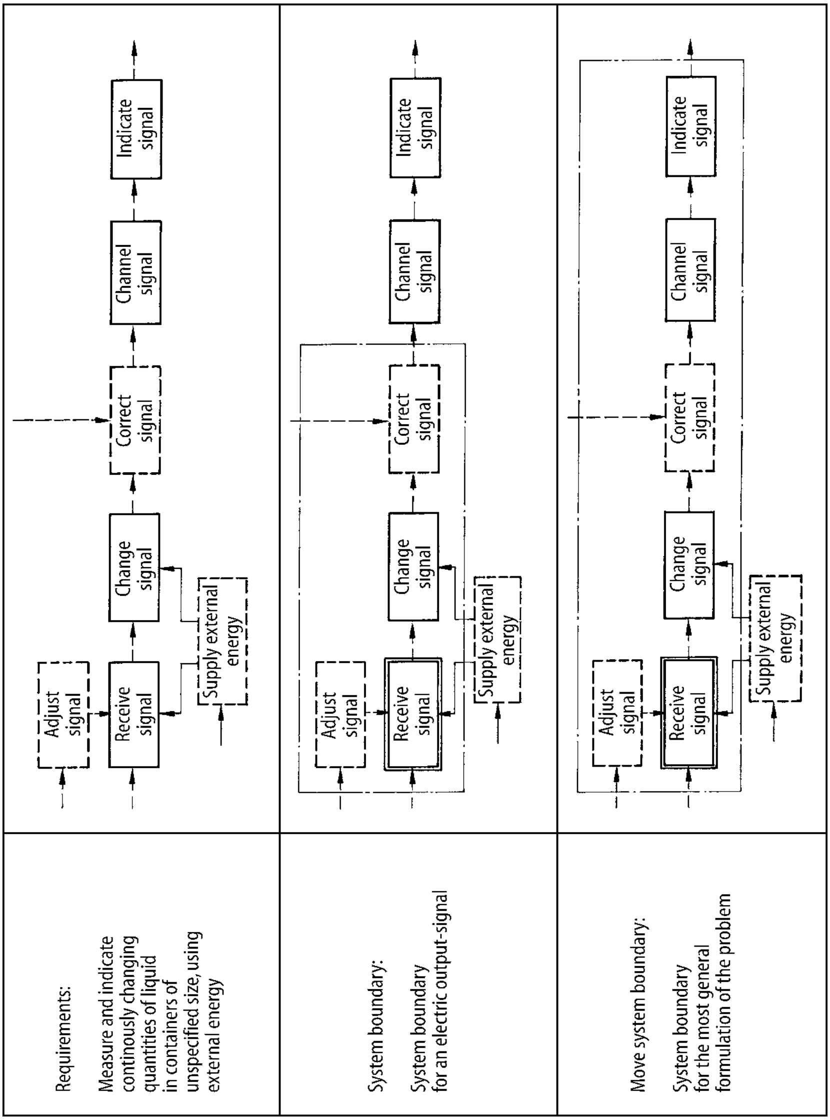


Figure 6.6. (continued)

structure can be modified by the variation, addition or omission of individual subfunctions or by changing the way that they are combined.

Function structures are of great importance in the development of modular systems. For this type of *variant design*, the physical structure—that is, the assemblies and individual components used as building blocks and also their interfaces—must be reflected in the function structure (see also Section 9.2.1).

A further advantage of setting up a function structure is that it permits the *clear definition* of existing subsystems or of those to be newly developed, so that they can be *dealt with separately*. If existing assemblies can be assigned directly as complex subfunctions, the subdivision of the function structure can be discontinued at a fairly high level of complexity. In the case of new assemblies or those requiring further development, however, the division into subfunctions of decreasing complexity must be continued until the search for solutions seems promising. By adapting function structures to the novelty of the task or the subsystem, the use of function structures can save a great deal of time and money.

Apart from aiding in the search for solutions, function structures or their subfunctions can also be used for purposes of classification. Examples are the "classifying criteria" of classification schemes (see Section 3.2.3) and the subdivision of design catalogues.

It may prove expedient not only to set up task-specific functions, but also to elaborate the function structure from *generally valid subfunctions* (see Figure 2.7). The latter recur in technical systems, and may be helpful when searching for a solution since they may lead to the discovery of task-specific subfunctions or because design catalogues may list solutions for them. Defining generally valid functions can also be of use when varying function structures, for example to optimise the energy, material and signal flows. The following list and examples should be helpful in this regard.

Conversion of energy:

- Changing energy (e.g. electrical into mechanical energy)
- Varying energy components (e.g. amplifying torque)
- Connecting energy with a signal (e.g. switching on electrical energy)
- Channelling energy (e.g. transferring power)
- Storing energy (e.g. storing kinetic energy)

Conversion of material:

- Changing matter (e.g. liquefying a gas)
- Varying material dimensions (e.g. rolling sheet metal)
- Connecting matter with energy (e.g. moving parts)
- Connecting matter with signal (e.g. cutting off steam)
- Connecting different types of materials (e.g. mixing or separating materials)
- Channelling material (e.g. mining coal)
- Storing material (e.g. keeping grain in a silo)

Conversion of signals:

- Changing signals (e.g. changing a mechanical into an electrical signal, or a continuous into an intermittent signal)
- Varying signal magnitudes (e.g. increasing a signal's amplitude)
- Connecting signals with energy (e.g. amplifying measurements)
- Connecting signals with matter (e.g. marking materials)
- Connecting signals with signals (e.g. comparing target values with actual values)
- Channelling signals (e.g. transferring data)
- Storing signals (e.g. in databases)

In many cases in industry it may not be expedient to build up a function structure from generally valid subfunctions, because they are, in fact, too general and thus do not provide a sufficiently concrete picture of the relationships to aid the subsequent search for solutions. In general, a clear picture only emerges after adding more task-specific details (see Section 6.3.3).

To illustrate the approach some expamples follow. Figures 6.7 and 6.8 show the function structure of a tensile testing machine with a relatively complex flow of energy, material and signals. In this type of overall function, the function structure is built up step-by-step from subfunctions, with attention initially focused on essential main functions. Thus, on a first functional level, only the subfunctions

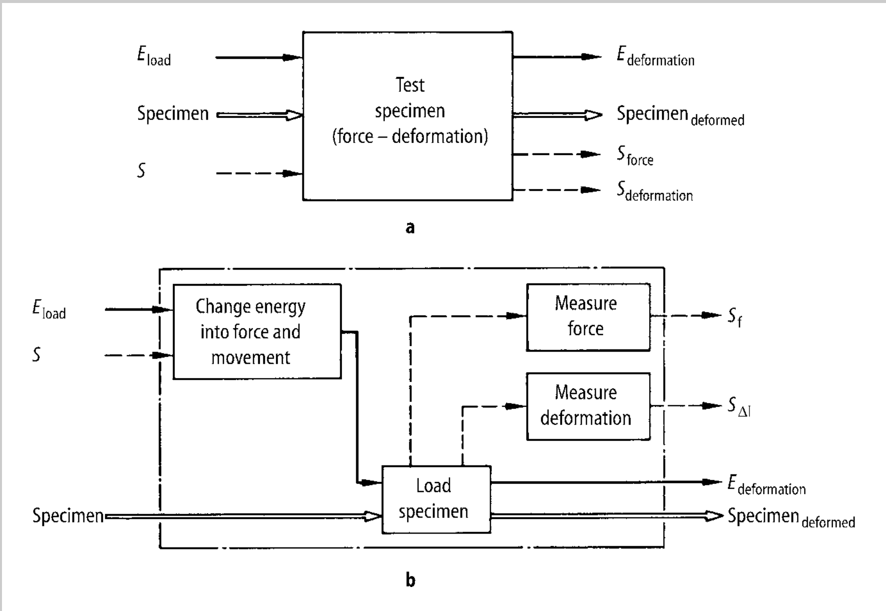


Figure 6.7. Overall function **a** and subfunctions (main functions) **b** of a tensile testing machine

that directly satisfy the required overall function are specified (see Figure 6.7). These are formulated as complex subfunctions, such as "change energy into force and movement" and "load specimen" in our example. Starting with complex subfunctions helps to establish a simple function structure.

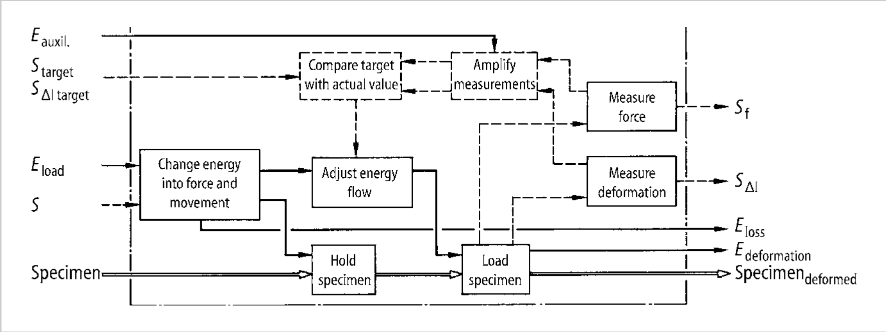


Figure 6.8. Completed function structure for the overall function set out in Figure 6.7

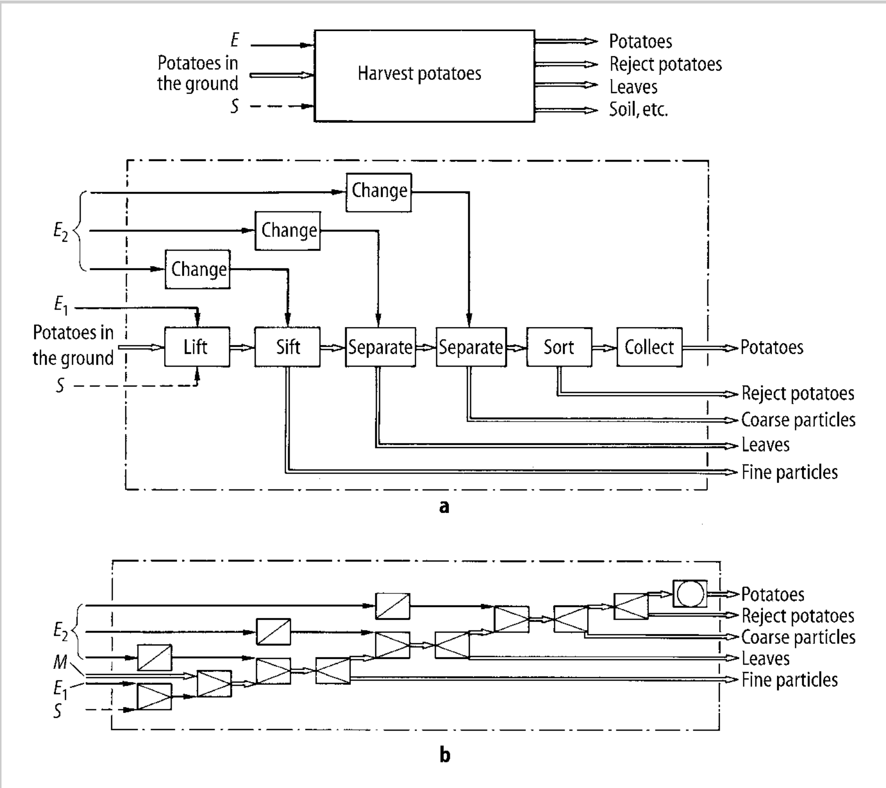


Figure 6.9. **a** Function structure of a potato harvesting machine **b** For comparison: diagram with generally valid functions based on [6.1], Figure 2.7

In the problem under consideration, the energy and signal flows are of roughly equivalent importance in the search for solutions, while the flow of material—the exchange of specimens—is only essential for the holding function added in Figure 6.8. In this figure, an adjusting function for the load magnitudes and, at the output of the system, the energy lost during the energy flow were also added because both clearly affect the design. The energy required to deform the specimen is lost with the material flow when the specimen is exchanged. Moreover, the auxiliary functions "amplify measurements" and "compare target with actual values" proved indispensable for the adjustment of the energy level.

There are, however, some problems in which variation of the main flow alone cannot lead to a solution, because *auxiliary flows* have a *crucial* bearing on the design and are solution-determining. As an example, let us consider the function structure of a potato harvesting machine. Figure 6.9a shows the overall function and the function structure based on the flow of material (the main flow) and the auxiliary flows of energy and signals. In Figure 6.9b, by comparison, the function structure is represented by means of generally valid functions, in order to emphasise the clear interrelationship of the different flows.

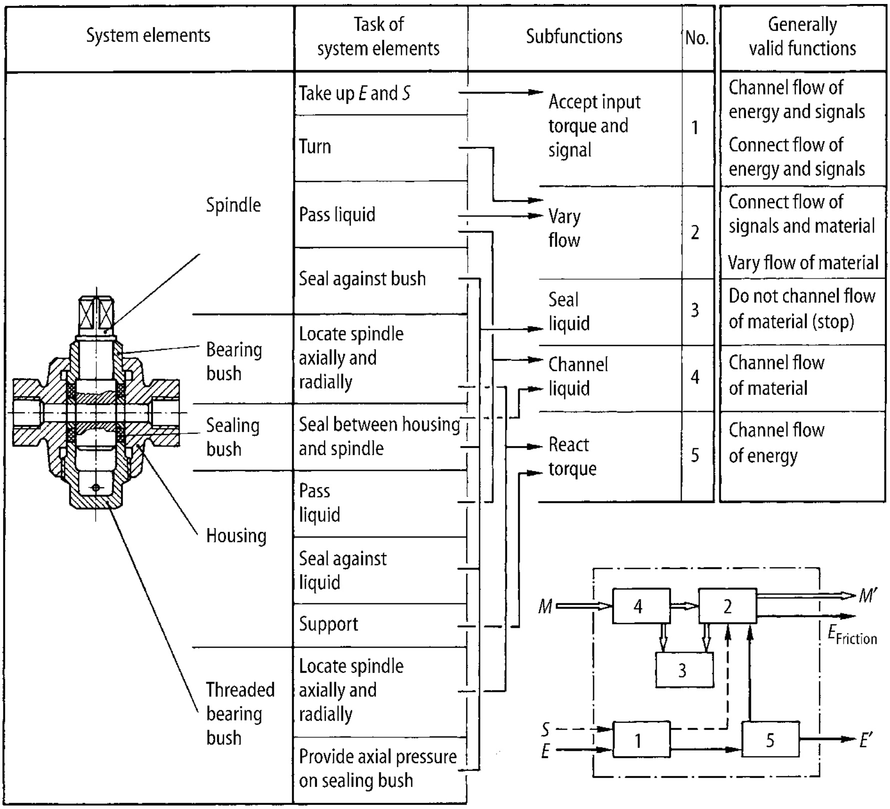


Figure 6.10. Analysis of a flow control valve with respect to its function structure

When generally valid functions are used, the separation into subfunctions is generally more pronounced than it is in the case of task-specific subfunctions. Thus, in the present example, the subfunction "separate" is replaced with the generally valid functions "connect energy with material mix" and "separate material mix" (the reverse of "connect"). The representation, however, is on such an abstract level that it is not easy to understand and requires further interpretation.

Our final example illustrates the derivation of function structures by the *analysis of existing systems*. This method is particularly suitable for developments in which at least one solution with the appropriate function structure is known, and the main problem is the discovery of better solutions. Figure 6.10 shows the steps used in the analysis of a flow control valve (a typical on–off switch), showing the individual tasks of the various elements and the subfunctions satisfied by the system. The function structure can be derived from the subfunctions and then varied in order to improve the product.

The function structure for the one-handed mixing tap examined in Section 6.6 clearly shows that the study of function structures may prove extremely useful, even after the physical effect has been selected, for determining the behaviour of the system at a very early stage of its development, and hence for identifying the structure that best suits the problem under consideration.

6.3.3 Practical Applications of Function Structures

When establishing function structures, we must distinguish between original and adaptive designs. In the case of *original designs*, the basis of a function structure is the *requirements list* and the *abstract formulation of the problem*. Among the demands and wishes, we are able to identify functional relationships, or at least the subfunctions at the inputs and outputs of a function structure. It is helpful to write out the functional relationships arising from the requirements list in the form of sentences and to arrange these in the order of their anticipated importance or in some other logical order [6.11].

In the case of *adaptive designs*, the starting point is the *function structure of the existing solution* obtained by analysing its elements. It helps to develop variants in order to open the path for other solutions, for subsequent optimisation and for the development of modular products. The identification of functional relationships can be facilitated by asking the right questions.

In modular systems, the function structure has a decisive influence on the modules and their arrangement (see Section 9.2). Here, the function structure and that of the assembly is affected not only by functional considerations, but also, and increasingly so, by production needs.

Function structures are intended to facilitate the discovery of solutions: they are not ends in themselves. The degree of detail used depends very much on the novelty of the task and the experience of the designers.

Moreover, it should be remembered that function structures are seldom completely free of physical or formal presuppositions, which means that the number of possible solutions is inevitably restricted to some extent. Hence, it is perfectly legitimate to conceive a preliminary solution and then abstract this by developing and completing the function structure by a process of iteration.

Anyone setting up a function structure ought to bear the following points in mind:

1. First derive a rough function structure with a few subfunctions from what functional relationships you can identify in the requirements list, and then break this rough structure down, step-by-step, by resolving complex subfunctions. This is much simpler than starting out with more complicated structures. In certain circumstances, it may be helpful to substitute a first solution idea for the rough structure and then, by analysing that first idea, to derive other important subfunctions. It is also possible to begin with subfunctions whose inputs and outputs cross the assumed system boundary. From these, we can then determine the inputs and outputs for the neighbouring functions; in other words, we work from the system boundary inwards.

2. If no clear relationship between the subfunctions can be identified, the search for a first solution principle may, under certain circumstances, be based on the mere *enumeration of identified subfunctions* without logical or physical relationships, but if possible these should be arranged according to the extent to which they have been realised.

3. *Logical relationships* may lead to function structures through which the logical elements of various working principles (mechanical, electrical, etc.) can be anticipated.

4. Function structures are not complete unless the existing or expected flows of energy, material and signals can be specified. Nevertheless, it is useful to begin by focusing attention on the *main flow* because, as a rule, it determines the design and is more easily derived from the requirements. The auxiliary flows then help with the further elaboration of the design, coping with faults, and when dealing with problems of power transmission, control, etc. The complete function structure, comprising all flows and their relationships, can be obtained by iteration; that is, by looking first for the structure of the main flow, completing that structure by taking the auxiliary flows into account, and then establishing the overall structure.

5. When setting up function structures it is useful to know that, in the conversion of energy, material and signals, several *subfunctions recur* in most structures and should therefore be introduced first. Essentially, these are the generally valid functions of Figure 2.7, and they can prove extremely helpful in the search for task-specific functions.

6. For the application of microelectronics, it is useful to consider signal flows as shown in Figure 6.11 [6.6]. This results in a function structure that clearly suggests the modular use of elements to detect (sensors), to activate (actuators), to operate (controllers), to indicate (displays) and, in particular, to process signals using microprocessors.

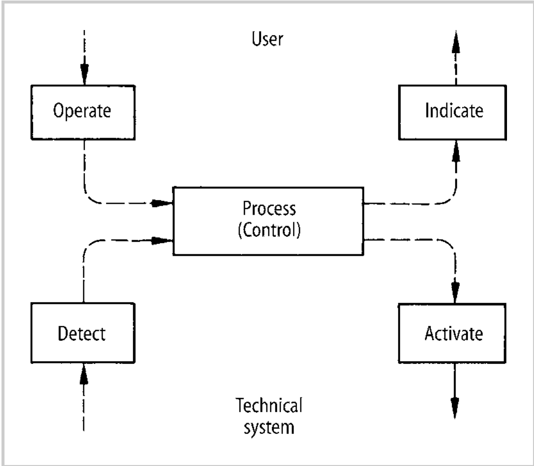


Figure 6.11. Basic signal flow functions for modular use in microelectronics. After [6.6]

7. From a rough structure, or from a function structure obtained by the analysis of known systems, it is possible to derive further *variants* and hence to optimise the solution, by:
   - breaking down or combining individual subfunctions
   - changing the arrangement of individual subfunctions
   - changing the type of switching used (series switching, parallel switching or bridge switching)
   - moving the system boundary.

   Because varying the function structure introduces distinct solutions, the setting up of function structures constitutes a first step in the search for solutions.
8. Function structures should be kept as *simple* as possible, in order to encourage simple and economical solutions. To this end, it is also advisable to aim at the combination of functions for the purpose of obtaining integrated function carriers. There are, however, some problems in which discrete functions must be assigned to discrete function carriers; for instance, when the requirements demand clarity in the solution, or when there is a need for extreme loading and quality. In this connection, the reader is referred to our discussion on the division of tasks (see Section 7.4.2).
9. In the search for solutions, only *promising function structures* should be introduced, which implies that a *selection procedure* (see Section 3.3.1) should be employed, even at this early stage.
10. For the *representation* of function structures it is best to use the *simple and informative symbols* shown in Figure 2.4, supplemented with task-specific verbal clarifications.

11. An *analysis* of the function structure leads to the identification of those subfunctions for which new working principles must be found, and of those for which known solutions can be used. This encourages an efficient approach. The search for solutions (see Section 3.2) then focuses on the subfunctions that are essential for the solution and on which the solutions of other subfunctions depend (see the example in Figure 6.6).

It is sometimes assumed wrongly that auxiliary functions are unimportant. Technical systems do not have functions that are "more important" or "less important". All functions are important because they are needed. Any functions that are not necessary or superfluous functions should be eliminated. It is only in order to reduce effort that designers start their search for solutions with the function that seems most important, i.e. solution-determining. All of the other functions are still necessary and must be fulfilled.

6.4 Developing Working Structures

6.4.1 Searching for Working Principles

Working principles need to be found for the various subfunctions, and these principles must eventually be combined into a working structure. The concretisation of the working structure will lead to the principle solution. A working principle must reflect the physical effect needed for the fulfilment of a given function and also its geometric and material characteristics (see Section 2.1.4). In many cases, however, it is not necessary to look for new physical effects, the form design (geometry and materials) being the sole problem. Moreover, in the search for a solution it is often difficult to make a clear mental distinction between the physical effect and the form design features. Designers therefore usually search for working principles that include the physical process along with the necessary geometric and material characteristics, and combine these into a working structure. Theoretical ideas about the nature and form of function carriers are usually presented by way of diagrams or freehand sketches.

It should be emphasised that the step we are now discussing is intended to lead to several solution variants, that is, a solution field. A solution field can be constructed by varying the physical effects and the form design features. Moreover, in order to satisfy a particular subfunction, several physical effects may be involved in one or several function carriers.

In Section 3.2 we discussed methods and tools for finding solutions. The same methods can be used in the search for working principles. Of particular importance, however, are literature searches, methods for analysing natural and known technical systems, and intuition-based methods (see Section 3.3.2). If preliminary solution ideas are available from product planning or through intuition, systematic analyses of physical processes and the utilization of classification schemes are also helpful (see Section 3.2.3). The last two methods usually provide several solutions.

Other important tools are design catalogues, in particular those proposed by Roth and Koller for physical effects and working principles (see Section 3.2.3)

[6.3, 6.11, 6.14]. When solutions need to be found for *several subfunctions*, it is expedient to select the functions as classifying criteria; that is, the subfunctions become the row headings and the possible working principles are entered in the columns. Figure 6.12 illustrates the structure of such a classification scheme, where the subfunctions are represented by F_i and the solution elements by S_{ij}. Depending on the level of concretisation, these solution elements can be physical effects or even working principles with geometric and material details.

As an example we consider the development of a cylinder–cylinder test rig in which two cylinders run against each other under a pulsating load. The aim was to investigate the friction characteristics for any combination of rolling and sliding speeds [6.9]. Figure 6.13 shows one possible function structure and Figure 6.14 the corresponding classification scheme. The main subfunctions identified are listed in the first column and potential solutions to those subfunctions are entered in the rows.

To sum up: the search for working principles for subfunctions should be based on the following guidelines:

- Preference should be given to the main subfunctions that determine the principle of the overall solution and for which no solution principle has yet been discovered.
- Classifying criteria and associated parameters (characteristics) should be derived from identifiable relationships between the energy, material and signal flows, or from associated systems.
- If the working principle is unknown, it should be derived from the physical effects and, for instance, from the type of energy. If the physical effect has been determined, appropriate form design features (working geometry, working motions and materials) should be chosen and varied. Checklists should be used to stimulate new ideas (see Figures 3.17 and 3.18).
- Designers should also enter solutions found intuitively and analyse which key classifying criteria influence particular working principles. These criteria should then be subdivided, limited or generalised using further headings.
- To prepare for the selection process, the important properties of the working principles should be noted.

Sub-functions \ Solutions		1	2	…	j	…	m
1	F_1	S_{11}	S_{12}		S_{1j}		S_{1m}
2	F_2	S_{21}	S_{22}		S_{2j}		S_{2m}
⋮	⋮	⋮	⋮		⋮		⋮
i	F_i	S_{i1}	S_{i2}		S_{ij}		S_{im}
⋮	⋮	⋮	⋮		⋮		⋮
n	F_n	S_{n1}	S_{n2}		S_{nj}		S_{nm}

Figure 6.12. Basic structure of a classification scheme with the subfunctions of an overall function and associated solutions

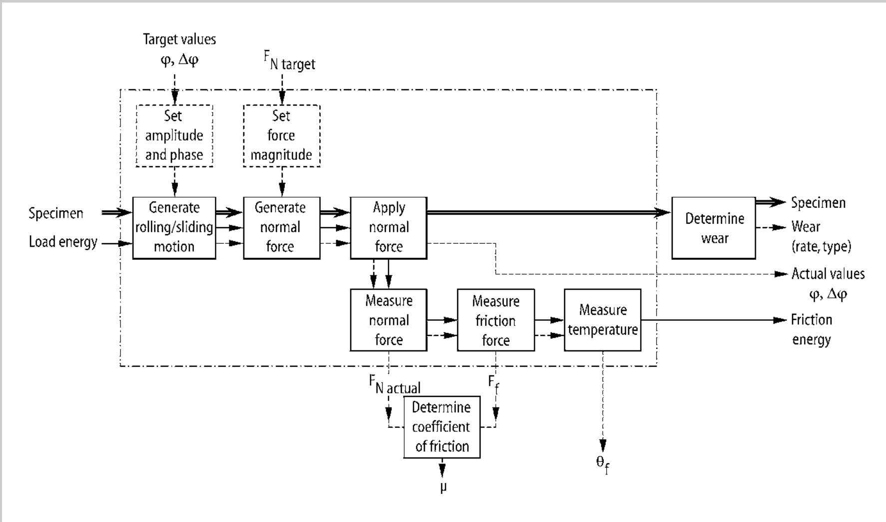


Figure 6.13. Possible function structure for a cylinder–cylinder test rig with a pulsating load for any combination of rolling and sliding motion

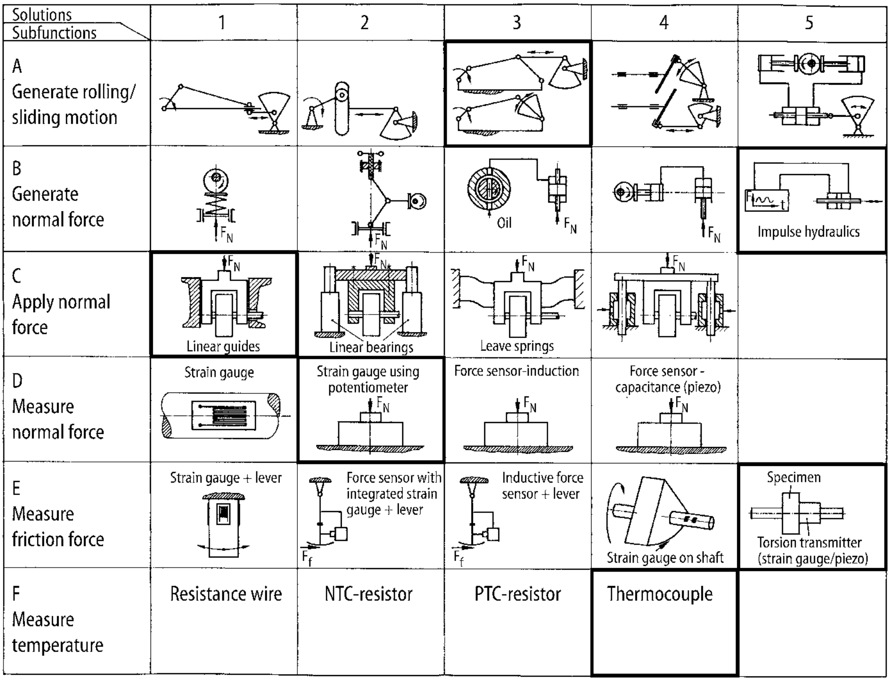


Figure 6.14. Classification scheme with possible solutions for the subfunctions identified in the function structure in Figure 6.13

Section 6.6 provides further examples that illustrate the search for working principles.

6.4.2 Combining Working Principles

To fulfil the overall function, it is then necessary to generate overall solutions by combining the working principles into a working structure, that is, system synthesis. The basis of such a combination is the established function structure, which reflects logically and physically possible or useful associations of the subfunctions.

In Section 3.2.4 the classification scheme of Zwicky (morphological matrix) was proposed as being particularly suitable for systematically combining solutions (see Figure 3.25). In this classification scheme, the subfunctions and the appropriate

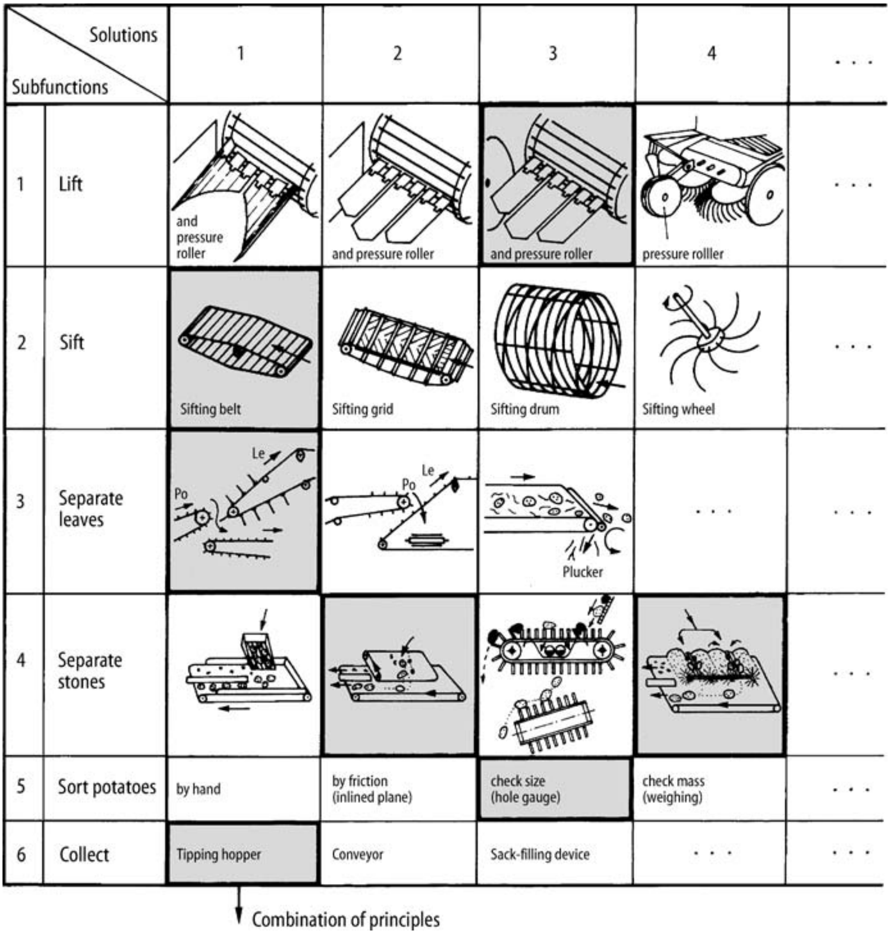


Figure 6.15. Combination of principles used to design a potato harvesting machine in accordance with the overall function structure shown in Figure 6.9. After [6.1]

solutions (working principles) are entered into the rows of the scheme. By systematically combining a working principle fulfilling a specific subfunction with the working principle for a neighbouring subfunction, one obtains an overall solution in the form of a possible working structure. In this process only those working principles that are compatible should be combined.

Figure 6.15 shows a possible combination of working principles for a potato harvesting machine [6.1]. It consists of working principles that are suitable for the subfunctions in the function structure shown in Figure 6.9. These have been made more concrete through rough sketches so that the assessment of their compatibility is facilitated. The principle solution of the harvesting machine based on this working structure is shown in Figure 6.16.

The main problem with combinatorial techniques is ensuring the physical and geometrical compatibility of the working principles to be combined, which in turn ensures the smooth flow of energy, material and signals. A further problem is the selection of technically and economically favourable combinations from the large field of theoretically possible combinations.

Combining solutions using mathematical methods (see Section 3.2.4) is only possible for working principles whose properties can be quantified. However, this is seldom possible at this early stage. Examples where it is possible are variant designs and control system designs, such as those using electronic or hydraulic components.

To sum up:

- Only combine compatible subfunctions (the compatibility matrix shown in Figure 3.26 is a useful tool).

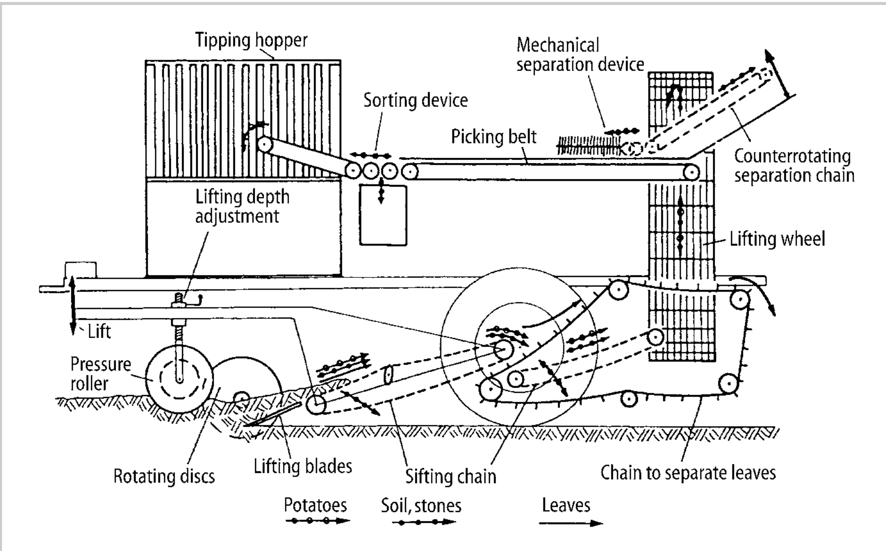


Figure 6.16. Principle solution of a potato harvesting machine, using a combination of principles from Figure 6.15

- Only pursue solutions that meet the demands of the requirements list and look like falling within the proposed budget (see the selection procedures in Sections 3.3.1 and 6.4.3).
- Concentrate on promising combinations and establish why these should be preferred above the rest.

6.4.3 Selecting Working Structures

Because working structures are generally not very concrete and the properties are only known qualitatively, the most suitable selection procedure is the one described in Section 3.3.1. This procedure is characterised by the activities of selecting and indicating preferences, and it makes use of a schematic selection chart that provides a clear overview and can be checked.

The solution field shown in Figure 6.14 for the cylinder–cylinder test rig is now evaluated for each subfunction's solution using a selection procedure. Figure 6.17 shows part of the selection chart indicating the most promising subfunction solutions, i.e. A3, B5, C1, etc. This suggests that combination A3-B5-C1-D2-E5-F4 could be a suitable combination for further concretisation. The working principles for this combination are highlighted in Figure 6.14.

Another way to make a rapid selection is to apply two-dimensional classification schemes, similar to the compatibility matrices shown in Figure 3.26. This will be illustrated using the gear coupling test rig shown in Figure 6.18.

The specification of the test rig demanded an axial displacement in the test coupling so that the axial forces which then appear could be measured. It was therefore necessary to move at least one half of the gear coupling.

The possible position of displacement (classifying criterion of the rows) and the axial force input (classifying criterion of the columns) were combined into the classification scheme shown in Figure 6.19. The various combinations were checked against the requirements list and unsuitable variants were eliminated for a number of immediately obvious reasons. These reasons were documented in the selection chart, but cannot be included because of space restrictions. The result is shown in the legend of Figure 6.19.

Selected working structures (the working combinations) now have to undergo further concretisation.

6.4.4 Practical Application of Working Structures

The development of working structures is the most important stage in the creation of original designs. This stage makes the most demands on the creativity of designers. This creativity is influenced by cognitive psychological processes associated with problem solving, by the use of a general working methodology, and by generally applicable solution finding and evaluation methods. As a consequence, various approaches can be employed at this stage and the one chosen depends on

TH Darmstadt	SELECTION CHART for Cylinder test rig	Part: 1 Page: 1

Solution variants (Sv) evaluated by

SELECTION CRITERIA
(+) Yes
(−) No
(?) Lack of information
(!) Check requirements list

DECISION

Mark solution variants (Sv)
(+) Pursue solution
(−) Eliminate solution
(?) Collect information (re-evaluate solution)
(!) Check requirements list for changes

Enter solution variant (Sv):

A: Compatibility assured
B: Fulfils demands of requirements list
C: Realisable in principle
D: Within permissible costs
E: Incorporates direct safety measures
F: Preferred by designer's company
G:

Sv		A	B	C	D	E	F	G	Remarks (Indications, Reasons)	DECISION
A1	1	+	−						Change of set up, rattling of bearings	−
A2	2	+	−						Change of set up, too much play	−
A3	3	+	+	+	+				Sinusoidal motion not full realised, error < 1%	+
A4	4	+	+	+	−				Production expenditure too high	−
A5	5	+	+	+	−				Total expenditure too high	−
B1	6	+	−						Not adjustable or only with high expenditure	−
B2	7	+	−						Not adjustable	−
B3	8	+	+	−					Too slow	−
B4	9	+	+	−					Too slow, little variability	−
B5	10	+	+	+	+				Flexible allocation, very fast	+
C1	11	+	+	+	+				Simple solution	+
C2	12	+	+	+	?				Expenditure questionable	?
C3	13	+	+	−					Too much space required	−
C4	14	+	+	−					Expenditure too high	−
D1	15	+	+	−					No space, force flow path too flexible	−
D2	16	+	+	+	+				Preferred measuring procedure of institute	+
D3	17	+	+	+	−				Expenditure higher than D2	−
D4	18	−	−	+	−				Expenditure higher than D2	−
E1	19	+	+	−					Too much space required, element not stiff	−
..										
..										
..										

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Figure 6.17. Part of the selection chart for the solution space shown in Figure 6.14

the novelty of the task (the number of new problems to be solved), on the mentality, ability and experience of the designers, and on the product ideas from product planning or clients.

The procedure suggested in Sections 6.4.1 to 6.4.3 only provides the basis for an expedient stepwise design process. The actual process can vary considerably.

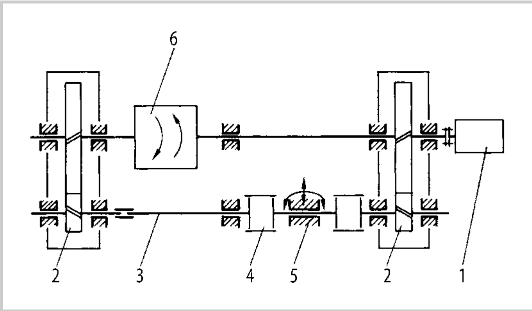


Figure 6.18. Sketch showing the principle of a test rig for gear couplings. *1* drive; *2* gearbox; *3* high-speed shaft; *4* test gear coupling; *5* adjustable bearing block for setting the alignment; *6* device for applying torque

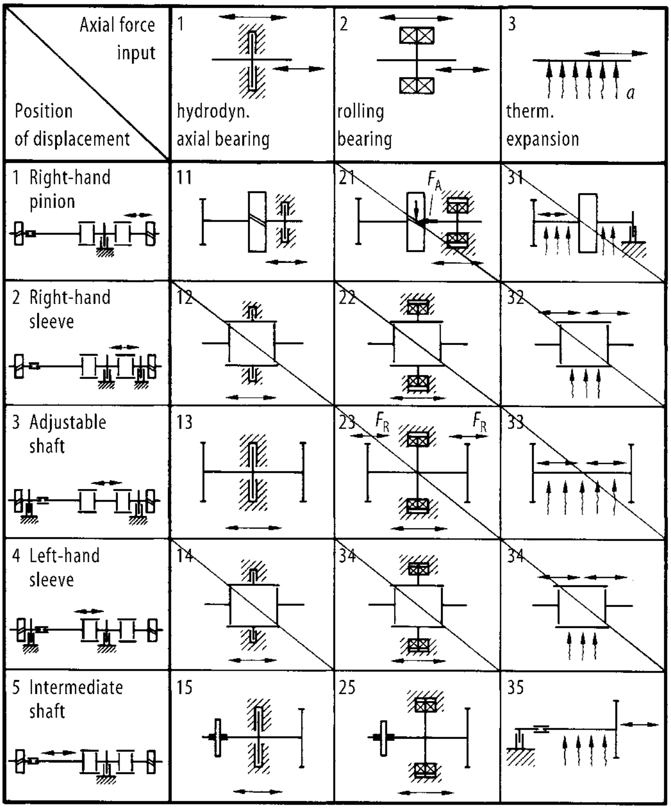


Figure 6.19. Systematic combination and elimination of variants that are unsuitable in principle.
Combinations 12, 14: Disturbance of coupling kinematics
Combination 21: F_A too great (life of rolling bearings too short)
Combination 23: 2 F_R, hence life of rolling bearings too short
Combinations 22, 24: Peripheral speed too great (life of rolling bearings too short)
Combinations 31–34: Thermal length too small

For *original designs without precedents*, the initial search for solutions should focus on the *main function* that appears to be *solution determining* for the overall function (see Figure 6.6). For the solution determining main function, one must first select some preliminary physical effects or working principles using intuition-based methods, literature and patent searches and previous products. The relationship between the functions in these solutions must be analysed to identify other important subfunctions for which physical effects and working principles need to be found. These working principles are selected from those that are compatible with the other working principles selected to fulfil the main functions. A simultaneous, independent search for working principles for all subfunctions will, in general, be too elaborate and will result in several working principles that will have to be eliminated later from the overall combination.

It is recommended that the most promising solution principles (not more than six) should be identified at a relatively low level of concretisation. One of these is then selected for elaboration to a higher level of concretisation. From the variants that then emerge at this level, the most promising is again taken forward to an even higher level of concretisation. Adopting this approach avoids the need to deal with too many variants at the same time, which can result in too much effort being devoted to variants that eventually turn out to be unsuitable.

An important strategy for the creation of solution fields is therefore the systematic variation of the physical effects and form design features that were recognised as being essential in the initial solutions. *Classification schemes* are very useful but usually need several trials, based on variation and correction of the classifying criteria, before an optimum scheme can be arrived at. This requires some experience.

When *concrete solution ideas* are available from product planning or other sources, these have to be analysed to identify their essential solution determining characteristics. These are then systematically varied and combined to arrive at a solution field.

In the case of *evolutionary developments*, the known working principles and working structures should be checked to see if they still meet current technological standards and the latest requirements.

When an approach is strongly based on *intuition*, or when previous experience is applicable, working structures that fulfil the overall function will often be found directly without first searching for solutions for the individual subfunctions.

In particular, the *stepwise* generation of working principles, through the search for physical effects and the subsequent form design features, is often integrated mentally by producing *sketches of solutions*. This is because designers think more in configurations and representation of principles than in physical equations.

The use of intuition-based and discursive–systematic methods can quickly lead quickly to extensive solution fields. To limit subsequent design effort, these should be reduced as soon as *feasible working principles* emerge by checking against the demands in the requirements list.

At this stage it is often not possible to assess the characteristics of a principle solution with quantitative data, particularly with regard to production and cost.

Therefore, the selection of suitable working principles requires an *interdisciplinary team* discussion, similar to a value analysis team (see Section 1.2.3(2)), in order to base the qualitative decision on a broad spectrum of experience.

6.5 Developing Concepts

6.5.1 Firming Up into Principle Solution Variants

The principles elaborated in Section 6.4 are usually not concrete enough to lead to the adoption of a definite concept. This is because the search for a solution is based on the function structure, and so it is aimed, first and foremost, at the fulfilment of a technical function. A concept must, however, also satisfy the conditions laid down in Section 2.1.7—at least in essence—for only then is it possible to evaluate it. Before concept variants can he evaluated they must be firmed up, and experience has shown that this almost invariably involves considerable effort.

The selection process may already have revealed gaps in information about very important properties, sometimes to such an extent that not even a rough and ready decision is possible, let alone a reliable evaluation. The most important properties of the proposed combination of principles must first be given a much more concrete *qualitative*, and often also a rough *quantitative*, definition.

Important characteristics of the working principle (such as performance and susceptibility to faults), of the embodiment (such as space requirements, weight and service life) and finally of important task-specific constraints must all be known, at least approximately. More detailed information need only be gathered for promising combinations. If necessary, a second or third selection process should follow the collection of further information.

The necessary data are essentially obtained with the help of such proven methods as:

- rough calculations based on simplified assumptions
- rough sketches or rough scale-drawings of possible layouts, forms, space requirements, compatibility, etc.
- preliminary experiments or model tests used to determine the main properties or to obtain approximate quantitative statements about the performance and scope for optimisation
- construction of models in order to aid analysis and visualisation (for example, kinematic models)
- analogue modelling and systems simulation, often with the help of computers; for example stability and loss analyses of hydraulic systems using electrical analogies
- further searches of patents and the literature with narrower objectives
- market research of proposed technologies, materials, bought-out parts, etc.

With these fresh data it is possible to firm up the most promising combinations of principles to the point at which they can be evaluated (see Section 6.5.2). The variants must reveal technical as well as economic properties, thus permitting the most accurate evaluation possible. When firming up into principle solutions, it is therefore advisable to keep in mind potential evaluation criteria (see Section 3.3.2), as this encourages purposeful elaboration of the information.

An example will show how it is possible to firm up working principles into principle solutions. To that end, we return once more to our fuel gauge.

Figure 6.20 shows the working principle of the first proposal shown in Figure 3.27 and Table 3.3. It is possible to obtain the total force statically, either by measuring three bearing forces or by measuring just one bearing force in combination with a pivot. The weight of the contents of the fuel tank, to be used as a measure of the quantity of liquid, can be determined by deducting the weight of the empty tank. The measuring devices to be used, however, measure the total force, including those components caused by accelerations. If the force is converted into motion it can be detected via a potentiometer for example.

Estimates of the weights and inertia forces form the basis of the firming up procedure.

Total force of 20 to 160 litres of the liquid (static):

$$F_{\text{tot}} = \varrho \cdot g \cdot V = 0.75 \times 10 \times (20 \ldots 160) = (150 \ldots 1200)\ \text{N (fuel)}\ .$$

Additional forces due to acceleration $\pm 30\ \text{m/s}^2$ (only the liquid is taken into consideration):

$$F_{\text{add}} = m \cdot a = (15 \ldots 120) \times \pm 30 = \pm(450 \ldots 3600)\text{N}\ .$$

The suppression of motions resulting from accelerational forces calls for considerable damping.

Conclusion: develop solution further, provide damping, seek appropriate subsolutions and firm up by means of rough scale drawings. Figure 6.21 shows the result. Once the necessary parts and their arrangements are drawn, the proposal can be evaluated. This confirms the indication in the selection chart (see Figure 3.27) that the effort required to complete solution variant 1 could be too high.

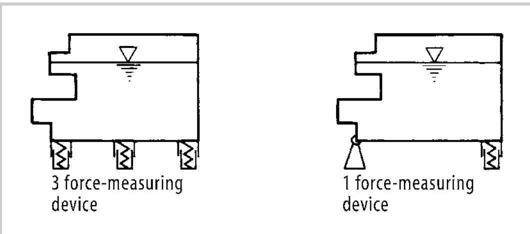


Figure 6.20. Solution principle 1 (Figure 3.27 and Table 3.3): measure weight of liquid (signal = force)

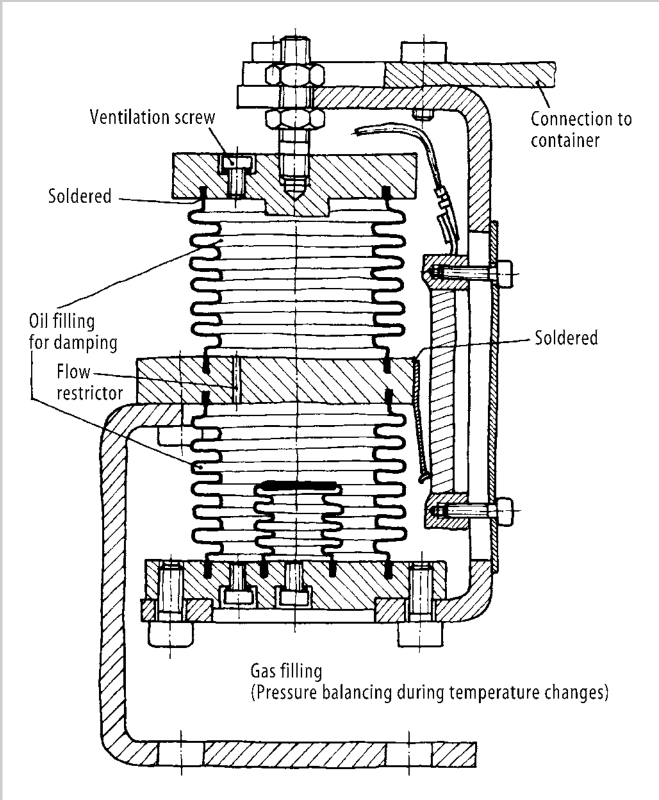


Figure 6.21. Firmed up principle solution shown in Figure 6.20

6.5.2 Evaluating Principle Solution Variants

In Section 3.3.2 we explained generally applicable evaluation methods, in particular Cost–Benefit Analysis and the VDI 2225 procedure [6.15].

When evaluating principle solution variants, the following steps are recommended.

1. Identifying Evaluation Criteria

This step is based, first of all, on the *requirements list*. During a previous selection procedure (see Section 6.4.3) unfulfilled demands may have led to the elimination of variants that were found to be unsuitable in principle. Further information was subsequently gathered during firming up into principle solutions. Hence it is advisable, with all the newly acquired information, to establish whether all of the proposals to be evaluated still satisfy the demands of the requirements list. This can involve new yes/no decisions—a new selection process.

Even though we are at a more concrete stage, we cannot expect this decision to be made with certainty for all of the variants unless much further effort is applied, which the designers may not wish or are not able to provide at this stage. At the current level of information, it may only be possible to decide how likely it is that certain requirements can be fulfilled. In that case, the likelihood of fulfilling particular requirements may become an additional evaluation criterion.

A number of requirements are minimum requirements. It is important to establish whether or not these should be exceeded. If they should, further evaluation criteria may be needed.

For evaluation during the conceptual phase, both the *technical* and the *economic characteristics* should be considered as early as possible [6.4]. At the firming up stage, however, it is not usually possible to give the costs in figures. Nevertheless, the economic aspects must be taken into consideration, at least qualitatively, and so must industrial and environmental safety requirements.

Hence it is necessary to consider technical, economic and safety criteria at the same time. It is suggested that the evaluation criteria are derived from the main headings in Figure 6.22. These are in accordance with the embodiment design checklist (see Section 7.6) and other proposals [6.8].

Main headings	Examples
Function	Characteristics of essential auxiliary function carriers that follow out of necessity from the chosen solution principle or concept variant
Working principles	Characteristics of the selected principle or principles with respect to 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 enviromental safety guaranteed
Ergonomics	Satisfactory man-machine relationship, no strain or impairment of health, good aesthetics
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 handing
Maintenance	Little and simple upkeep and cleaning, easy inspection, easy repair
Recycling	Easy recovery of parts, safe disposal
Costs	No special running or other associated costs, no scheduling risks

Figure 6.22. Checklist with main headings for design evaluation during the conceptual phase

Every heading in the checklist relevant to the task must be assigned at least one evaluation criterion. The criteria must, moreover, be independent of one another in terms of the overall objective, so as to avoid multiple evaluations. Consumer criteria are essentially contained in the first five and last three headings, while producer criteria are contained in the following headings: embodiment, production, quality control, assembly and costs.

Evaluation criteria are accordingly derived from:

1. The requirements list:
   - Probability of satisfying the demands (how probable, despite which difficulties?)
   - Desirability of exceeding minimum requirements (exceed by how much?)
   - Wishes (satisfied, not satisfied, how well are they satisfied?)
2. General technical and economic characteristics from the checklist, see Figure 6.22 (to what extent are they present, how well are they satisfied?)

During the conceptual phase, the total number of evaluation criteria should not be too high: 15–30 criteria are usually enough (see Figure 6.41).

2. Weighting the Evaluation Criteria

The evaluation criteria adopted may differ markedly in importance. During the conceptual phase, in which the level of information is fairly low because of the relative lack of embodiment, weighting is not generally advisable. It is much more advantageous in the selection of evaluation criteria to strive for an approximate balance, ignoring low-weighted characteristics for the time being. As a result, evaluation will be concentrated on the main characteristics and hence provide a clear picture at a glance. Extremely important requirements, however, which cannot be ignored until later, must be introduced with the help of weighting factors.

3. Compiling Parameters

It has proved useful in the past to list the identified evaluation criteria in the sequence of the checklist headings and to assign the parameters of the variants to them. Whatever quantitative information is available at this stage should also be included. Such quantitative data generally result from the step we have called "firming up into principle solution variants". However, since it is impossible to quantify all the parameters during the conceptual phase, the qualitative aspects should be put into words and correlated with the value scale.

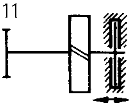
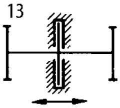
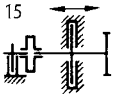
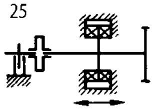
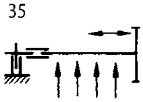
4. Assessing Values

Though the attribution of points raises problems, it is not advisable to evaluate too timidly during the conceptual phase.

Those using the 0–4 scale proposed in VDI Guideline 2225 may feel the need to assign intermediate values, particularly when there are many variants, or when the evaluation team cannot agree on a precise point. It may prove helpful in such cases to attach a tendency sign (↑ or ↓) to the point in question (see Figure 6.41). Identifiable tendencies can then be taken into account when estimating the evaluation uncertainties. The 0–10 scale, again, may suggest a degree of accuracy that does not really exist. Here, arguments about a point are often superfluous. If there is absolute uncertainty in the attribution of points, which happens quite often during the evaluation of concept variants, the point under consideration should be indicated with a question mark (see Figure 6.41).

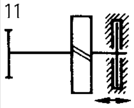
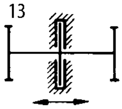
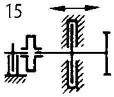
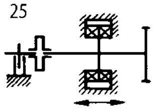
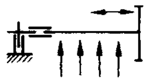
During the conceptual phase it may prove difficult to put actual figures to the costs. It is not therefore generally possible to establish an *economic rating* R_e with respect to the production costs. Nevertheless, the technical and economic aspects can be identified and separated qualitatively, to a greater or lesser extent. The *strength diagram* (see Figure 3.35) can be used to much the same effect (see also Figures 6.23 to 6.25 which are for the test rig shown in Figure 6.18).

In a similar way, a classification based on consumers' and producers' criteria often proves useful. Since the consumers' criteria usually involve *technical ratings* R_t

Variants / Technical criteria	11 	13 	15 	25 	35 
1) Small disturbance of coupling kinematics	(1) 3	4	4	4	3
2) Simple operation	3	4	4	4	3
3) Easy exchange of coupling	4	3	4	4	4
4) Functional safety	2	4	3	3	3
5) Simple construction	(1) 2	2	2	2	3
Total	14	17	17	17	16
$R_t = \frac{\text{Total}}{20}$	0.7	0.85	0.85	0.85	0.80

(1) Torque changes with axial displacement of pinion

Figure 6.23. Technical evaluation of the remaining principle solution variants, see Figure 6.19

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

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

Figure 6.24. Economic evaluation of the remaining principle solution variants, see Figure 6.19

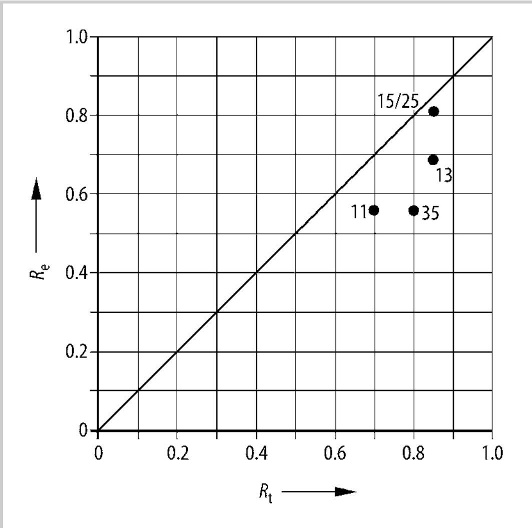


Figure 6.25. Comparison of the technical and economic ratings of the principle solution variants in Figures 6.23 and 6.24

and the producers' criteria involve *economic ratings* R_e, it is possible to proceed to a similar classification to the one mentioned above.

Depending on the problem and the amount of information available, one of the following three possible forms of representation is chosen:

- technical rating with implicit economic aspects (see Figures 6.41 and 6.55)
- separate technical and economic ratings (see Figures 6.23 to 6.25)
- additional comparison of consumers' and producers' criteria.

5. Determining Overall Value

The determination of the overall value is a matter of simple addition, once the points have been assigned to the evaluation criteria and the variants. If, because of the evaluation uncertainty, it is only possible to assign a range of points to individual variants, or if tendency signs are used, one can additionally determine the possible minimum and maximum overall point number and so obtain the probable overall value range (see Figure 6.41).

6. Comparing Concept Variants

An absolute value scale is generally more suitable for the purposes of comparison. In particular, it makes it fairly simple to tell whether particular variants are relatively close to or far from the target (theoretical ideal).

Concept variants that are some 60% below the target are not worth further development. Variants with ratings above 80% and a balanced value profile—those without extremely bad individual characteristics—can generally be moved on to the embodiment design phase without further improvement.

Intermediate variants should only be released for embodiment design after the elimination of weak spots or an improved combination.

It often happens that two or more variants are found to be practically equivalent. It is a very grave mistake, in that case, to base the final decision on such slight differences. Instead, evaluation uncertainties, weak spots and the value profile should be looked at more closely (see Figure 3.38). It may also be necessary to firm up on such variants in a further step. Schedules, trends, company policy and so on must be assessed separately and taken into account [6.4].

7. Estimating Evaluation Uncertainties

This step is very important, especially during the conceptual phase, and must not be omitted. Evaluation methods are mere tools, not automatic decision mechanisms. Uncertainties must be determined as indicated earlier. At this point, however, only the information gaps that impact on the best concept variants (for example, variant B in Figure 6.41) need to be closed.

8. Searching for Weak Spots

During the conceptual phase, the value profile plays an important role. Variants with a high rating but definite weak spots (unbalanced value profile) may prove extremely troublesome during subsequent development. If, because of an unidentified evaluation uncertainty, which is more likely to occur in the conceptual than in the embodiment phase, a weak spot should make itself felt later, then the whole concept may be put in doubt and all the development work may prove to have been in vain.

In such cases it is very much less risky to select a variant with a slightly lower rating but a more balanced value profile (see Figure 3.38).

Weak spots in favourite variants can often be eliminated by the transfer of better subsolutions from other variants. Moreover, with better information, it is possible to search for a replacement for the unsatisfactory subsolution. Thus the criteria we have listed played an essential role in the selection of the best variant in the problem discussed in Section 6.6 (see Figure 6.41). When estimating evaluation uncertainties and also when searching for weak spots it is advisable to assess the probability and magnitude of the possible risk, especially in the case of important decisions.

6.5.3 Practical Application of Developing Concepts

The selection of the concept, or the principle solution, provides the *basis for starting the embodiment design phase* (see Figure 6.1). This often indicates a need for changes in organisation and personnel because the nature of the work alters. Thus, firming up of suitable working structures into principle solution variants and the subsequent evaluation at the end of the conceptual design phase are of major importance for product development. The large number of variants has to be reduced to one concept, or just a few, to be pursued further. This decision incurs a heavy responsibility and can only be made when the principle solutions are in a state suitable for evaluation. In extreme cases this may require rough scale layouts backed up by preliminary calculations and sometimes tests. From research in industry and universities [6.8], it is known that calculating and representation add up to 60% of the total time spent on conceptual design.

The *representation* of working principles and working structures is likely to remain the domain of conventional sketching. Rough layouts, and in particular the more important details of solutions are now commonly represented using CAD. Sketching working structures by hand has the advantage that one does not need to consider the formalities of CAD user interfaces during this highly creative stage. Firming up solution principles using CAD is useful, despite the effort needed to enter the initial product model into the system, because making variations to the layout and individual components becomes very efficient. For dynamic systems it is also possible to do initial simulations using the CAD model.

In any case, it is expedient (for *reasons of efficiency* and to identify essential characteristics) not to firm up the whole working structure to the same level of detail. The aim should be to focus on those working principles, components or parts of the structure that are essential for the evaluation of the concepts and the selection of the one that will be transferred to the embodiment stage. Richter provides proposals for this task [6.10].

At this point it must be emphasised again that *iterations* often occur in the steps mentioned in Sections 6.4 and 6.5. On the one hand, it might be necessary to detail working principles in order to combine and select them, and on the other hand a completely new idea for a working principle might emerge while making a rough layout of a principle solution.

It must be stressed that principle solutions or concepts have to be *unambiguously documented*. It must also be clear which parts of the working structure or function carriers can be realised by existing and standard components, and which ones will need to be specially designed.

6.6 Examples of Conceptual Design

This section provides two examples of how the approach can be applied: the first to a task whose main flow is material, and the second to one whose main flow is energy. The embodiment design phase of the second example is continued in Section 7.7. An example of signal flow has been used throughout the previous sections in this chapter (see Figures 6.4 to 6.6 and 6.20).

6.6.1 One-Handed Household Water Mixing Tap

A one-handed mixing tap is a device for regulating water temperature and throughflow independently with one hand. This task was sent to the design department by the planning department in the form shown in Figure 6.26.

One-handed water mixing tap

Required: one-handed household water mixing tap with the following characteristics:

Throughput	10 l/min
Max. pressure	6 bar
Normal pressure	2 bar
Hot water temperature	60 °C
Connector size	10 mm

Attention to be paid to appearance. The firm's trade mark to be prominently displayed. Finished product to be marketed in two years' time. Manufacturing costs not to exceed DM 30 each at a production rate of 3000 taps per month.

Figure 6.26. One-handed mixing tap. Example of an assignment suggested by the product planning department

Step 1: Clarifying the Task and Setting Up the Requirements List

New data on fittings, standards, safety regulations and ergonomic factors led to the replacement of the original requirements list by the revised version shown in Figure 6.27.

TH Darmstadt	Requirements list for one-handed mixing tap		Page 1
Changes	**D W**	**Requirements**	**Responsible**
	D	1 Throughput (mixed flow) max. 10 l/min at 2 bar	KMW
	D	2 Max. pressure 10 bar (test pressure 15 bar as per DIN 2401)	LTMB
	D	3 Temp. of water standard 60 °C, 100 °C (short-time)	
	D	4 Temperature setting independent of throughput and pressure	
	W	5 Permissible temp fluctuation ± 5 °C at a pressure diff. of ± 5 bar between hot and cold supply	
	D	6 Connection 2 x Cu pipes, 10 x 1 mm, l = 400 mm	
	D	7 Single-hole attachment $\varnothing 35^{+2}_{-1}$ mm, basin thickness 0–18 mm (Observe basin dimension DIN EN 31, DIN EN 32, DIN 1368)	
	D	8 Outflow above upper edge of basin, 50 mm	
	D	9 To fit household basin	
	W	10 Convertible into wall fitting	
	D	11 Light operation (children)	
	D	12 No external energy	
	D	13 Hard water supply (drinking water)	
	D	14 Clear identification of temperature setting	
	D	15 Trade mark prominently displayed	
	D	16 No connection of the two supplies when valve shut	
	W	17 No connection when water drawn off	
	D	18 Handle not heated to above 35 °C	
	W	19 No burns from touching the fittings	
	W	20 Provide scalding protection if extra costs small	
	D	21 Obvious operation, simple and convenient handling	
	D	22 Smooth, easily cleaned contours, no sharp edges	
	D	23 Noiseless operation, (≤ 20 dB as per DIN 52218)	
	W	24 Service life 10 years at about 300 000 operations	
	D	25 Easy maintenance and simple repairs. Use standard spare parts	
	D	26 Max. manuf. costs DM 30 (3000 units per month)	
	D	27 Schedules from inception of development	

	conceptual design	embodiment design	detail design	prototype	
after	2	4	6	9	months

	Replaces 1st issue of 12.6.1973	

Figure 6.27. Requirements list for a one-handed mixing tap

Step 2: Abstracting to Identify the Essential Problems

The basis for abstraction is the requirements list, from which it is possible to arrive at Figure 6.28. Simple household solutions for mixing taps suggested that the chosen solution principle must be based on metering out the water through a diaphragm or valve. Alternatives such as heating and cooling by the introduction of external energy through heat exchangers could be dismissed: they were more expensive and involved a time lag. Selecting sound solution principles without further investigation, because they have proved their worth in previous company products, is a common and justified approach in some branches of engineering.

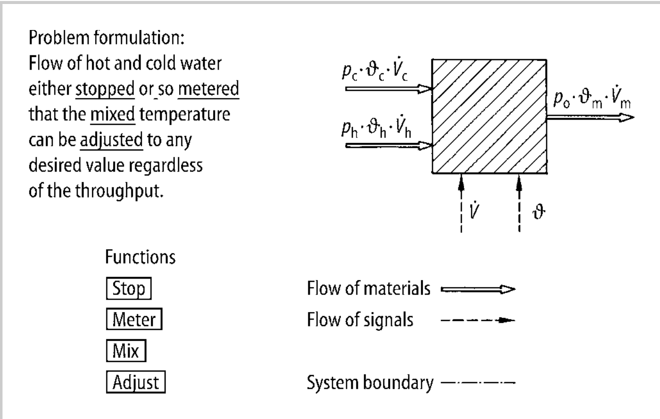
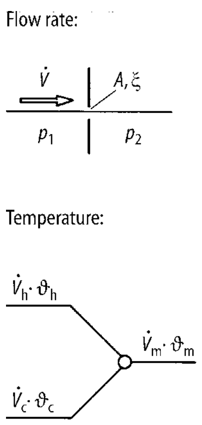


Figure 6.28. Problem formulation and overall function as per the requirements list, see Figure 6.27. $\dot{V}$ = volume rate, p = pressure, ϑ = temperature. Index: c = cold, h = hot, m = mixed, o = atmosphere



$$p_1 - p_2 = \xi \cdot (\varrho/2) \cdot v^2; \dot{V} = v \cdot A$$

$$\boxed{\dot{V} = \frac{A}{\sqrt{\xi}} \cdot \sqrt{\frac{2}{\varrho}} \cdot \sqrt{p_1 - p_2}}$$

$$\dot{V}_m = \dot{V}_h + \dot{V}_c$$

$$\dot{V}_m \cdot \vartheta_m = \dot{V}_h \cdot \vartheta_h + \dot{V}_c \cdot \vartheta_c$$

$$\boxed{\vartheta_m = \frac{\dot{V}_h \cdot \vartheta_h + \dot{V}_c \cdot \vartheta_c}{\dot{V}_m} = \frac{\vartheta_h + \frac{\dot{V}_c}{\dot{V}_h} \cdot \vartheta_c}{1 + \frac{\dot{V}_c}{\dot{V}_h}}}$$

Figure 6.29. Physical relationships for flow rate and temperature of a mixed flow of the same fluid

Next, the physical relationships for the diaphragm (or valve) flow rate and the temperature of a mixed flow of similar fluids were determined (see Figure 6.29).

Temperature and flow rate adjustments are based on the same physical principle—a diaphragm or valve.

Upon *changing the flow rate* $\dot{V}_m$, the flows must be changed linearly and in the same sense as the signal setting $s_{\dot{V}}$. The output temperature ϑ_m, however, must remain unchanged: that is, the relationship $\dot{V}_c/\dot{V}_h$ must remain constant and independent of the signal positions $s_{\dot{V}}$.

Upon *changing the output temperature* ϑ_m, the volume flow rate $\dot{V}_m$ must remain unchanged: that is, the sum of $\dot{V}_c + \dot{V}_h = \dot{V}_m$ must remain constant. To that end the component flows $\dot{V}_c$ and $\dot{V}_h$ must be changed linearly and in the opposite sense to the signal setting for the output temperature s_ϑ.

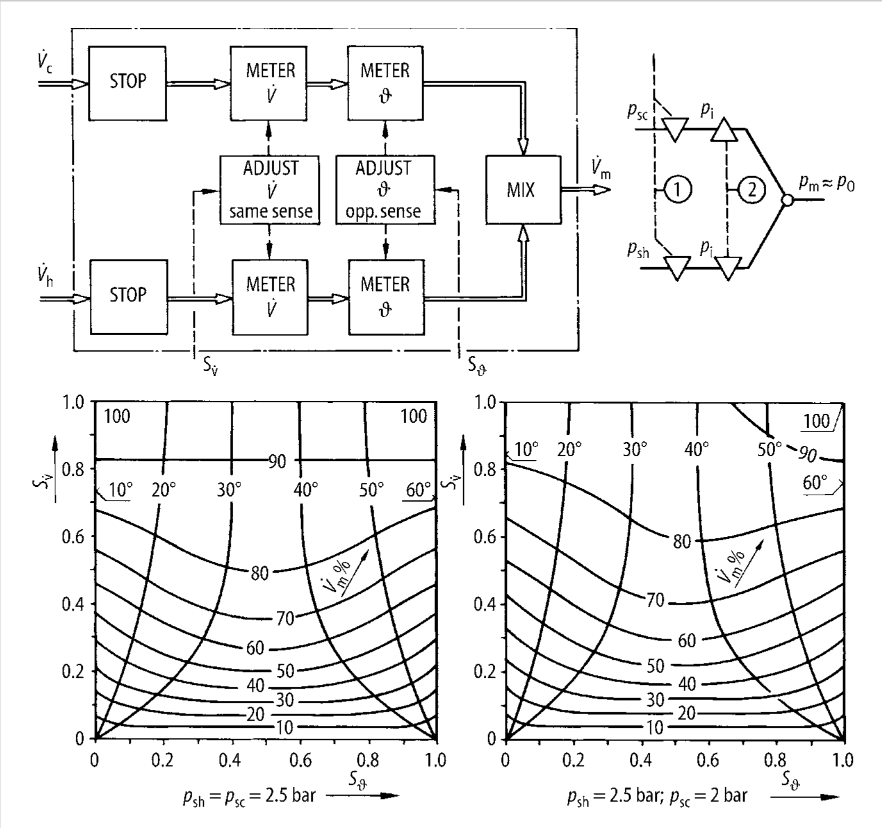


Figure 6.30. Function structure for a one-handed water mixing tap based on Figure 6.28, metering flow ① and adjusting temperature ② separately before mixing. In the graphs, lines of constant temperature and constant percentage flow rate have been plotted for given temperature settings (s_ϑ) and flow rate settings ($s_{\dot{V}}$). Due to the mutual effects of the pressures on the inlets at ① and ②, the temperature and flow characteristics are not linear except for the setting $s_{\dot{V}} = 0.825$, and hence are unsuitable for small flow rates. At a particular pressure difference between the cold and hot water supplies (in this case $p_{sh} - p_{sc} = 0.5$bar) the lines shift. The settings are no longer independent of each other, even for the settings $s_{\dot{V}} = 0.825$ (*diagram on right*)

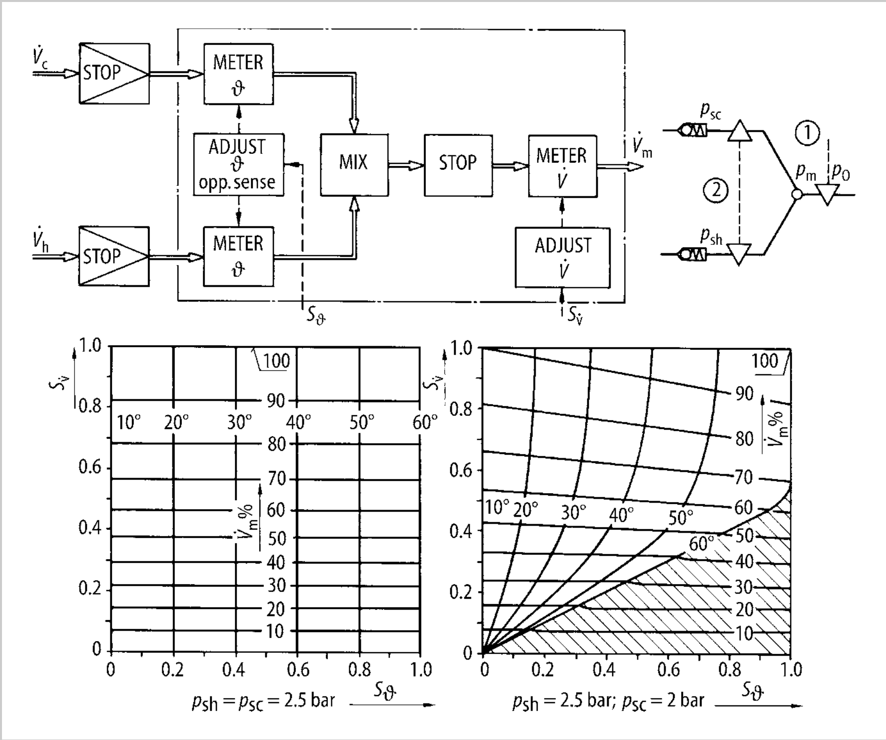


Figure 6.31. Function structure based on Figure 6.28 in which the temperature is set before and the flow metered after mixing. With equal pressures in the supply pipes, the flow and temperate settings are independent of each other due to equal pressure differences across each temperature-flow-metering valve. The behaviour is linear. With different supply pressures, however, the characteristic ceases to be linear and is strongly displaced, especially with small quantities, when the pressure in the mixing chamber approximates the smaller supply pressure. If it is exceeded, then only cold or (here) hot water will run out regardless of the temperature setting

Step 3: Establishing Function Structures

The first function structure was derived from the subfunctions:

- Stop–meter–mix
- Adjust flow rate
- Adjust output temperature.

Since the physical principle was well-known—metering using a valve—the structural layout of the first function structure was varied and developed to determine the best system and its behaviour (see Figures 6.30 to 6.32). From the results, the function structure shown in Figure 6.32 was chosen as being the most satisfactory because of its approximately linear characteristic for the output temperature.

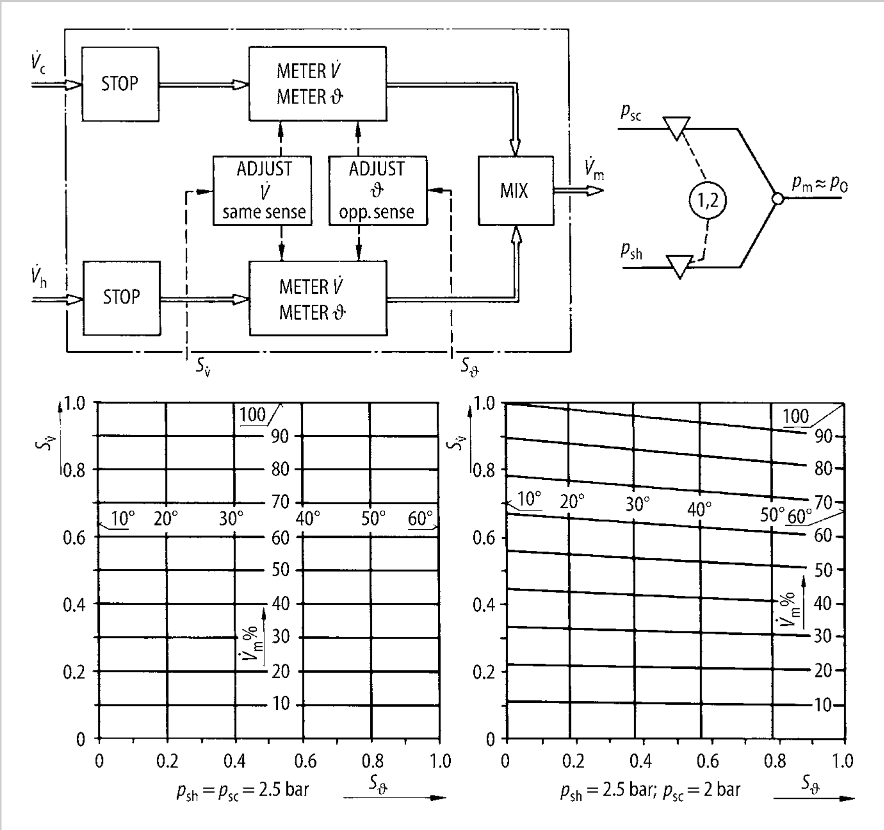


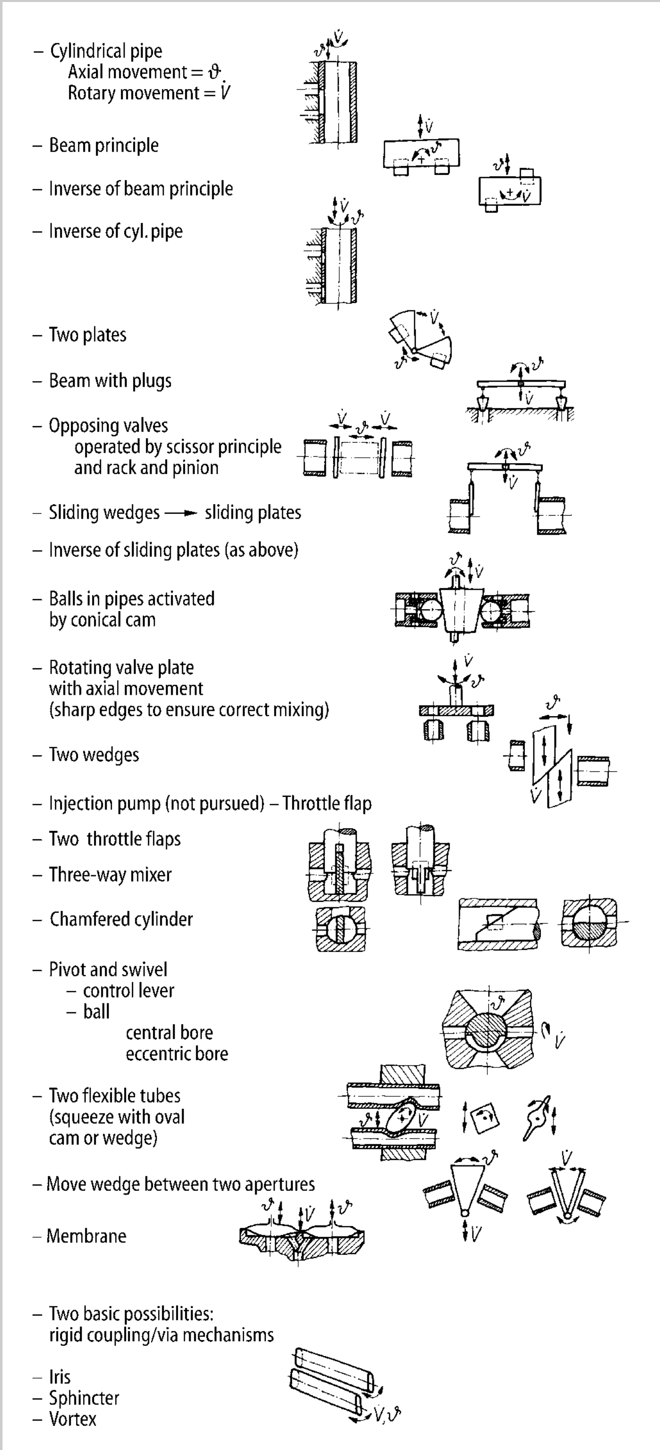
Figure 6.32. Function structure based on Figure 6.28, in which the temperature and flow at each inlet is metered out independently and then mixed. Linear temperature and flow characteristics are obtained. No serious changes are seen, even at different supply pressures

Step 4: Searching for Working Principles

Because the function structure shown in Figure 6.32 exhibited the best behaviour, the task became one of "varying two flow areas, simultaneously or successively, in one sense by one movement and in the opposite sense by a second, independent, movement". Brainstorming was used as a first attempt to find solutions. The results are shown in Figure 6.33.

The solutions suggested during the brainstorming session were checked, in particular, to establish whether the $\dot{V}$ and ϑ settings were independent. An analysis of the combined movements suggested the following characteristics for the working principles that were generated:

Figure 6.33. Result of a brainstorming session to discover solution principles for the assignment "vary two flow areas, simultaneously or successively, in one sense by one movement and in the opposite sense by a second, independent movement"


– Cylindrical pipe
Axial movement = ϑ
Rotary movement = $\dot{V}$
– Beam principle
– Inverse of beam principle
– Inverse of cyl. pipe
– Two plates
– Beam with plugs
– Opposing valves
operated by scissor principle
and rack and pinion
– Sliding wedges ⟶ sliding plates
– Inverse of sliding plates (as above)
– Balls in pipes activated
by conical cam
– Rotating valve plate
with axial movement
(sharp edges to ensure correct mixing)
– Two wedges
– Injection pump (not pursued) – Throttle flap
– Two throttle flaps
– Three-way mixer
– Chamfered cylinder
– Pivot and swivel
– control lever
– ball
central bore
eccentric bore
– Two flexible tubes
(squeeze with oval
cam or wedge)
– Move wedge between two apertures
– Membrane
– Two basic possibilities:
rigid coupling/via mechanisms
– Iris
– Sphincter
– Vortex

1. Solutions with separate movements for $\dot{V}$ and ϑ tangential to the valve seat face

- The independence of the $\dot{V}$ and ϑ settings is only guaranteed if each of the flow areas of the valves are bounded by two edges running parallel to the corresponding movements. This implies that the movements must proceed at an angle to each other and in a straight line. Every valve setting thus has two pairs of straight and parallel bounding edges (see Figure 6.34). This ensures that when one setting is adjusted the other setting is not simultaneously adjusted.
- Distribution of bounding edges: each of the components producing the valve flow areas must have at least two edges that face each other and lie in the direction of the movement.
- When setting $\dot{V}$, both valve areas must approach zero simultaneously.
- When setting ϑ, one area must approach zero as the other approaches its maximum $\dot{V}_{\max}$.
- This implies, when setting $\dot{V}$, that the bounding edges on both valve areas must move towards each other or away from each other in the same sense. When setting ϑ, the bounding edges on the two valve areas must move in the opposite sense to each other.
- The seat face may be plane, cylindrical or spherical.
- Solutions of this type can be effected with a single valve element, and seem simple to design.

2. Solutions with separate movements for $\dot{V}$ and ϑ normal to the valve seat face

- This group includes all movements which involve lifting a valve from its seat face. However, only a movement at right angles to the seat face is possible in practice.
- The independent settings of $\dot{V}$ and ϑ can only be achieved with additional control elements (coupling mechanism).
- The design seems to require greater effort.

3. Solutions with one type of movement for $\dot{V}$ and ϑ tangential to the seat face

- To guarantee the independence of the $\dot{V}$ and ϑ settings, additional coupling elements are needed.

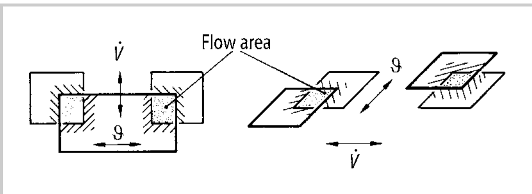


Figure 6.34. Movements and bounding edges of valve positions

	Classifying Criteria	Parameters
Rows	Form of working elements	Flate plate Wedge (–) Cylinder Cone (–) Ball Special elastic body (–)
Columns	Coupling of movements	Direct (one part) Indirect (mechanism) (–)
	Movement	$\left.\begin{matrix}\dot V\\ \vartheta\end{matrix}\right\}$ One element $\left.\begin{matrix}\dot V\\ \vartheta\end{matrix}\right\}$ Several elements
	Direction of movement $\dot V$ and ϑ	Normal to seat face (⊥) (–) Tangential to seat face (⇌)
	Type of movement $\dot V$ and ϑ	Transitional Rotational

Figure 6.35. Classifying criteria and parameters for working principles of one-handed water mixing tap

- The solutions are similar to those listed under 2. They only differ in the shape of the seat face and the resulting movement.

4. Solutions with one movement for $\dot V$ normal to, and one movement for ϑ tangential to, the seat face and vice versa

- These solutions do not, even with the help of coupling mechanisms, satisfy the demand for independent $\dot V$ and ϑ settings. The overall function is not achieved.

The first group of solutions (movements for $\dot V$ and ϑ tangential to the valve seat face) have unambiguous behaviour and seem to be less complex. Therefore they were pursued; a formal selection procedure was not necessary. On the other hand

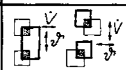
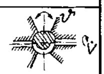
Type of movement / Form of valve		trans./trans.	trans./rot.	rot./rot.
		1	2	3
plane plate	A		○	○
cylinder	B	○		○
cone	C	○	○	○
sphere	D	○	○	

Figure 6.36. Classification scheme for solutions to the one-handed mixing tap problem. Movement tangential to the seat face. Two independent movements at an angle for $\dot V$ and ϑ

useful working parts and types of movement still had to be analysed. This analysis resulted in the classification criteria shown in Figure 6.35, with the least suitable characteristics indicated with (−). Figure 6.36 shows a classification scheme of possible working principles based on different forms and working movements.

Step 5: Selecting Working Principles

All the working principles shown in Figure 6.36 fulfil the demands of the requirements list and appear to be economic. Hence all three were firmed up into principle solutions.

Step 6: Firming Up into Principle Solution Variants

With the help of further research into possible setting or operating elements that we have not discussed here, the working principles could then be firmed up into principle solution variants and evaluated (see Figures 6.37 to 6.40).

Step 7: Evaluating Principle Solution Variants

In accordance with VDI 2225, this step was taken with the help of an evaluation chart. In addition, evaluation uncertainties and weak spots were examined (see Figure 6.41).

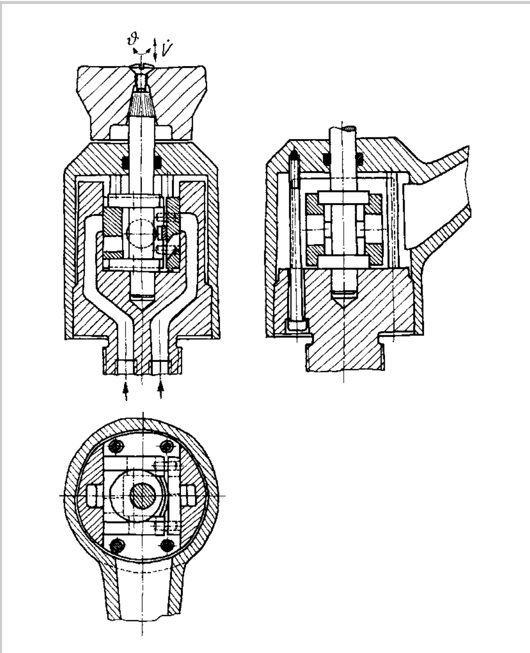


Figure 6.37. One-handed mixing tap, solution variant A: "plate solution with eccentric and pull-and-turn grip"

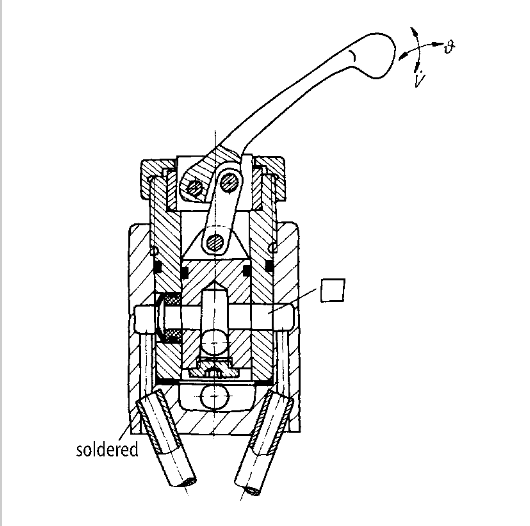


Figure 6.38. One-handed mixing tap, solution variant B: "cylinder solution with lever"

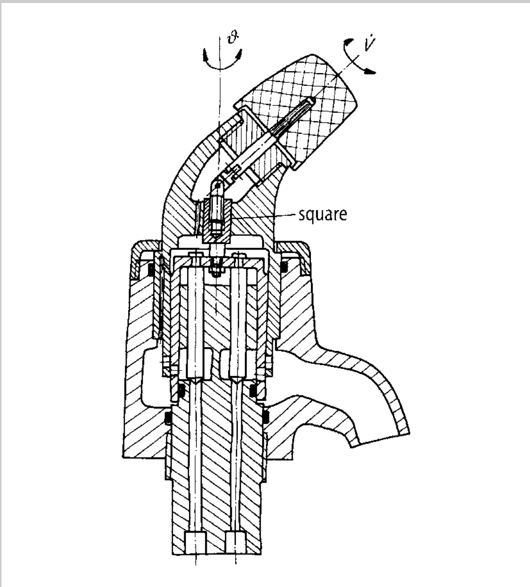


Figure 6.39. One-handed mixing tap, solution variant C: "cylinder solution with end valves and additional sealing"

Thanks to the balanced profile and the discernible improvement possibilities, Solution B (see Figure 6.38) was found to be preferable to all the others. The ball solution D (see Figure 6.40) would only have been considered if further studies into production and assembly problems had been undertaken and had led to positive results.

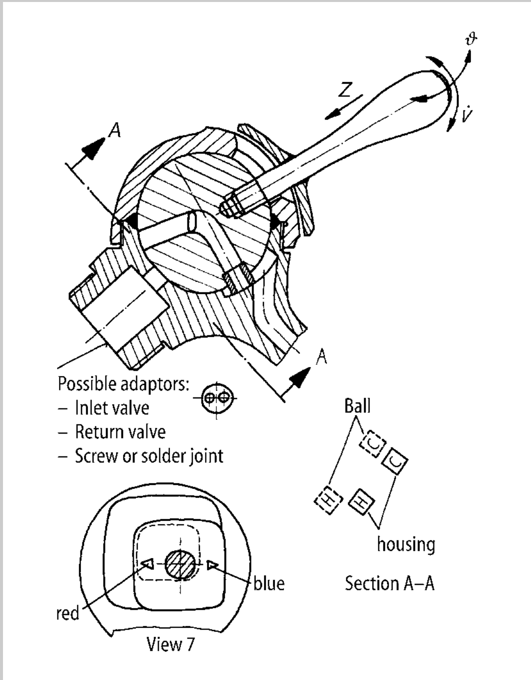


Figure 6.40. One-handed mixing tap, solution variant D: "ball solution"

Step 8: Determining the Next Steps

It was decided to produce dimensional layout drawings of Solution B with improvements to the operating lever with respect to space requirements, easier cleaning and number of parts, and also to improve the level of information for Solution D with a view to reexamining it for final evaluation.

6.6.2 Impulse-Loading Test Rig

Step 1: Clarifying the Task and Setting Up the Requirements List

The second example describes the development of a test rig [6.12]. This test rig was used to investigate the durability of shaft–hub connections subjected to impulsive loads with predefined torques, applied both singly and continuously. Prior to setting up the requirements list, the following questions had to be answered:

- What is meant by impulsive loading?
- Which impulsive torques occur in rotating machines in practice?
- Which stress measurements are possible and useful for keyed connections?

To answer the first two questions, the characteristics of torque–time variations for milling machines, crane drives, agricultural machines and rolling presses were

TH Darmstadt	EVALUATION CHART for: One-handed mixing tap	Page 1

In the order of the checklist headings		P: present variant (P): possible after improvement		A		B		C		D		E		F	
	No.	Evaluation criterion	W	P	(P)	P	(P)	P	(P)	P	(P)	P	(P)	P	(P)
Funct.	1	Reliability of stopping flow without drips	1	1		3		3 I	4	1					
Work Princ.	2	Reliable, reproducible setting (calcium-resistant, few wearing parts)	1	2		3		2 I	3	3					
Embod	3	Low space requirement	1	3↑		2		2		4					
Prod.	4	Few parts	1	1		2 I		1 W		4					
	5	Simple manufacture	1	1		3		2		1?	4				
Assy.	6	Easy assembly	1	2		3		2		2↑ J	3				
Operation	7	Convenient operation, sensitive setting	1	1		3		4		2					
	8	Easy upkeep (easy to clean)	1	4↓		2 I		3		2					
Maint.	9	Simple maintenance (with standard tools, fittings need not be dismantled)	1	1		3		2 W		1? J	3				
	10														
	11														
	12														
	13														
	14														
? Evaluation uncertain ↑ Tendency: better ↓ Tendency: worse		$P_{max} = 4$	Σ	16		24	(26)	21	(23)	(20)	(26)				
		R_t		0,45		0,67		0,58		0,56					
		Ranking		4		1	(1)	2	(3)	3	(2)				

Justification (J), Weak spot (W), Improvement (I) of variant/criterion			
C1	Provide rubber seal		
B4	Simplify lever mechanism		
D6 D9	Indeterminate position of ball during assembly		
B8	Improve with B4		
D9	Attachment of lever		

Decision	
	Develop solution B with improvement of control elements Solution D: Examine production possibilities, present result in 2 months

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Figure 6.41. One-handed mixing tap: evaluation of principle solution variants A, B, C, D

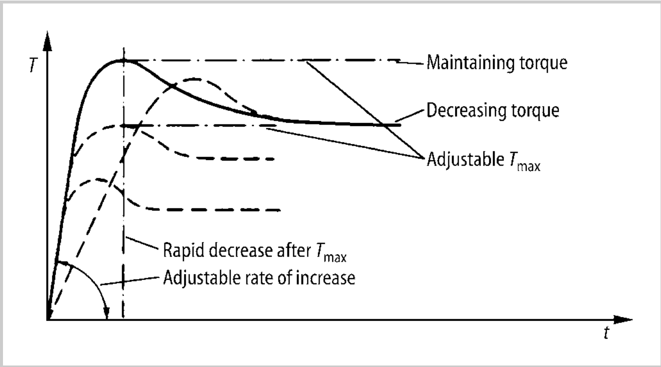

Figure 6.42. Setting magnitudes for an impulsive torque: rate of increase, magnitude and duration

TU Berlin		REQUIREMENT LIST for: Impulse-loading test ring	Part: 1 Page: 1
Changes	D W	Requirements	Responsible
		<u>Geometry:</u>	
	D	Test connection held in position	
	D	Diameter of shaft to be tested $\leq$ 100 mm (dimensions of the key according to DIN 6885)	
	D	Hubside load take off variable in axial direction	
		<u>Kinematics:</u>	
	D	Loading applied to stationary shaft	
	D	Oscillating load applied in one sense only	
	W	Sense of loading selectable	
	W	Torque input variable (from hub to shaft or from shaft to hub)	
		<u>Forces:</u>	
	D	Shaft-hub connection subjected to torque only (i.e. free of shear forces and bending moments)	
	D	Maximum torque maintained for at least 3 seconds	
	D	Loading frequency low (reason: chosen measuring principle)	
	W	As little vibration as possible in the shaft-hub-key system	
	D	Torque adjustable up to 15 000 Nm in accordance with the load capacity of a shaft of 100 mm diameter	
	D	Rapid decrease of torque after reaching the maximum should be possible	
	D	Adjustable torque increase dT/dt of up to $125 \cdot 10^3$ Nm/s	
	D	Reproducible torque profile	
	W	Plastic deformation, or even destruction, of the connection should be possible	
		<u>Energy:</u>	
	D	Power consumption $\leq$ 5 kW/380 Volt	
		<u>Material:</u>	
	W	Shaft and hub: C45	
		Replaces issue of	

Figure 6.43. Requirements list for impulse-loading test rig. After [6.12]

TU Berlin		REQUIREMENT LIST for: Impulse-loading test ring	Part: 1 Page: 2
Changes	D W	Requirements	Responsible
		<u>Signal:</u>	
	D	Quantities to be measured: torque in front of and behind the test connection, surface pressure over the length of the connection and the key	
	D	Quantities to be measured should be recordable	
	W	Accessible measuring locations	
		<u>Safety and Ergonomics:</u>	
	W	Easy operation of the test rig (i.e. quick and easy resetting of the test rig)	
	W	Environmentally-friendly operating principle (little noise, dirt, vibration ...)	
		<u>Production and Control:</u>	
	D	One-off production of all parts	
	D	Quality of shaft-hub-connection according to DIN 6885 (as far as described in this standard), otherwise according to standards for shaft ends on drives, electric motors etc: DIN 748, Parts 2 and 3	
	W	Production of the test rig in own workshops	
	W	Use bought-out and standard parts wherever possible	
		<u>Assembly and Transport:</u>	
	W	Test rig with small dimensions and low weight	
	W	No special foundation	
		<u>Operation and Maintenance:</u>	
	W	Parts subjected to wear should be few and simple	
	W	Preferably free of maintenance	
		<u>Costs:</u>	
		Manufacturing costs ~ 20 000 DM (see research proposal)	
		<u>Schedule:</u>	
	D	Concept phase finished by July 1973 Concept phase finished by 20 July 1973	Mr. Militz
		Replaces issue of	

Figure 6.43. (continued)

obtained from the literature. A maximum rate of torque increase of $\mathrm{d}T/\mathrm{d}t = 125 \times 10^3$ Nm/s was selected. The torque–time graph shown in Figure 6.42 was used to establish the necessary parameters to vary.

These requirements, along with others, were documented in the requirements list shown in Figure 6.43. They were classified according to the checklist in Figure 6.22.

Step 2: Abstracting to Identify the Essential Problems

Following the recommendations in Section 6.2.3, the requirements list was abstracted. The results are shown in Table 6.2.

Table 6.2. Abstraction and problem definition on the basis of the requirements list shown in Figure 6.43

Results from Steps 1 and 2

- Diameter of shaft to be tested $\leq$ 100 mm
- Hubside load take off variable in axial direction
- Loading applied to stationary shaft
- Pure torque loading: adjustable up to 15 000 Nm
- Maximum torque maintained for at least 3 seconds
- Rapid decrease of torque possible
- Maximum torque increase dT/dt of 125×10^3 Nm/s
- Reproducible torque profile
- Quantities $T_{\text{in front}}$, T_{behind} and p measurable

Results from Step 3

- Loading of the shaft-hub-key connection adjustable regarding torque magnitude, torque increase, torque holding time and torque decrease
- Check torque and loading with shaft stationary

Results from Step 4

- Adjustable dynamic torque to be applied when testing the specimen
- Measurements of input load levels and of stresses and strains should be possible

Result from Step 5

- "Apply dynamically changing torque while at the same time measuring load levels, stresses and strains"

Step 3: Establishing Function Structures

Establishing the function structure initially involved formulating the overall function, which was extracted directly from the problem statement, see Figure 6.44.

In this example, the essential subfunctions result from the energy flow and, for the measurements, from the signal flow:

- Transform input energy into load (torque)
- Transform input energy into auxiliary energy for the control functions
- Store energy for the impulsive action
- Control load energy and magnitude
- Change load magnitude
- Guide load energy
- Apply load to specimen, i.e. its working surface
- Measure load
- Measure specimen stresses

Setting up the function structure in a stepwise manner resulted in different arrangements and, by adding and removing individual subfunctions, several func-

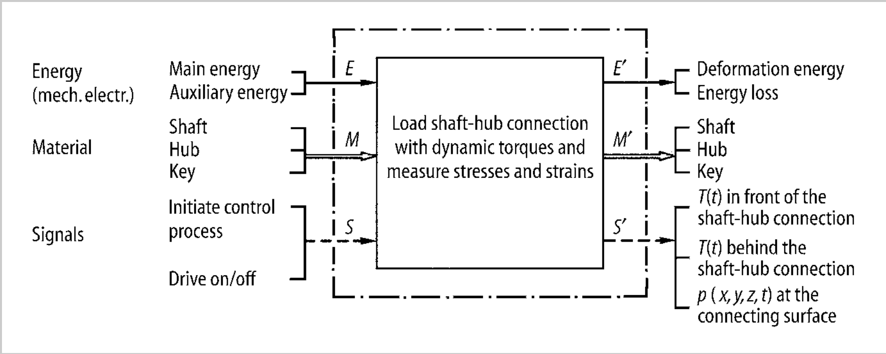

Figure 6.44. Overall function of the impulse-loading test rig

tion structure variants were produced. Figure 6.45 shows these variants in the order in which they appeared. At this stage, the measuring functions do not appear to determine the concept. Variant 4 was chosen to search for solutions because it contained all of the subfunctions of the equally promising Variant 5.

Step 4: Searching for Working Principles

To find working principles, the following methods discussed in Section 3.2 were applied:

- Conventional methods: literature search and analysis of an existing test rig
- Intuitive methods: brainstorming
- Discursive methods: systematic search with the help of classification schemes using types of energy, working movements and working surfaces, as well as the use of a catalogue on varying forces.

To combine the working principles that were found, a classification scheme was produced (see Figure 6.46). For reasons of space, only the most important subfunctions and working principles are shown. Those principles that were clearly unsuitable were either rejected early on or crossed out in the classification scheme. Timely rejection is important in order to minimise subsequent effort.

Step 5: Combining Working Principles

The working principles were combined based on the classification scheme shown in Figure 6.46. Figure 6.47 shows the seven possible combinations (variants) in accordance with the selected function structure variants 4 and 5. The sequences of the subfunctions differ in parts from those of the function structure variants.

Step 6: Selecting Suitable Combinations

A preselection is recommended when a large number of combinations (working structures) have been generated before firming up is attempted (see Section 6.4.3).

Comments **Function structures**

Energy flow with control signals. "Change" and "Control" can be interchanged.

Input energy first changed into a more easily controllable intermediate energy.

Addition of program storage, energy storage, energy increase and energy release (i.e. switching).

Division of "increase" function. Before loading, the sub-function "change" has been added to convert the controlled energy in to the loading quantity "torque".

Input electrical or hydraulic energy. Storage of program outside of the system.

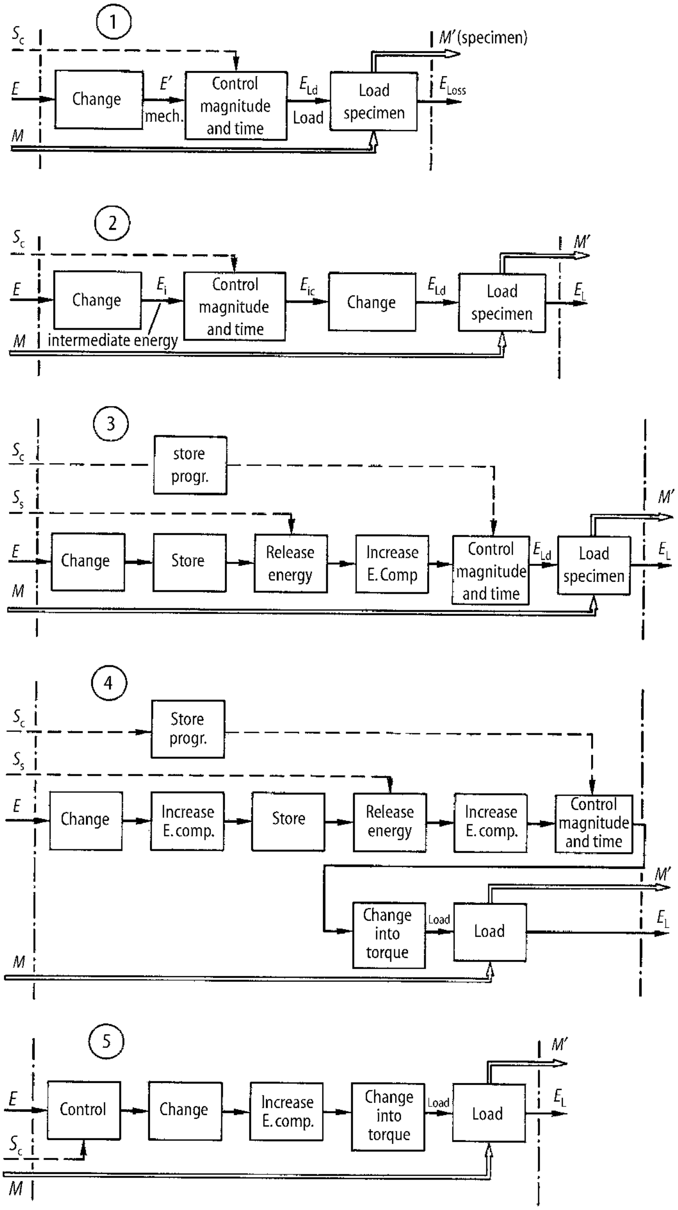

Figure 6.45. Stepwise development of function structure variants

This reduces effort by rejecting less suitable combinations as early as possible. After using the procedure presented in Section 3.3.1, four out of seven combinations appeared promising (see Figure 6.48), but had to be firmed up further to allow for more precise evaluation.

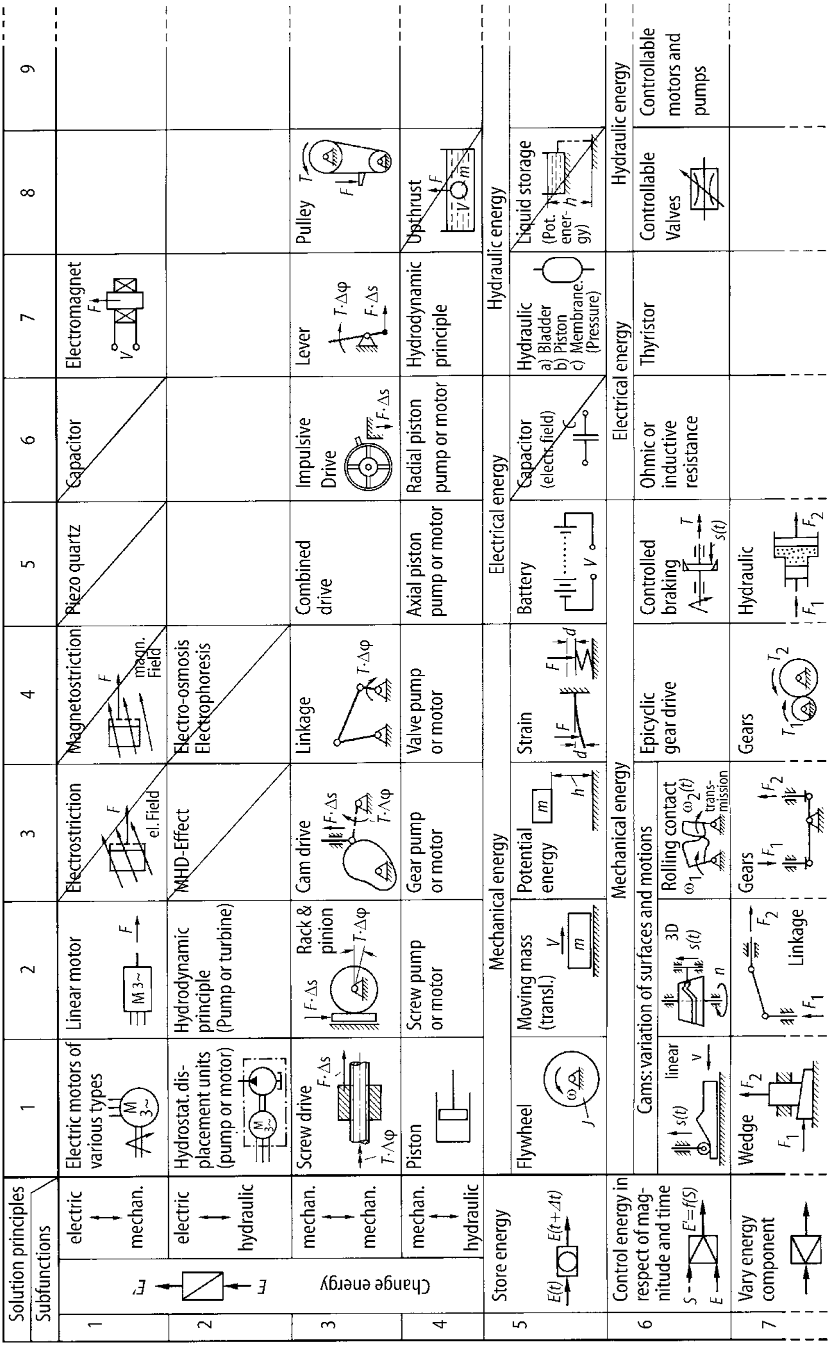

Figure 6.46. Extract from a classification scheme for an impulse-loading test rig

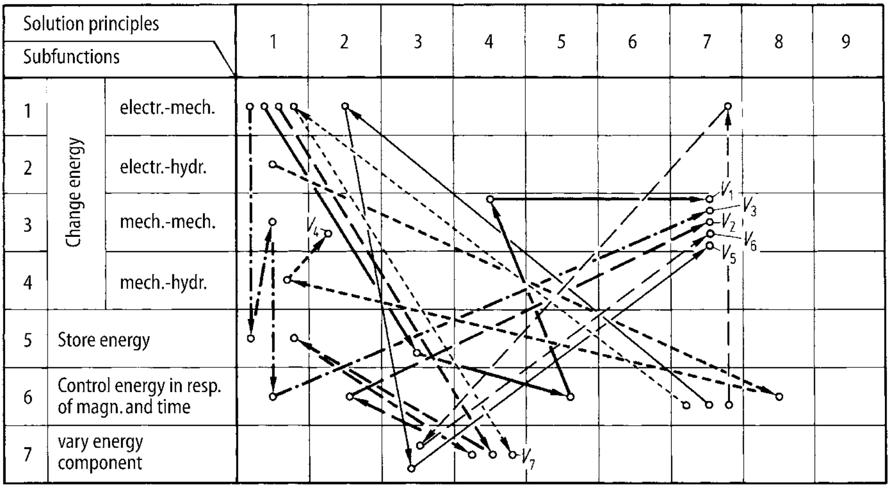

Figure 6.47. Combination scheme showing seven combinations of solution principles in accordance with Figure 6.46.
Variant 1: 1.1 – 5.3 – 6.5 – 3.4 – 3.7;
Variant 2: 1.1 – 7.4 – 5.1 – 7.4 – 6.2 – 3.7;
Variant 3: 1.1 – 5.1 – 3.1 – 6.1 – 3.7;
Variant 4: 2.1 – 6.8 – 4.1 – 3.2;
Variant 5: 6.7 – 1.2 – 7.3 – 3.7;
Variant 6: 6.7 – 1.7 – 7.3 – 3.7;
Variant 7: 6.7 – 1.1 – 7.4

Step 7: Firming Up into Principle Solution Variants

To allow a confident decision to be made about the most suitable principle solution (concept) variant, the selected working structures have to be developed to a state that allows evaluation. This requires that suitable concept drawings such as those shown in Figures 6.49 to 6.52 are produced. Rough sketches often do not provide sufficient detail to assess how well proposals fulfil their functions.

Rough calculations or model tests can be useful at this stage. As an example, calculations will now be made for the cylindrical cam drive used to control the impulsive torque and also the required moment of inertia of the flywheel (energy store) for concept variant V_2.

Can the cylindrical cam shown in Figure 6.53 produce the required torque increase of $\mathrm{d}T/\mathrm{d}t = 125 \times 10^3$ Nm/s and the maximum torque of $T_{\max} = 15 \times 10^3$ Nm?

Calculation steps:

- Time needed to reach the maximum torque at the required rate:

$$\Delta t = \frac{15 \times 10^3}{125 \times 10^3} = 0.12 \text{ s}$$

- Force at the end of the loading lever:

$$F_{\max} = \frac{T_{\max}}{l} = \frac{15 \times 10^3}{0.85} = 17.6 \times 10^3$$

TU Berlin

SELECTION CHART

for Impulse-loading test rig

Part: 1 Page: 1

Solution variants (Sv) evaluated by

SELECTION CRITERIA

- (+) Yes
- (–) No
- (?) Lack of information
- (!) Check requirements list

DECISION

Mark solution variants (Sv)

- (+) Pursue solution
- (–) Eliminate solution
- (?) Collect information (re-evaluate solution)
- (!) Check requirements list for changes

Enter solution variant (Sv):

- A: Compatibility assured
- B: Fulfils demands of requirements list
- C: Realisable in principle
- D: Within permissible costs
- E: Incorporates direct safety measures
- F: Preferred by designer's company
- G: Adequate information

Sv		A	B	C	D	E	F	G	Remarks (Indications, Reasons)	DECISION
V1	1	+	?	+	+	?	–	–	Layout of controlable brakes problematic	+
V2	2	+	+	+	+	+	+	+		+
V3	3	+	+	+	+	+	+	+		+
V4	4	+	+	+	?	+	–	+	Hydraulics not yet applied	+
V5	5	+	?	+	–	+	–	–	No experience with linear motors	–
V6	6	+	?	+	?	+	–	?	Power demand of magnet too great	–
V7	7	+	?	+	–	+	–	?	No experience with thyristor control	–
	8									
	9									
	10									
	11									
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Date: 15. 7. 73 Initials:

Figure 6.48. Selection chart for the seven combinations in Figure 6.47

The loading lever is treated as a weak cantilever spring with the end moving through a distance of $h = 30$ mm with a force of F_{max} in such a way that the permissible bending stress is not exceeded.

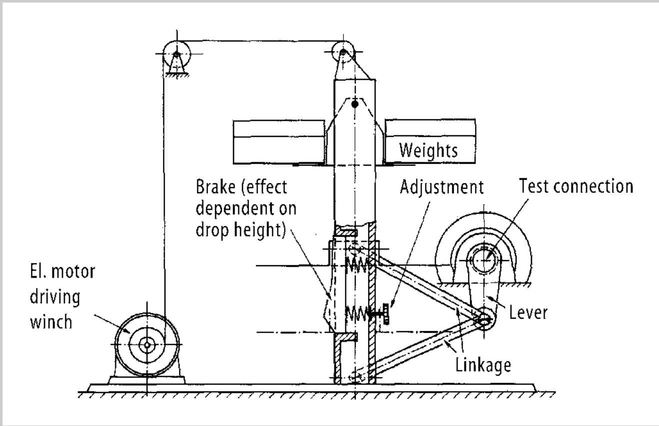


Figure 6.49. Concept variant V_1

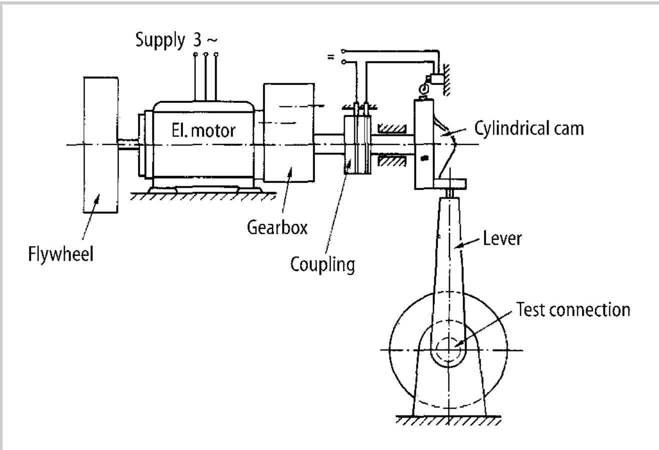


Figure 6.50. Concept variant V_2

- Tangential velocity of the cylindrical cam:

$$v_x = v_y = \frac{h}{\Delta t} = \frac{30}{0.12} = 250 \text{ mm/s}$$

- Angular velocity and rpm of cylindrical cam:

$$\omega = \frac{0.25}{0.125} = 2.0 \text{ rad/s}; \; n = \frac{60\omega}{2\pi} = 19 \text{ rev/min}$$

- Period of revolution:

$$t_\text{r} = \frac{2\pi}{\omega} = 3.14 \text{ s}$$

Since the switching times of the electromagnetically operated clutches used to connect and disconnect the cam drive are in the region of a few tenths of a second, there

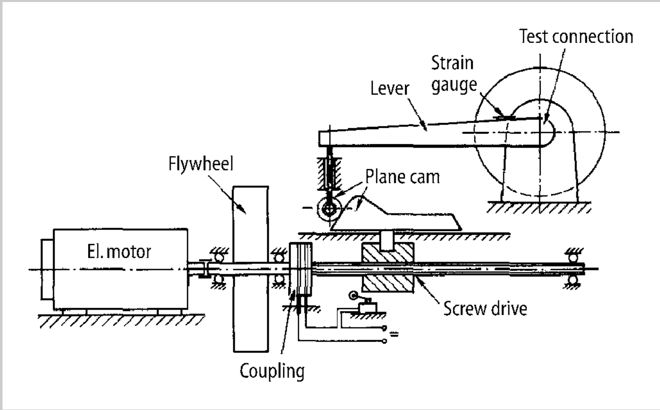


Figure 6.51. Concept variant V_3

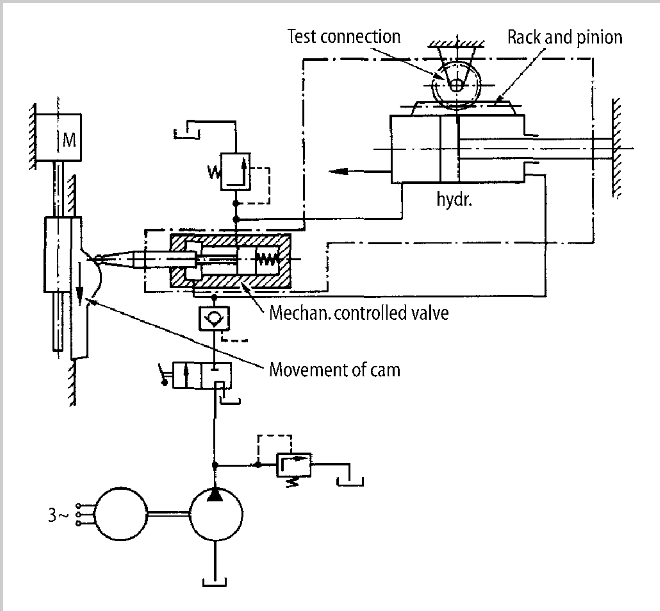


Figure 6.52. Concept variant V_4

should be no problem with applying this principle. The magnitude of, and rate of increase in, the impulse torque loading can be altered by means of interchangeable cams and also by varying the period of revolution.

Steps for estimating the flywheel's moment of inertia:

- The estimate of the energy needed for the impulse (and hence of the energy to be stored) is based on the assumption that all load-carrying parts are elastically deformed.

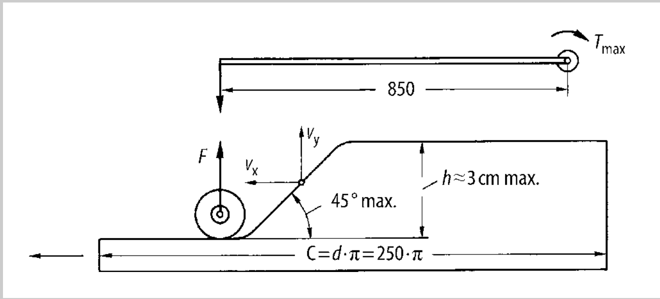


Figure 6.53. Development of cylindrical cam

Stored energy at maximum impulse torque loading:

$$E_{max} = \frac{1}{2} F_{max} \cdot h = 260 \text{ J}$$

This amount of energy is needed in the time interval $\Delta t = 0.12$ s.

- Flywheel dimensions:

  Selected maximum rpm, $n_{max} = 1200$ rev/min; $\omega \mathrel{\hat{=}} 126$ rad/s.

  For flywheel dimensions $r = 0.2$ m and $w = 0.1$ m, the flywheel mass $m_f = 100$ kg, and moment of inertia $J_f = \frac{1}{2} m_f \cdot r^2 = 2 \text{ kg m}^2$.

  Stored energy of flywheel:

$$E_f = \frac{1}{2} J_f \cdot \omega^2 = 159 \times 10^2 \text{ J}$$

- Rotational speed after the impulse:

$$E_{after} = E_f - E_{max} = 15\,640 \text{ J}$$

$$\omega_{after} = \sqrt{\frac{2E_{after}}{J_f}} = 125 \text{ rad/s}; \; n_{after} = 1190 \text{ rev/min}$$

The drop in rpm is therefore very low, and so a motor with a small output is all that is needed.

Step 8: Evaluating Principle Solution Variants

The four variants that were selected in Step 6 and firmed up in Step 7 are evaluated using Cost–Benefit Analysis (see Section 3.3.2).

Important wishes in the requirements list provide a series of evaluation criteria of varying complexity. These are assessed and elaborated with the help of the checklist shown in Figure 6.22. Next, a hierarchical classification (objectives tree) is drawn up to facilitate closer identification and better assignment of the weighting factors and the parameters of the variants. Figure 6.54 shows an objectives tree for the test rig. Its lowest objective level provides the evaluation criteria entered into the table shown in Figure 6.55.

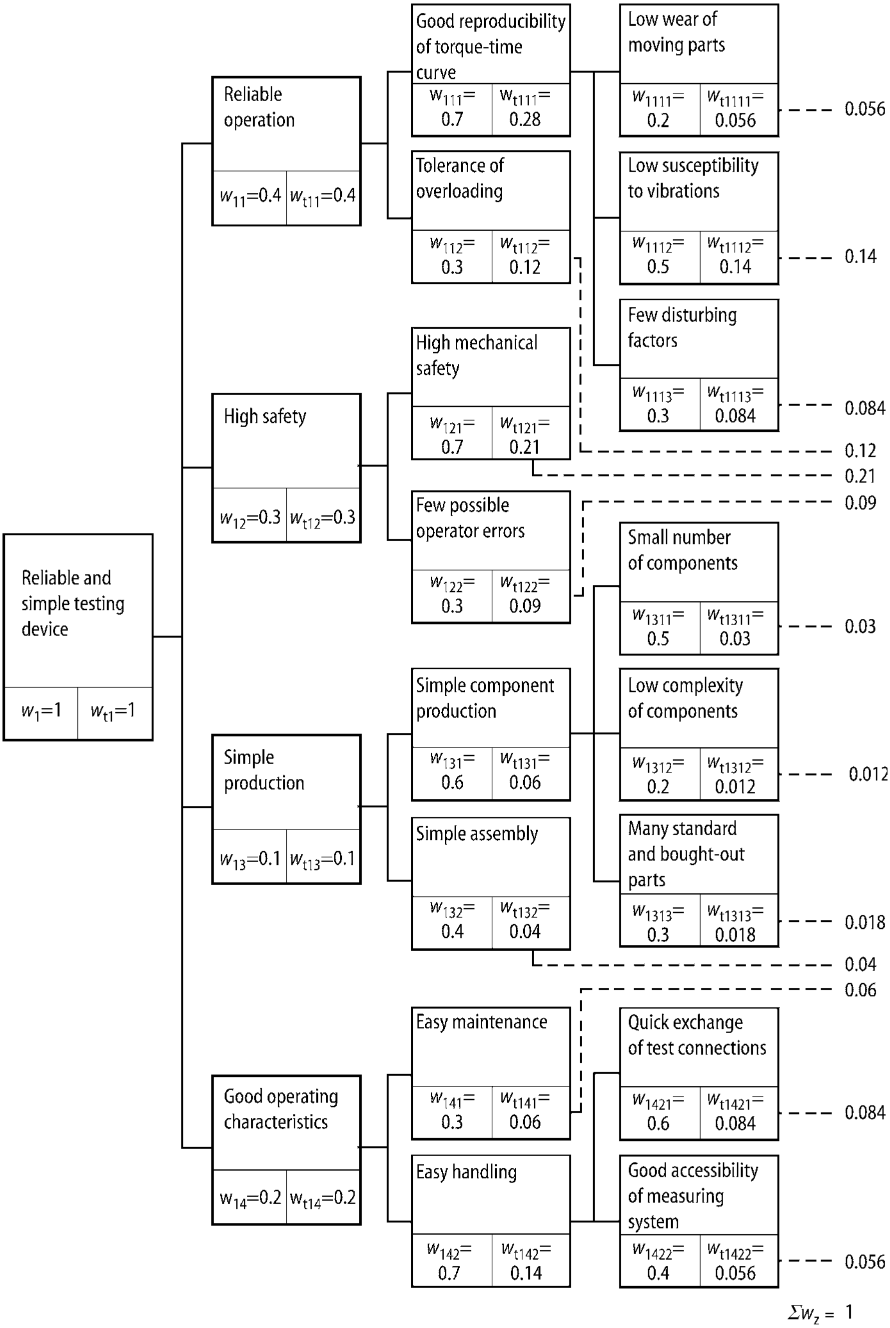


Figure 6.54. Objectives tree for impulse-loading test rig

Evaluation criteria			Parameters		Variant V_1			Variant V_2			Variant V_3			Variant V_4		
No.		Wt.		Unit	Magn. m_{i1}	Value V_{i1}	Weighted value WV_{i1}	Magn. m_{i2}	Value V_{i2}	Weighted value WV_{i2}	Magn. m_{i3}	Value V_{i3}	Weighted value WV_{i3}	Magn. m_{i4}	Value V_{i4}	Weighted value WV_{i4}
1	Low wear of moving parts	0.056	Amount of wear	–	high	3	0.168	low	6	0.336	average	4	0.224	low	6	0.336
2	Low susceptibility to vibrations	0.14	Natural frequencey	s^{1}	410	3	0.420	2370	7	0.980	2370	7	0.980	< 410	2	0.280
3	Few disturbing factors	0.084	Disturbing factors	–	high	2	0.168	low	7	0.588	low	6	0.504	(average)	4	0.336
4	Tolerance of overloading	0.12	Overload reserve	%	5	5	0.600	10	7	0.840	10	7	0.840	20	8	0.960
5	High mechanical safety	0.21	Expected mechanical safety	–	average	4	0.840	high	7	1.470	high	7	1.470	very high	8	1.680
6	Few possible operator errors	0.09	Possibilities of operator errors	–	high	3	0.270	low	7	0.630	low	6	0.540	average	4	0.360
7	Small number of components	0.03	No. of components	–	average	5	0.150	average	4	0.120	average	4	0.120	low	6	0.180
8	Low complexity of components	0.012	Complexity of components	–	low	6	0.072	low	7	0.084	average	5	0.060	high	3	0.036
9	Many standard and bought-out parts	0.018	Proportion of standard and bought-out components	–	low	2	0.036	average	6	0.108	average	6	0.108	high	8	0.144
10	Simple assembly	0.04	Simplicity of assembly	–	low	3	0.120	average	5	0.200	average	5	0.200	high	7	0.280
11	Easy maintenance	0.06	Time and cost of maintenance	–	average	4	0.240	low	8	0.480	low	7	0.420	high	3	0.180
12	Quick exchange of test connections	0.084	Estimated time needed to exchange test connections	min	180	4	0.336	120	7	0.588	120	7	0.588	180	4	0.336
13	Good accessibility of measuring systems	0.056	Accessibility of measuring system	–	good	7	0.392	good	7	0.392	good	7	0.392	average	5	0.280
		$\sum w_i = 1.0$				$OV_1=51$ $R_1=0.39$	$OWV_1=3.812$ $WR_1=0.38$		$OV_2=85$ $R_2=0.65$	$OWV_2=6.816$ $WR_2=0.68$		$OV_3=78$ $R_3=0.60$	$OWV_3=6.446$ $WR_3=0.64$		$OV_4=68$ $R_4=0.52$	$OWV_4=5.388$ $WR_4=0.54$

Figure 6.55. Evaluation of the four principle solution variants for the impulse-loading test rig

It appears that variant V_2 has the highest overall value and the best overall rating. However, variant V_3 follows close behind. For the detection of weak spots, a value profile was drawn (see Figure 6.56). The profile shows that variant V_2 is well-balanced with respect to all of the important evaluation criteria. With a weighted rating of 68%, variant V_2 thus represents a good principle solution (concept) with which to start the embodiment design phase, during which the identified weak spots have to be addressed (see Section 7.7).

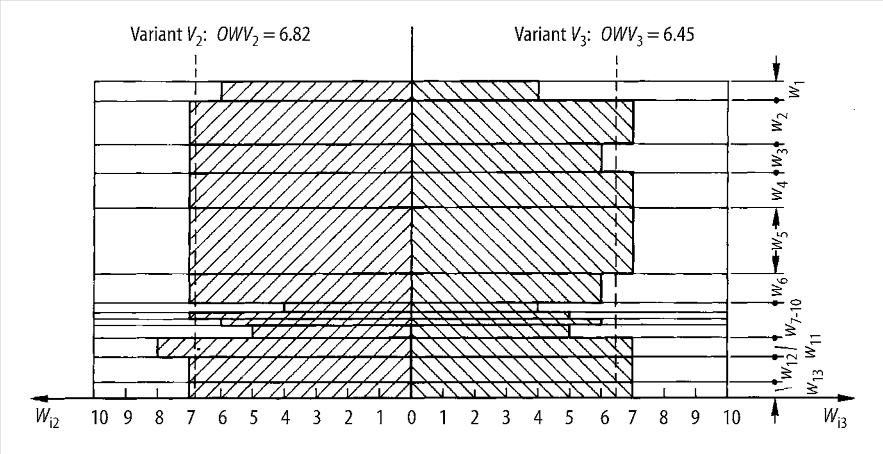


Figure 6.56. Value profile for detection of weak spots

7 Embodiment Design

Embodiment design is the part of the design process in which, starting from the principle solution or concept of a technical product, the design is developed in accordance with technical and economic criteria and in the light of further information, to the point where subsequent detail design can lead directly to production (see Section 4.2).

The draft guideline VDI 2223: *Systematic Embodiment of Technical Products* [7.295] builds on recommendations from the fourth German edition of this book along with other sources. In doing so, it presents a generally established systematic procedure for embodiment design.

7.1 Steps of Embodiment Design

Having elaborated the principle solution during the conceptual phase, the underlying ideas can now be firmed up. During the embodiment phase at the latest, designers must determine the overall layout design (general arrangement and spatial compatibility), the preliminary form designs (component shapes and materials) and the production processes, and provide solutions for any auxiliary functions. During all of this, technological and economic considerations are of paramount importance. The design is developed with the help of scale drawings, critically reviewed, and subjected to a technical and economic evaluation.

In many cases several embodiment designs are needed before a definitive design appropriate to the desired solution can emerge.

In other words, the *definitive layout* must be developed to the point where a clear check of function, durability, production, assembly, operation and costs can be carried out. Only when this has been done is it possible to prepare the final production documents.

Unlike conceptual design, embodiment design involves a large number of corrective steps in which analysis and synthesis constantly alternate and complement each other. This explains why the familiar methods underlying the search for solutions and evaluation must be complemented with methods facilitating the identification of errors (design faults) and optimisation. The collection of information on materials, production processes, repeat parts and standards involves considerable effort.

The embodiment process is complex in that:

- many actions must be performed simultaneously
- several steps must be repeated at a higher level of information
- additions and alterations in one area have repercussions on the existing design in other areas.

Because of this, it is not always possible to draw up a strict plan for the embodiment design phase. However, it is possible to suggest a general approach with main working steps, see Figure 7.1. Particular problems may demand deviations and subsidiary steps, which can rarely be predicted precisely. The approach has to be planned to match the problem at hand, realising that further modifications will have to be made. Basically, the process will proceed from the qualitative to the quantitative, from the abstract to the concrete, and from rough to detailed designs. It is important to make provision for checks and, if necessary, for corrections.

1. Starting with the principle solution, and using the requirements list, the first step is to identify those *requirements that have a crucial bearing* on the embodiment design:
   - size-determining requirements, such as output, throughput, size of connectors, etc.
   - arrangement-determining requirements, such as direction of flow, motion, position, etc.
   - material-determining requirements, such as resistance to corrosion, service life, specified materials, etc.

   Requirements such as those based on safety, ergonomics, production, assembly and recycling involve special embodiment considerations, which may affect the size, arrangement, and selection of materials (see Sections 7.2 to 7.5).
2. Next, the *spatial constraints* determining or restricting the embodiment design must be identified (for instance clearances, axle positions, installation requirements, etc.).
3. Once the embodiment-determining requirements and spatial constraints have been established, a rough layout, derived from the concept, is produced with the emphasis on the overall embodiment-determining *main function carriers*, that is, the assemblies and components fulfilling the main functions. The following subsidiary questions must be settled, with due regard paid to the principles of embodiment design (see Section 7.4):
   - Which main functions and function carriers determine the size, arrangement and component shapes of the overall layout (for instance, the blade profiles in turbomachines or the flow area of valves)?
   - Which main functions must be fulfilled by which function carriers jointly or separately (for instance, transmitting torque and allowing for radial movement by means of a flexible shaft or by means of a stiff shaft plus a special coupling)? This step is similar to division into realisable modules, as shown in Figure 1.9.

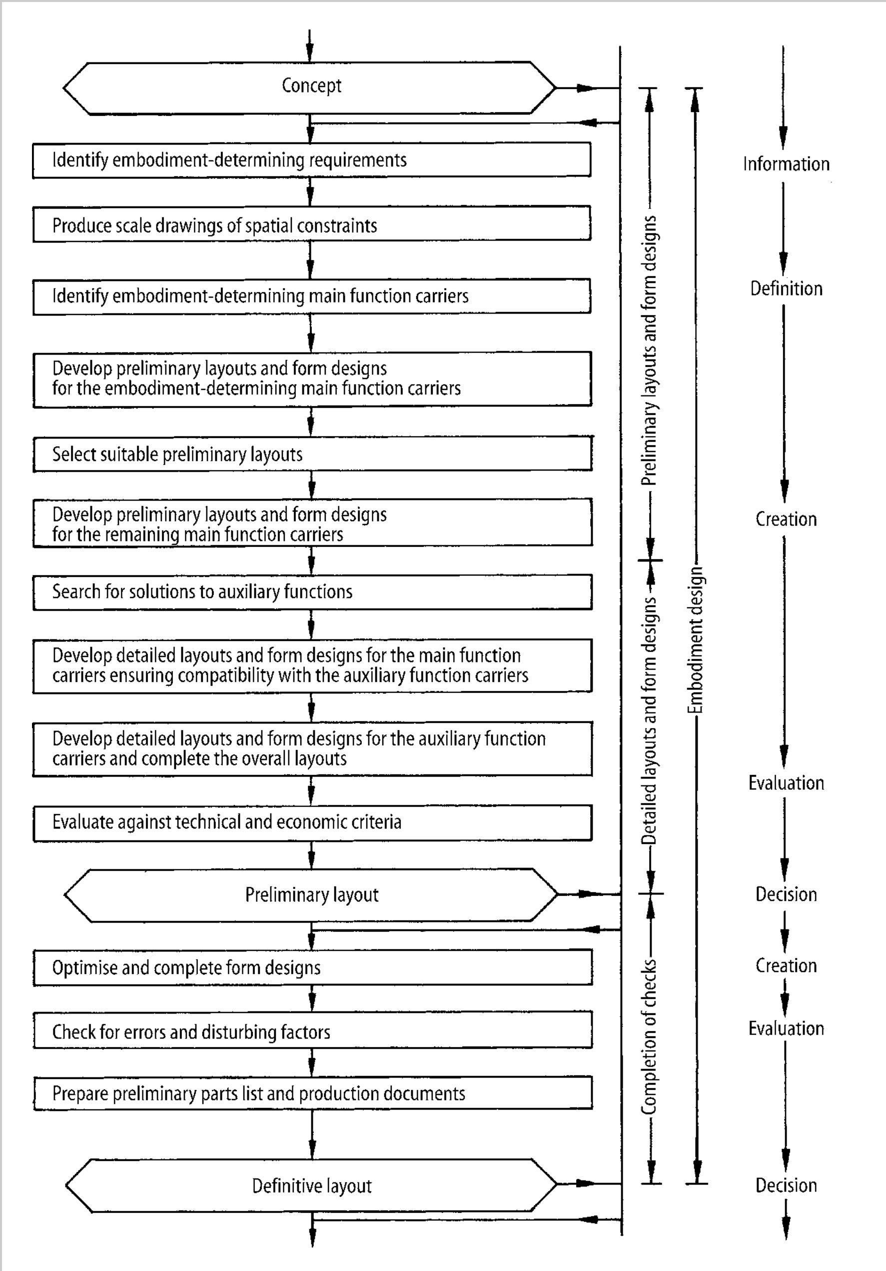


Figure 7.1. Steps of embodiment design

4. Preliminary scale layouts and form designs for the embodiment-determining main function carriers must be developed; that is, the general arrangement, component shapes and materials must be determined provisionally. To that end, it is advisable to work systematically through the items under the heading "layout" in the checklist shown in Figure 7.3. The result must meet the overall spatial constraints and then be completed so that all of the relevant main functions are fulfilled (for instance by specifying the minimum diameters of drive shafts, provisional gear ratios, minimum wall thicknesses, etc.). Known solutions or existing components (repeat parts, standard parts, etc.) must be shown in simplified form. It may be useful to start working on selected areas only, combining these into preliminary layouts later.
5. One or more suitable *preliminary layouts* must be selected in accordance with the procedure described in Section 3.3.1 (modified if necessary) by considering the relevant items in the checklist shown in Figure 7.3.
6. Preliminary layouts and form designs must now be developed for the remaining main function carriers that have not yet been considered because known solutions exist for them or they are not embodiment-determining until this stage.
7. Next, determine which essential *auxiliary functions* (such as support, retention, sealing and cooling) are needed and, where possible, *exploit known solutions* (such as repeat parts, standard parts, catalogue solutions). If this proves impossible, *search for special solutions*, using the procedures already described in Section 3.2 and Chapter 6.
8. *Detailed layouts and form designs for the main function carriers* must now be developed in accordance with the embodiment design rules and guidelines (see Sections 7.3 to 7.5), paying due attention to standards, regulations, detailed calculations and experimental findings, and also to the problem of compatibility with those auxiliary functions that have been realised. If necessary, divide into assemblies or areas that can be elaborated individually.
9. Proceed to develop the *detailed layouts and form designs for the auxiliary function carriers*, adding standard and bought-out parts. If necessary, refine the design of the main function carriers and combine all function carriers into overall layouts.
10. *Evaluate* the layouts against technical and economic criteria (see Section 3.2.2). If a particular project requires several concepts to be put in more concrete form prior to evaluation, then the embodiment process must not, of course, be pursued beyond what the evaluation of the variants demands. Depending on the circumstances, it is thus possible, in some cases, to take a decision just as soon as the main function carriers have reached the preliminary layout stage, while in other cases the decision will have to be deferred until after a great deal of detail design. In either event, all of the designs to be compared must be at the same level of embodiment, since no reliable evaluation is possible otherwise.

11. Fix the preliminary overall layout. The overall layout describes the complete construction structure (see Figure 2.13) of the system or product being designed.
12. Optimise and complete the form designs for the selected layout by *eliminating the weak spots* that have been identified during the course of the evaluation. If it should prove advantageous, repeat the previous steps and adopt suitable subsolutions from less favoured variants.
13. *Check* this layout design for *errors* (design faults) in function, spatial compatibility, etc. (see Figure 7.3), and for the effects of *disturbing factors*. Make what improvements may be needed. The achievement of the objectives with respect to cost (see Chapter 11) and quality (see Chapter 10) must be established at this point at the latest.
14. Conclude the embodiment design phase by preparing a preliminary *parts list* as well as a preliminary *production and assembly documents*.
15. Fix the *definitive layout* and pass on to the detail design phase.

The representation of the spatial constraints and the embodiment is now generally obtained by creating a full 3-D digital model. Irrespective of whether a 2-D or 3-D representation is used [7.213]:

- the function and type of the objects must be shown
- the positions of and the necessary space for the objects must be recognisable through characteristic dimensions, e.g. the overall dimensions, which can be used to check the overall spatial compatibility and assembly operations.

When 2-D CAD systems or drawing boards are still used simplifications, such as those proposed by Lüpertz [7.174], could be used.

In the embodiment phase, unlike the conceptual phase, it is not necessary to lay down special methods for every individual step, however the following recommendations might prove useful.

The *search for solutions* for auxiliary functions and other subsidiary problems should be based either on the procedure described in Chapter 3, but simplified as far as possible, or else directly on catalogues. Requirements, functions and solutions with appropriate classifying criteria have already been elaborated.

The *embodiment* (layout and form designs) of the function carriers should be based on the checklist (see Figure 7.3) and involves reference to the principles of mechanics and structures, and to materials technology. It calls for calculations ranging from the simplest through to complex differential equations and finite element analyses. For these calculations, the reader is referred to the literature listed in Section 7.5.1, and for even more complex calculations to the domain specific literature. In some cases it might be necessary to build prototypes or to undertake specific tests.

In the elaboration of embodiment designs, many details have to be clarified, confirmed and optimised. The more closely they are examined, the more obvious it becomes as to whether the right solution concept has been chosen. It may appear that this or that requirement cannot be met, or that certain characteristics of the chosen concept are unsuitable. If this is discovered during the embodiment phase, it is advisable to re-examine the procedure adopted in the conceptual phase, for no embodiment design, however perfect, can hope to correct a poor concept. This is equally true of the working principles applicable to the various subfunctions. However, even the most promising concept can cause difficulties in embodiment and detail design. This often happens because various features were originally treated as subordinate or as not in need of further clarification. Attempts to solve these subproblems compel designers to reiterate the appropriate steps while retaining the selected working structure and overall arrangement.

Experience with the proposed approach for embodiment design has confirmed its basic validity, but has also revealed the following important points [7.211]:

- If prior research has been undertaken or embodiment variants already exist, the step of producing preliminary embodiments can often be left out.
- Preliminary embodiments can always be left out when only detailed improvements are required.
- The solutions for auxiliary functions usually influence the preliminary embodiment of the main function carriers, so working on these solutions must not be left until too late in the process.
- A characteristic of successful designers is that they continuously check and monitor their actions to identify direct and indirect effects.

Many products are not developed from scratch, but are developments or improvements of existing ones that take into account new requirements, new knowledge and experiences. Experience has shown that it is useful to start by analysing the failures and disturbing factors for an existing solution (see Sections 10.2 and 10.3) and, based on that analysis, to develop a new requirements list (see Figure 7.2). The result of the clarified task will show whether a new working structure—a new principle solution—is required, or whether it is sufficient to modify the existing embodiment. It is possible to start at many different places within the overall approach. In some cases a new product can be produced by making improvements to the details. In other cases, tests of the existing or modified modules may be necessary. The required steps in the overall approach must be selected appropriately.

To sum up, embodiment design involves a flexible approach with many iterations and changes of focus. The individual steps have to be selected and adapted to the particular situation. The ability to organise one's own approach while paying due regard to the fundamental links between the steps and the recommendations we provide is important (see Section 2.2.1).

In embodiment design, the rules and principles elaborated in Sections 7.2 to 7.5 should be followed. Because of the fundamental importance of the identification of errors (design faults) in several of the steps, the reader is referred to Chapter 10 in particular.

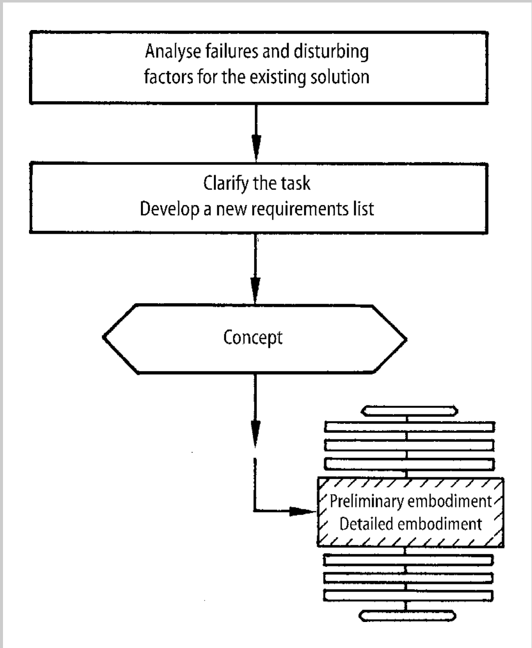


Figure 7.2. Embodiment design phase based on the development of an existing solution. Which of the steps shown in Figure 7.1 needs to be completed follows from an analysis of failures and disturbing factors

7.2 Checklist for Embodiment Design

Embodiment design is characterised by *repeated deliberation and verification* (see Section 7.1). Every embodiment design is an attempt to fulfil a given function with appropriate layout, component shapes and materials. The process starts with preliminary scale layouts based on a rough analysis of spatial requirements, and proceeds to consider safety, ergonomics, production, assembly, operation, maintenance, recycling, costs and schedules.

In dealing with these factors, designers will discover a large number of interrelationships, so that their approach must be progressive as well as iterative (verification and correction). Notwithstanding this double character, however, the approach must always be such as to allow the speedy identification of those problems that must be solved first.

The checklist shown in Figure 7.3 has been derived from the general objectives and constraints discussed in Section 2.1.7. Although the factors are interrelated, this checklist presents them in a useful procedural order and provides designers with a systematic check on each one. The checklist thus not only provides a strong mental impetus, but also ensures that nothing essential is forgotten.

All in all, continuous reference to the headings will help designers to develop and test their progress in a systematic and time-saving way. Each heading should be examined in turn, regardless of its interrelationship with the rest.

Headings	Examples
Function	Is the stipulated function fulfilled? What auxiliary functions are needed?
Working principle	Do the chosen working principles produce the desired effects and advantages? What disturbing factors may be expected?
Layout	Do the chosen overall layout, component shapes, materials and dimensions provide: adequate durability (strength) permissible deformation (stiffness) adequate stability freedom from resonance unimpeded expansion acceptable corrosion and wear with the stipulated service life and loads?
Safety	Have all the factors affecting then safety of the components, of the function, of the operation and of the environment been taken into account?
Ergonomics	Have the human–machine relationships been taken into account? Have unnecessary human stress or injurious factors been avoided? Has attention been paid to aesthetics?
Production	Has there been a technological and economic analysis of the production processes?
Quality control	Can the necessary checks be applied during and after production or at any other required time, and have they been specified?
Assembly	Can all the internal and external assembly processes be performed simply and in the correct order?
Transportt	Have the internal and external transport conditions and risks been examined and taken into account?
Operation	Have all the factors influencing the operation, such as noise, vibration, handling, etc. been considered?
Maintenance	Can maintenance, inspection and overhaul be easily performed and checked?
Recycling	Can the product be reused or recycled?
Costs	Have the stipulated cost limits been observed? Will additional operational or subsidiary costs arise?
Schedules	Can the delivery dates be met? Are there design modifications that might improve the delivery situation?

Figure 7.3. Checklist for embodiment design

The actual sequence is no indication of the relative importance of the various headings, but ensures a systematic approach. For instance, it would be futile to deal with assembly problems before ascertaining if the required performance or minimum durability is ensured. The checklist thus provides a consistent scrutiny of embodiment design and one that is easily memorised.

7.3 Basic Rules of Embodiment Design

The following basic rules apply to all embodiment designs. If they are ignored problems are introduced and breakdowns or accidents may occur. They underlie nearly all of the steps listed in Section 7.1. When used in conjunction with the checklist (see Figure 7.3) and with the design fault identification methods (see Chapter 10), they also provide essential assistance with selection and evaluation.

The *basic rules* of clarity, simplicity and safety are derived from the general objectives set out in Section 2.1.7, that is:

- fulfilment of the technical function
- economic feasibility
- individual and environmental safety.

The literature contains numerous rules of, and guidelines for, embodiment design [7.168, 7.180, 7.198, 7.205]. On closer analysis it appears that clarity, simplicity and safety are fundamental to all of them and are important prerequisites for a successful solution.

Clarity—that is, clarity of function or lack of ambiguity of a design—facilitates reliable prediction of the performance of the final product and in many cases saves time and costly analyses.

Simplicity generally guarantees economic feasibility. A smaller number of components and simple shapes are produced more quickly and easily.

Safety imposes a consistent approach to the problems of strength, reliability, accident prevention and protection of the environment.

In short, by observing these three basic rules, designers can increase their chances of success because they focus attention on, and help to combine, functional efficiency, economy and safety. Without this combination no satisfactory solution is likely to emerge.

7.3.1 Clarity

In what follows we shall be applying the basic rule of clarity to the various headings of the checklist in Figure 7.3.

Function

Within a given function structure, an unambiguous interrelationship between the various subfunctions and the appropriate inputs and outputs must be guaranteed.

Working Principle

The chosen working principle, in terms of the physical effects, must reveal a clear relationship between cause and effect, thus ensuring an appropriate and economical layout.

The chosen working structure, comprising several individual working principles, must guarantee an orderly flow of energy, material and signals. If it does not, undesirable and unpredictable effects such as excessive forces, deformations and wear may ensue.

By paying attention to the deformations associated with a given loading, and also to thermal expansion, designers must make the necessary allowances for possible expansion in a given direction.

The widely used bearing pairs, with a locating and a nonlocating bearing (see Figure 7.4a) have a clearly defined behaviour. The stepped bearing pair (see Figure 7.4b), on the other hand, should be specified only when the expected changes

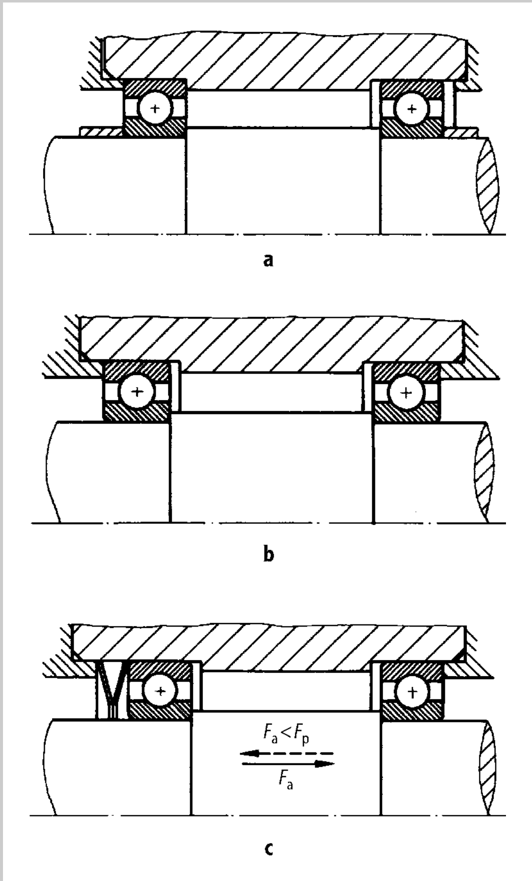


Figure 7.4. Basic bearing arrangements: **a** Locating and nonlocating arrangement: left-hand locating bearing takes up all the axial forces, right-hand sliding bearings permit unimpeded axial movement due to thermal expansion; accurate calculations are possible. **b** Stepped bearing arrangement: the axial loading of the bearings depends on the preload and thermal expansion and cannot be clearly determined; a modification is the "floating arrangement" in which the bearings are provided with axial clearance; in that case, thermal expansion is possible to a limited extent but there is no precise shaft location. **c** Spring-loaded bearing arrangement: here the disadvantages of the stepped bearing arrangement are largely eliminated, though the constantly applied axial load may reduce the bearing life; forces resulting from thermal expansion can be determined by spring force deflection diagrams; the shaft is located precisely provided the axial force F_a acts only towards the right or does not exceed the preloading F_p

in length are negligible or when the resulting play in the bearings is permissible. By contrast, a spring-loaded arrangement, in which the operating axial force F_a does not exceed the pre-load F_p, will permit a clear definition of the force transmission path (see Figure 7.4c).

Combined bearing arrangements often present problems. The combination shown in Figure 7.5a consists of a needle roller bearing which is intended to transmit the radial forces and a ball bearing which is meant to transmit the axial forces. However, this particular arrangement does not clearly define the transmission path for the radial forces, because the inner and outer races of both bearings

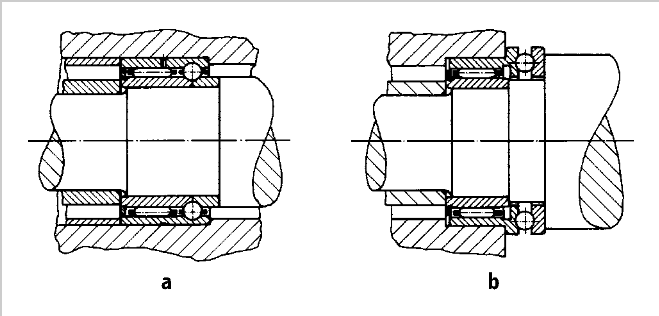


Figure 7.5. Combined rolling-element bearing. **a** Transmission path of radial forces not clear; **b** combined rolling bearing with the same elements as in **a**, but clear identification of the transmission paths of the radial and axial forces

are restrained radially. As a result, the service life cannot be predicted accurately. The arrangement shown in Figure 7.5b, on the other hand, satisfies the clarity rule with similar elements, provided the designer ensures during assembly that the right-hand race has enough radial play, thus making certain that the ball bearing transmits axial forces only.

Double fits conflict with the basic rule of clarity. These occur when a component is supported or guided by two surfaces at the same time, and these surfaces are either on different planes or on different cylindrical sections. In such cases, the surfaces have to be machined separately and will therefore have different dimensions caused by the tolerances. As a consequence, the force flow cannot be predicted clearly and assembly is made more difficult. Even though modern production machines have reduced the problems with tolerances, the lack of clarity will still affect function fulfilment and ease of assembly unless double fits are avoided. Double fits appear in various forms. Figure 7.6 shows examples and corrective measures.

Layout

The layout (general arrangement) and form design (shapes and materials) require a clear definition of the magnitude, type, frequency and duration of loads. If these data are not available, the implementation must be based on reasonable assumptions and the expected service life specified accordingly.

In any case, the embodiment must be such that the loads can be defined and calculated under all operating conditions. No impairment of the function or the durability of a component must be allowed to arise.

Similarly, following the checklist in Figure 7.3, behaviour with respect to stability, resonance, wear and corrosion must be clearly established.

Very often one comes across *double arrangements*, i.e. doubling up working principles for safety's sake, which conflict with the rule of clarity. Thus a shaft–hub connection designed as a interference fit will not have a better load-carrying capacity if it is also provided with a key, as in Figure 7.7. The extra element merely ensures correct positioning in the circumferential sense, but because of the reduction in the area at *A*, the resulting stress concentration at *B* and the presence

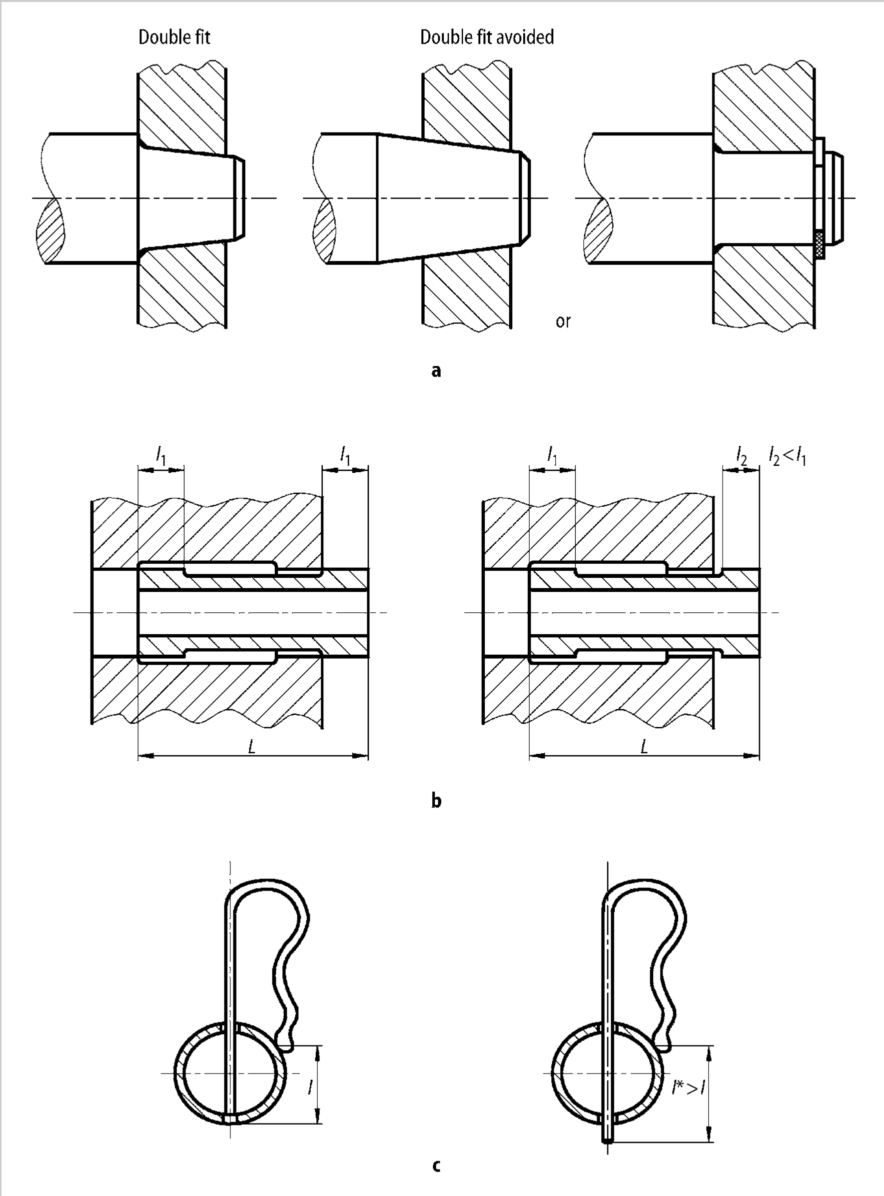


Figure 7.6. Avoiding double fits: **a** Tapered shaft–hub connection with interference (shrink) fit. The simultaneous axial location against the shaft collar and the taper seat creates a double fit: the radial pressure due to the interference fit cannot be determined. The right solution would be to use either a taper without a shaft collar or to use a cylindrical seat with a shaft collar. **b** Supported linear slide using a guiding sleeve in a housing. The simultaneous location of the housing at two points complicates the assembly process. A possible solution is shown in the figure on the right. **c** Spring clip of such a length that the lower end touches the tube at the same time as the pressure point touches the tube. The user will not be able to determine whether the clip is blocked by the tube or whether the spring force has to be overcome. The correct solution is shown in the figure on the right

of complicated and almost incalculable stresses at *C*, it decreases the strength in a drastic and fairly unpredictable manner.

Schmid [7.242] has shown that an axially preloaded taper joint for the transmission of torque requires a spiralling motion when the hub is assembled on the shaft in order to ensure a reliable interference fit, and the use of a key prevents this.

The employment of an interference fit to achieve the maximum torque capacity is only possible by leaving out the key. The solution shown in Figure 7.7 is only acceptable when the correct positioning of the hub relative to the shaft is the crux of the task, in which case a sliding fit is more appropriate.

Figure 7.8 shows a housing adapter for a centrifugal pump which can be used to provide various annulus profiles to fit different blade shapes so that new housings need not be constructed for each case. Unless the intermediate pressure in the gap between the adapter and the housing can be clearly regulated, or some other means of attachment is used, the adapter might travel upwards and damage the blades by rubbing against them.

This is particularly true when similar fits (H7-j6) are chosen for the two locating diameters which are approximately the same size. This is because, depending on production tolerances and working temperatures, gaps may appear, the relative sizes of which are unpredictable and which produce unknown intermediate pressures in the space between the adapter and the housing. The solution shown in Figure 7.8 (detail) ensures, by means of the specially designed connecting passage *A* (which must have a flow area roughly four to five times greater than the maximum gap area that might appear at the upper locating diameter), a clearly definable intermediate pressure, corresponding to the lower inlet pressure of the pump. As a result, the housing adapter is always pressed

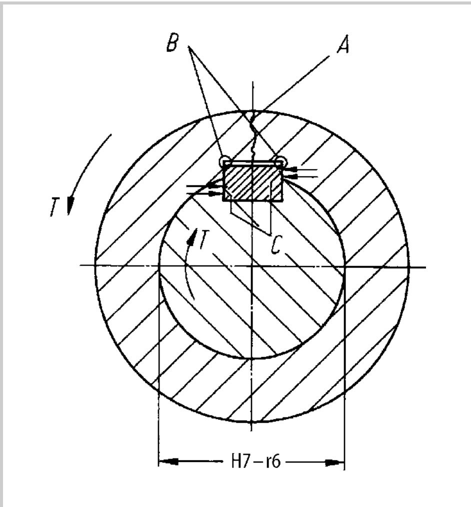


Figure 7.7. Combined shaft–hub connection achieved by means of shrink fit and key: an example of not applying the principle of clarity

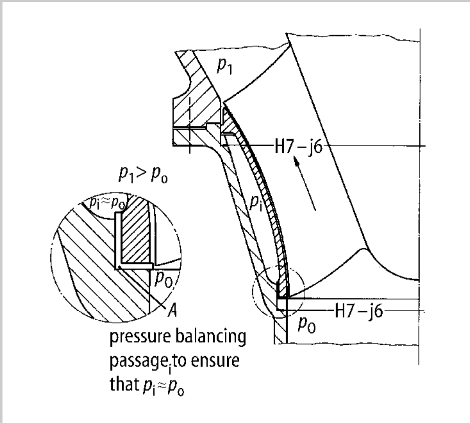


Figure 7.8. Housing adapter in a cooling-water pump

downwards when the pump is in operation, and attachments are only needed as locating aids for assembly and to prevent any tendency of the adapter to rotate.

Serious damage has been reported in gate valves whose operational or loading conditions were not clearly defined [7.130, 7.131]. When closed, gate valves separate, say, two steam pipes and at the same time close off the inside of the valve housing. The result is a self-contained pressure chamber, as shown in Figure 7.9. If condensate has collected in the lower part of the valve housing, and steam appears on the inlet side with the valve closed so that the valve is heated, then the enclosed condensate may evaporate and produce an unpredictable increase in pressure inside the valve housing. The result is either a ruptured housing or serious damage to the housing cover connection. If the latter is self-sealing, serious accidents may ensue since, in contrast to what happens with overloaded bolted flange connections, there is no preliminary leakage and hence no warning. The danger lies in the failure to specify clear operational and loading conditions. Possible remedies are as follows:

- Connect the inner chamber of the gate valve housing to an appropriate steam pipe, operational conditions permitting ($p_{\text{valve}} = p_{\text{pipe}}$)
- Protect the valve housing against excess pressure (p_{valve} restricted)
- Drain the valve housing, thus avoiding collection of condensate ($p_{\text{valve}} \approx p_{\text{external}}$)
- Design valves in such a way as to minimise the housing volume (collection of condensate kept low).

Similar phenomena in welded membrane seals are discussed in [7.206].

Safety

See basic rule in Section 7.3.3.

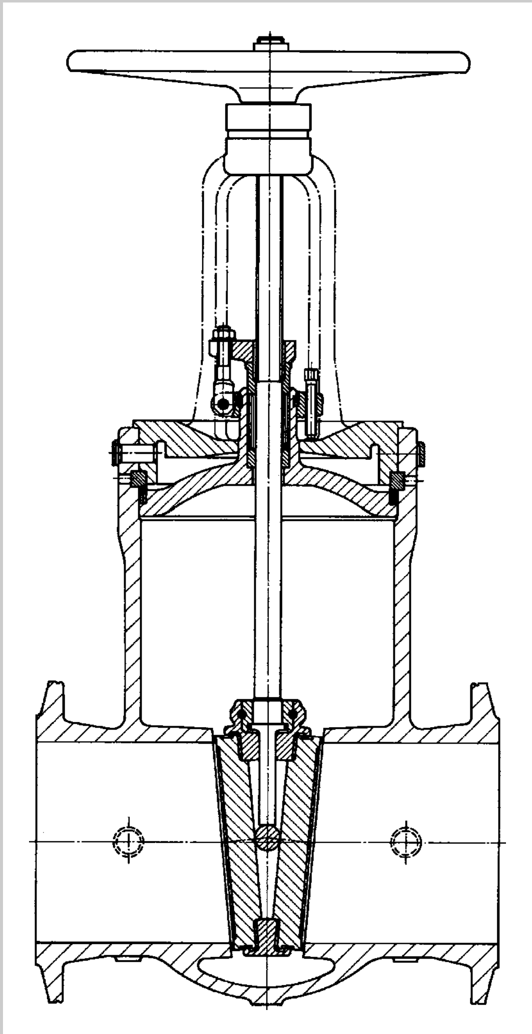


Figure 7.9. Gate valve with relatively large lower collecting area

Ergonomics

In human–machine relationships, correct operation must be ensured via the logical layout of equipment and controls.

Production and Quality Control

These must be facilitated by clear and comprehensive data in the form of product models as well as drawings, parts lists and instructions; and adherence to the prescribed production and quality control procedures.

Assembly and Transport

Much the same is true of assembly and transport. A clear assembly sequence preventing mistakes should be incorporated into the design (see Section 7.5.8).

Operation and Maintenance

Clear installation instructions and the appropriate embodiment design must ensure that:

- the performance is easily checked
- inspection and maintenance involves the smallest possible variety of tools and equipment
- the scope and schedules of inspection and maintenance are defined
- inspection and maintenance can be checked after they have been carried out (see Section 7.5.10).

Recycling

Designers should provide (see Section 7.5.11):

- clear separation of materials that are incompatible with regard to recycling
- clear sequences of assembly and disassembly.

7.3.2 Simplicity

For technical applications, the word "simple" means "not complex", "easily understood" and "easily done".

A solution seems simpler if it can be effected with fewer components, because, for example, the probability of lower production costs, less wear and lower maintenance is then greater. However, this is only true if the arrangement and shapes of the components are kept simple. Hence designers should always aim at the minimum number of components with the simplest shapes [7.168, 7.198, 7.206].

As a rule, however, a compromise has to be made. The fulfilment of a function always demands a certain minimum number of components. Cost efficiency often necessitates a decision between numerous components with simple shapes but with greater overall production effort, and, for example, a single cheaper cast component with the greater uncertainty it may entail in delivery. Simplicity must always be assessed from a holistic perspective—what constitutes "simpler" in individual cases depends on the problem and the constraints.

In what follows we shall be applying the basic rule of simplicity to the various headings of the checklist shown in Figure 7.3.

Function

In principle, only a minimum number and a clear and consistent combination of subfunctions should be pursued when considering the function structure.

Working Principle

In selecting working principles, only those involving a small number of processes and components, that have obvious validity and involve low costs should be taken into consideration.

In the development of the one-handed mixing tap (see Section 6.6.1), several solution principles were proposed. One group (see Figure 6.36) involved the use of only one component to realise two independent adjustments in directions tangential to the valve seat face (types of motion: translation and rotation). The other group (see Figure 6.33), though involving only movements in one direction (normal or tangential to the seat face), required an additional coupling mechanism to convert the two single adjustments into one direction of movement. Quite apart from the fact that, in the second group, the preset temperature is often lost when the tap is shut off, all solutions represented in Figure 6.33 involve a greater design effort than those in the first group. Hence, designers should always begin with a group like that depicted in Figure 6.36.

Layout

Here the simplicity rule requires:

- geometrical shapes which can be analysed simply for strength and stiffness
- symmetrical shapes which provide clearer identification of deformations during production and under mechanical or thermal loads.

In many cases, designers can reduce the work of calculation and experimentation significantly if they try, by means of a simple design, to facilitate the application of basic mathematical principles.

Safety

See under Section 7.3.3.

Ergonomics

The human–machine relationship should also be simple (see Section 7.5.5) and can be significantly improved by means of:

- obvious operating procedures
- clear physical layout
- easily comprehensible signals.

Production and Quality Control

Production and quality control can be simplified, and at the same time made faster and more accurate, if:

- geometrical shapes permit the use of well-established, time-saving methods
- production operations are minimised and have short setting-up and waiting times
- shapes are chosen to facilitate the inspection process.

Leyer, when discussing changes in production methods [7.166], uses the example of a sliding control valve approximately 100 mm long to demonstrate how the replacement of a complicated casting by a brazed product made of geometrically simple turned parts helped to overcome difficulties and paved the way for more economical production. Even though modern casting techniques now allow more intricate shapes to be produced relatively easily, further simplifications might still be expedient (see Figure 7.10). Step 3 helps to simplify the geometrical shape of the central, tubular part. Step 4 (fewer parts) can be taken when the surface areas at right angles to the valve axis need not be retained.

A further example is provided by the one-handed mixing tap discussed earlier. The design of the lever arrangement shown in Figure 7.11 is expensive to make, difficult to clean (slits, open recesses) and not aesthetically pleasing. The one shown in Figure 7.12 is much simpler and also more suitable for longer production runs. The lever, whose end can slide and rotate in a circumferential groove, requires a smaller number of parts and avoids wear in areas that are difficult to readjust. All in all, therefore, this solution is by far the better because it is more economic, easier to clean and looks nicer.

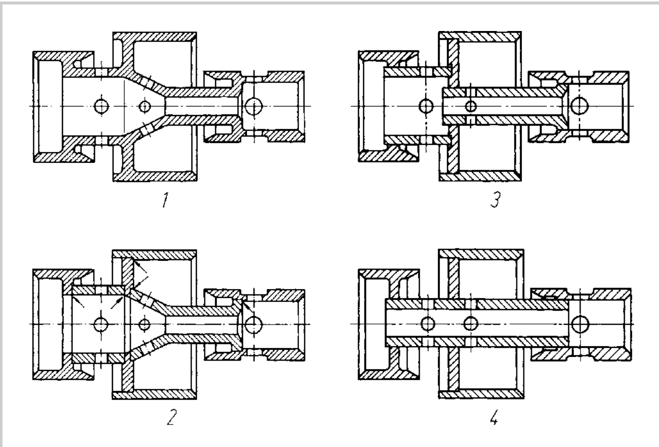


Figure 7.10. Simplification of a sliding control valve: 1 Casting is difficult and expensive; 2 Improvement by splitting into simple, brazed parts; 3 Simplification of central tubular part; 4 Further simplification possibility (1 and 2 after [7.166])

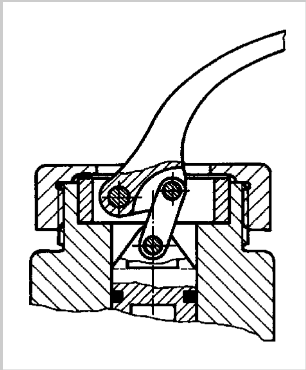


Figure 7.11. Proposed lever arrangement for a one-handed mixing tap with translational and rotational movements

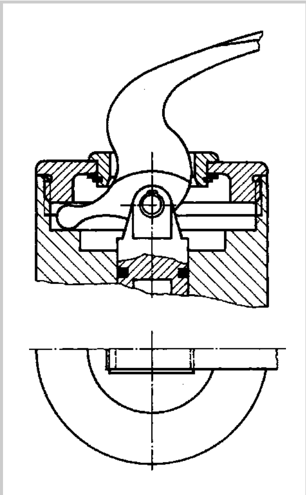


Figure 7.12. Simpler solution with improved embodiment (based on Schulte)

Assembly and Transport

Assembly is simplified—that is, facilitated, speeded-up and rendered more reliable—if:

- the components to be assembled can be identified easily
- the assembly instructions can be followed easily and quickly
- no adjustment has to be repeated
- reassembly of previously assembled components is avoided (see Section 7.5.9).

During assembly, the adjustment ring of a small steam turbine has to be moved vertically and horizontally with the turbine shaft already assembled, in order

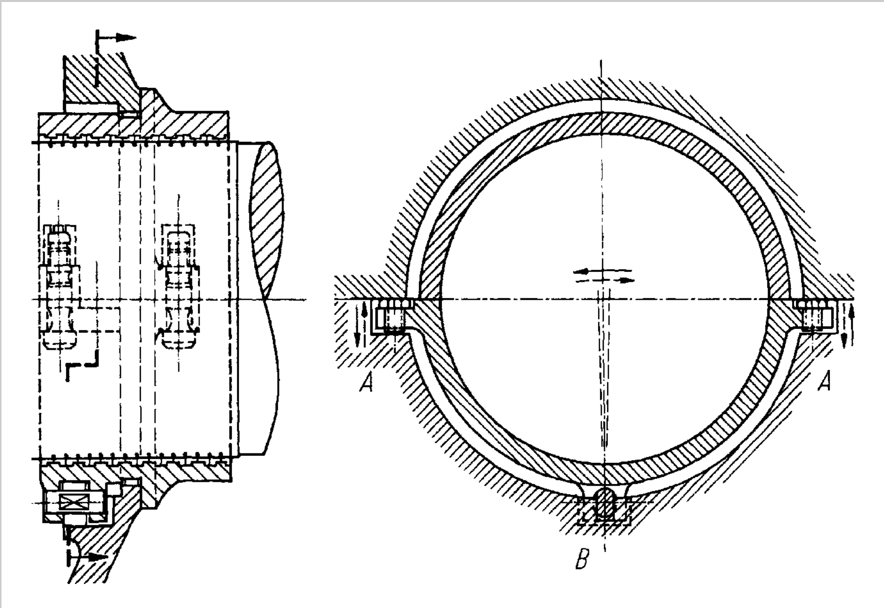


Figure 7.13. Adjustable sealing ring of an industrial steam turbine; adjustments at *A* in the same sense produce vertical movement, adjustments at *A* in the opposite sense produce a rotation about *B* that approximates to a horizontal movement

to ensure uniform clearance around the labyrinth seal. Doing this without having to remove the shaft several times for adjustment poses a problem that can be solved by the design shown in Figure 7.13. The adjustment can be made at the joint by rotating the adjustment screws *A* in the same sense, producing vertical movement only, and by rotation in the opposite sense, producing a tilting movement about pivot *B* that approximates to horizontal movement. The pivot itself must, however, allow for vertical movement during the adjustment and also for radial heat expansion when the turbine is operating. This is achieved with a few easily produced elements with simple shapes. A suitable arrangement of the surfaces, moreover, obviates the need to secure the pivot pin with additional locking elements: it is located in such a way that it can not fall out.

Operation and Maintenance

With respect to operation and maintenance, the simplicity rule means:

- operation must be possible without special or complicated instructions
- the sequence of operations must be clear and simple, and any deviations or faults easily identified
- maintenance must not be awkward, laborious and time-consuming.

Recycling

Simplicity for recycling can be realised by:

- use of recyclable materials
- simple assembly and disassembly processes
- simplicity of the parts themselves (see Section 7.5.11).

7.3.3 Safety

1. Nature and Scope of Safety Measures

Safety considerations affect both the reliable fulfilment of technical functions and also the protection of humans and the environment. Designers have recourse to a safety methodology that, following the German industry standard DIN 31 000 [7.57], includes the following three levels:

- direct safety
- indirect safety
- warnings.

In general, designers should try to guarantee safety by using *direct safety*, that is, by choosing a solution that precludes danger from the outset. Only when this proves impossible should they have recourse to *indirect safety*, in other words, constructing special protective systems [7.58 to 7.60]. *Warnings*, which merely point out dangers and indicate danger areas, can be used to support direct and indirect safety measures by, for example, pointing out special features, obstructions and disturbances. Only as a last resort should warnings be used on their own, and never as an easily implemented safety measure.

In the solution of technical problems, designers are faced with several constraints, not all of which they can hope to overcome simultaneously. They must nevertheless strive to provide a solution that comes nearest to satisfying all the requirements. The strength of an unavoidable safety requirement may, under certain circumstances, put the realisation of the whole project in doubt. A high demand for safety can greatly complicate a design and, by reducing clarity, may even lower the inherent safety of the product. Moreover, safety provisions may also render a product uneconomic and lead to its abandonment.

Such cases, however, are exceptional, because safety and economy generally go hand-in-hand in the long term. This is particularly true of expensive and complex plant and machinery. Only smooth, accident-free and safe operation can ensure long-term economic success. Protection against accidents or damage, moreover, goes hand-in-hand with reliability [7.75, 7.312]. Reliability makes it possible to operate a machine to full capacity, even though poor reliability may not necessarily lead to accidents or damage. All in all, it is therefore advisable to achieve safety by treating direct and indirect safety measures as an integral part of system design.

There are many different ways of applying safety measures in mechanical engineering. Therefore, we consider it necessary to provide some definitions before discussing the measures in detail. The withdrawn German industry standard DIN 31 004 (1979) defined safety as "being free from danger", a "danger" being a threat for which the type, size and action is known. A dangerous situation is one that can cause damage to persons or things. This DIN standard was replaced in November 1982 by DIN 31 004 Part 1 [7.61]. The basic terms are defined as follows:

Safety	is a state in which the risk is smaller than the risk limit.
Risk limit	is the largest but still acceptable system-specific risk relating to a particular technical process or situation.
Risk	is described by the frequency (probability) and the expected extent of the damage (scope).

Whereas the initial DIN standard defined protection as the limitation of danger in order to prevent damage, the 1982 standard uses the following definition:

Protection	is the reduction of risk by suitable means in order to reduce the frequency of occurrence and/or the extent of damage.

The DIN EN 292 standard [7.57] now uses these terms in a more general way. This development of the standard demonstrates that there is no absolute safety in the sense of complete freedom from danger. In common with many aspects of life, the use of technical systems always involves a certain risk. Safety measures aim to reduce risks to an acceptable level. However, what is acceptable (the risk limit) can only be quantified in a few cases. Now and in the future this limit will be determined by technical knowledge and social standards, and in no small measure by the experience and responsibilities of design engineers.

In the context of safety, it is very important to ensure reliability:

Reliability	is the ability of a technical system to satisfy its operational requirements within the specified limits and for the required life (definition based on [7.75, 7.76]).

It is clear that the reliability of individual components of a machine or the machine itself, as well as the reliability of any protective systems and devices, are important requirements for safety. Without state-of-the-art quality that ensures reliability, protective measures are of doubtful value.

One measure of reliability is the operational availability of a technical system.

Availability	is the percentage of time the system is available for operation compared to the maximum possible time or compared to a particular target time.

Safety concerns the following areas (see Figure 7.14):

Operational safety	is the limitation of danger (reducing risk) during the operation of technical systems in order to prevent damage to the systems themselves and their immediate environment, such as the workplace, neighbouring systems, etc.

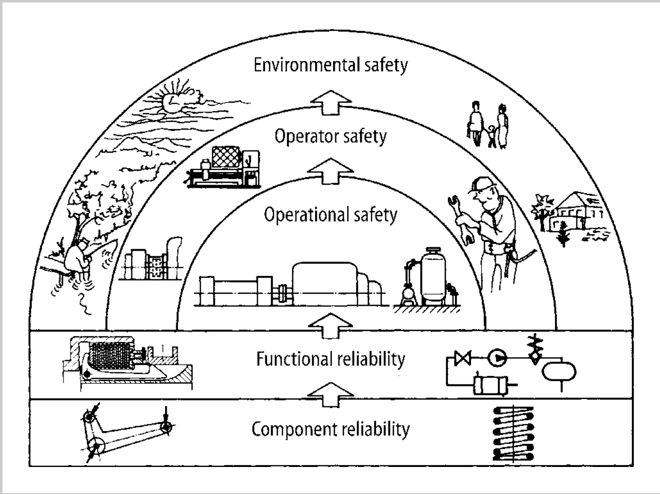


Figure 7.14. Relationship between component and functional reliability on the one hand and operational, operator and environmental safety on the other

Operator safety	is the limitation of danger to persons using technical systems either at their workplace or outside, for example for sport or leisure.
Environmental safety	is the limitation of damage to the environment in which technical systems are used.
Protective measure	is the use of protective systems or devices to limit existing dangers and reduce risks to acceptable levels where these cannot be achieved through direct safety measures.

The reliability of assemblies and of their interaction—that is, the functional reliability of a machine or a protective system—is crucial for operational, operator and environmental safety [7.179]. For designers, all these areas of safety are closely connected when developing a concept and its embodiment. A safety methodology should therefore give equal weight to each of the areas [7.210].

2. Direct Safety

Direct safety measures achieve safety through systems or components actively involved in the performance of a particular task. To ensure and evaluate the safe functioning and durability of components, designers can adopt one of several safety principles [7.210]. There are three basic principles, namely:

- safe-life principle
- fail-safe principle
- redundancy principle.

The *safe-life principle* demands that all components and their connections be constructed in such a way as to allow them to operate without breakdown or malfunction throughout their anticipated lives. This is ensured by:

- clear specification of the operating conditions and environmental factors, such as the anticipated loads, service life, operating conditions, etc.
- adequately safe embodiment based on proven principles and calculations
- numerous and thorough inspections during production and assembly
- analysis of components or systems to determine their durability when they are overloaded (load levels and/or running time) or subjected to adverse environmental influences
- determination of the limits of safe operation, with due regard being paid to possible breakdowns.

It is characteristic of this principle that it bases safety exclusively on accurate qualitative and quantitative knowledge of all of the influences at work or on the determination of the limits of failure-free operation. The application of this principle calls for a great deal of experience, or for costly and time-consuming preliminary investigations, and for continuous monitoring of the state of components. If a failure should nevertheless occur, and if a safe-life is essential, then as a rule there will be a serious accident, for instance the fracture of an aeroplane wing or the collapse of a bridge.

The *fail-safe principle* allows for the failure of a system function or for a component fracture during the service life by ensuring that grave consequences do not ensue. To that end:

- a function or capacity, however small, must be preserved to prevent dangerous conditions
- a restricted function must be fulfilled by the failing component or by some other component until such time as the plant or machine can be removed from operation without danger
- the failure or breakdown must be identifiable
- the effect of the failing component on the overall safety of the system must be assessable.

In essence, the impairment of a main function must be signalled. The signal can take various forms (increasing vibrations, loss of sealing, loss of power, slowing down), each without causing immediate danger. In addition, special monitoring systems may be provided to indicate the incipient failure to the operator. Their layout should be governed by the general principles of protective systems. The fail-safe principle presupposes knowledge of the progress of a failure and provides a means for taking over or maintaining the impaired function.

By way of example, let us consider a spherical rubber element in an elastic coupling (see Figure 7.15). The first visible crack appears on the outer layer, but the function is not yet impaired (State 1). Only when the number of revolutions under load is increased does the stiffness begin to decrease with a consequent change in the behaviour of the coupling, which manifests itself, for instance, by a lowering of the critical speed (State 2). With further operation, the crack grows larger and causes the stiffness to decrease still further (State 3), but even if the

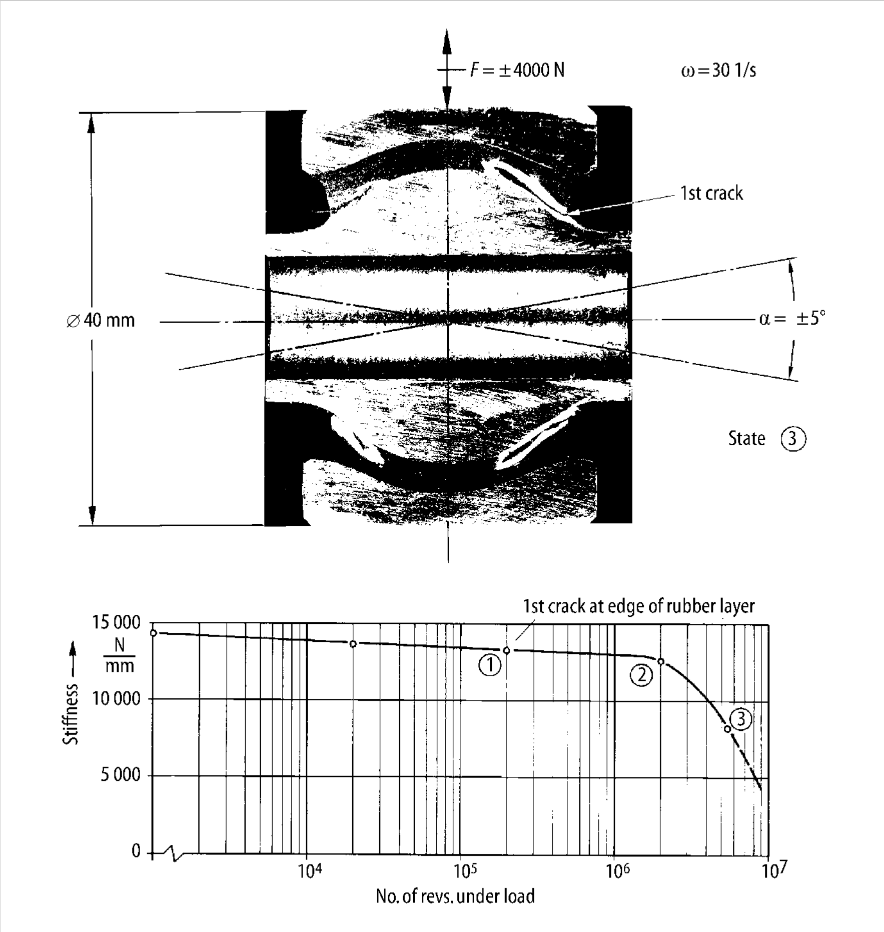


Figure 7.15. Fail-safe behaviour of an elastic coupling: crack-state and stiffness against number of revolutions

crack went right through, there would not be a complete failure of the coupling. Therefore, no sudden effect with serious consequences need be feared.

Another example is the behaviour of flange bolts made of a tough material which, on overloading, exceed their yield strength and deform plastically, resulting in a reduction of preload and, hence, a reduction of the clamping force. Their impaired function is indicated by the resulting loss in flange sealing but does not give rise to sudden failure.

Figure 7.16 illustrates two safe methods of fastening components. The means of attachment should be designed such that, even if the bolts begin to fail, the mountings remain in place, no broken parts can migrate, and the equipment continues to function to some extent [7.206].

The *redundancy principle* provides another means of increasing both the safety and the reliability of systems.

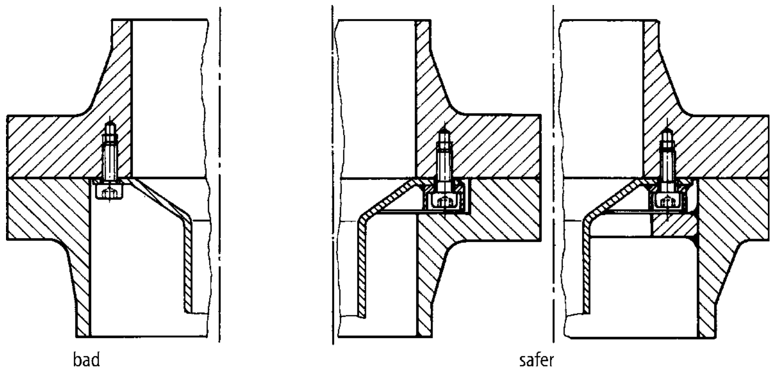


Figure 7.16. Fastening of components: the covering of the bolted connection maintains function and prevents broken parts migrating in the event of bolt failure

In common usage, redundancy means superfluity or excess. In information theory, redundancy refers to that fraction of a message that may be eliminated without loss of essential information. Redundancy is often used deliberately to allow for transmission losses, and hence to safeguard the system. The fact that this safety principle is common in electronics and information technology is useful when integrating these technologies with mechanical engineering systems.

Redundant safety arrangements lead to an increase in safety, provided that the breakdown of a particular element of the system is not dangerous in itself, and that other elements, arranged in parallel or in series, can take over its function fully or at least in part.

The provision of several engines in aircraft, of multistrand cable for a high-voltage transmission line, and of parallel supply lines or generators, all ensure that, should a particular element break down, the function is not completely impaired. In that case, we speak of *active redundancy*, because all the components are actively involved. Partial breakdowns lead to a corresponding reduction in energy or performance.

If reserve elements (for instance alternative boiler feed pumps)—usually of the same type and size—are provided and put into operation during breakdowns, then we speak of *passive redundancy*.

If a multiple arrangement is to be equal in function but different in working principle, then we have *principle redundancy*.

Depending on the situation, safety-enhancing elements can be arranged in parallel, for instance emergency oil pumps, or in series, for instance filter installations. In many cases, layouts in parallel or series will not suffice and crossover links will have to be introduced to guarantee transmission, despite the breakdown of several elements (see Figure 7.17).

In a number of monitoring systems, signals are collected in parallel and compared with one another. *Selective redundancy* (two out of three) and *comparative redundancy* arrangements are shown in Figure 7.17.

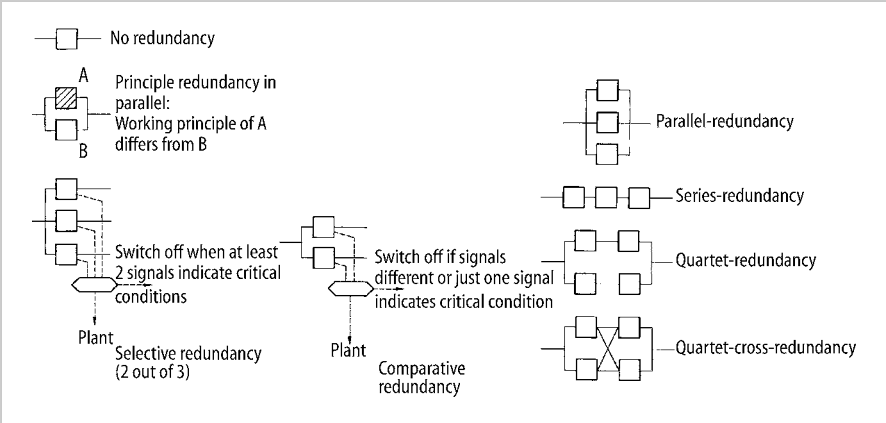


Figure 7.17. Redundant arrangements

Redundancy layouts cannot, however, replace the safe-life or fail-safe principles. Two cable cars operating in parallel will, admittedly, increase the reliability of passenger transport, but this will contribute nothing to the safety of the individual cars. The redundant layout of aircraft engines will not increase safety if any of the engines might explode and hence to endanger the system. In short, an increase in safety can only be guaranteed if the redundant element satisfies the safe-life or the fail-safe principle.

Adherence to all the principles we have mentioned—that is, the attainment of safety in general—is greatly facilitated by the principle of the division of tasks (see Section 7.4.2) and by the two basic rules of clarity and simplicity, as we shall now try to show with the help of an example.

The principle of the division of tasks and the clarity rule have been applied with great consistency to the construction of a helicopter rotor head (see Figure 7.18), and helped the designers to come up with a particularly safe construction based on the safe-life principle. Each of the four rotor blades exerts a radial force on the rotor head due to the centrifugal inertia force, and a bending moment due to the aerodynamic loading. The rotor blades must also be able to swivel so that their angles of incidence can be changed. A high safety level is achieved by the following measures:

- A completely symmetrical layout so that the external bending moments and the radial forces at the rotor head cancel out.
- The radial forces are transmitted exclusively by the torsionally flexible member *Z* to the main central component where they cancel each other out.
- The bending moment is only transmitted through part *B* and is taken up by the roller bearings in the rotor head.

As a result, every component can be optimally designed in accordance with its task. Complicated joints and shapes are avoided and the necessary high level of safety is attained.

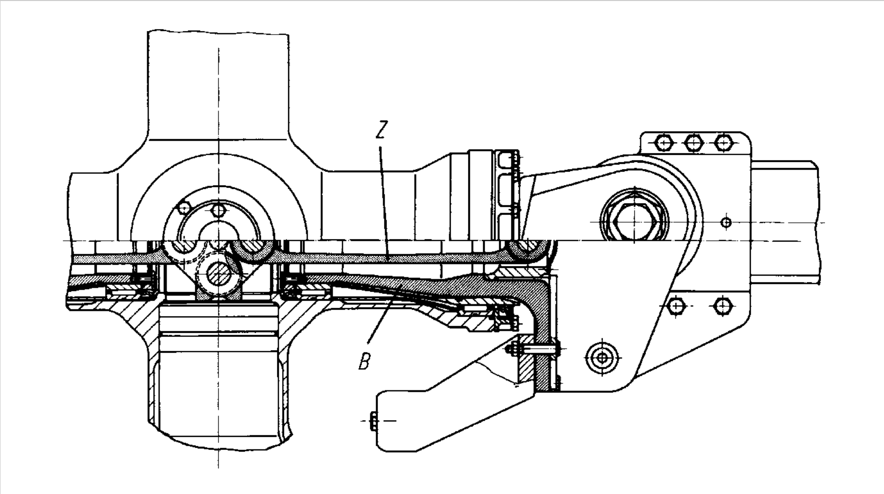


Figure 7.18. Rotor blade attachment of a helicopter based on the principle of the division of tasks (Messerschmitt–Bölkar system)

3. Indirect Safety

Indirect safety measures involve the use of special protective systems and protective devices. They are applied whenever direct safety measures prove inadequate. A detailed discussion of indirect safety measures for technical systems can be found in [7.215]. In what follows, the most important elements of these measures are described.

Protective systems react when danger occurs. To that end, their function structure includes a signal transformation with an input that captures the danger and an output that removes it.

The working structure of a protective system is based on a function structure with the following main functions: capture–process–act. Examples are the multiple redundant monitoring of temperatures in a nuclear reactor; the monitoring of robots in inaccessible workplaces; the sealing of areas when they are subject to X-rays; and the automatic checking of the locking of centrifuge covers prior to operation. The required actions can involve removing, limiting or separating.

Protective devices fulfil protective functions without transforming signals.

Examples are a pressure safety valve (see Figure 7.22); a shaft coupling that slips with torque overload; a pin that shears to limit excessive forces; and safety belts in cars. Their main action is removing or limiting. They can form part of a protective system.

Protective barriers fulfil protective functions without acting.

These barriers are passive, and not able to act on their own. They do not transform signals and therefore do not require a function structure that involves this transformation. They protect by separating; that is, by keeping persons and equipment at a distance from danger using physical barriers, covers, fences, etc. They are described in DIN 31 001, Parts 1 and 2 [7.58, 7.59]. Locking devices, according to Part 5 of this standard [7.60], are regarded as protective systems.

Basic Requirements

Indirect safety measures have to fulfil the following basic requirements:

- operate reliably
- function when danger occurs
- resist tampering.

Operate Reliably

Reliable operation means that: the working principle and the embodiment allow unambiguous operation; the layout follows the established rules; production and assembly are quality-controlled; and the protective systems and devices are rigorously tested. The safety modules and their functional links should be based on direct safety principles and demonstrate safe-life or fail-safe behaviour.

Function When Danger Occurs

This requirement means that:

- the protective function has to be available from the start of the dangerous situation and must last throughout the period of danger
- the protective function should not cease or the protective device should not be removed before the dangerous situation has completely ended.

Figure 7.19 shows example layouts for safety fence contacts for a machine guard. Closed contacts signal that the safety fence is in position. Layout *a* has severe deficiencies because the contact movement relies upon the spring force alone and is not bi-stable (see Section 7.4.4). If the spring breaks or the contacts stick together, the contact will not be broken, that is, the machine can be started with the safety

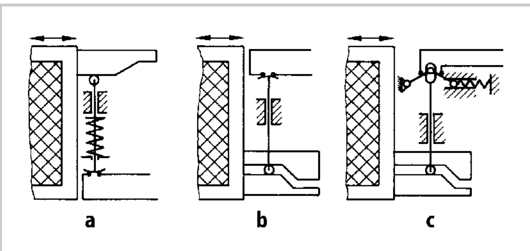


Figure 7.19. Layouts for safety fence contacts for a machine guard. **a** Protection not guaranteed because contact movement relies on a spring force alone. **b** Protection guaranteed because activation relies on form fit. **c** Bi-stable behaviour added to form fit activation in **b**

fence open. Layout *b* will always function when danger occurs. Sticking contacts will be opened because the effect relies on form rather than spring force, and if parts break they will not fall onto the contacts. Layout *c* also makes use of form for activation, but adds spring force and bi-stable behaviour. Further examples can be found in [7.215].

Resist Tampering

Resistance to tampering means that the protection cannot be reduced or removed by unintended or intended actions. If we consider the safety fence contact in Figure 7.19, it should be designed such that actions that prevent correct operation are not possible. The best way to achieve this is to use a cover that cannot be opened without tools or without stopping the machine.

The requirements of protective systems and devices are listed in the following paragraphs followed by those of protective barriers.

Protective Systems and Devices

Protective systems and devices render endangered plant or machinery safe automatically, with the aim of preventing danger to persons and machinery. In principle, the following approaches are available:

- When danger occurs, prevent the consequences by disabling the plant or machinery or preventing any plant or machinery in a dangerous state from being put into operation.
- When there is a continuous danger, avoid its effects by introducing protective measures.

The basic requirements "operate reliably", "function when danger occurs", and "resist tampering" are supported by fulfilling the following requirements.

Warning

When a protective system notes changes in the working conditions, a warning must be provided that indicates the change and the cause of the warning. Examples are "oil level too low", "temperature too high", and "safety fence open". Recommended acoustic and optical signals are given in DIN 33 404 [7.69], colours for warning lights and push buttons in DIN IEC 73/VDE 0199 [7.77], and special safety symbols in DIN 4844 [7.40–7.42].

Two-Step Action

If the dangerous situation emerges so *slowly* that operator action can reduce the danger, then a warning should be given before a protective action is initiated.

Between the two steps, there should be a sufficiently large and clearly defined change in the danger variable. For example, if pressure is the danger variable being monitored, a warning could be given at 1.05 p_{normal} and shutdown initiated at 1.1 p_{normal}.

If the dangerous situation emerges too *quickly*, the protective system should react immediately and signal its response clearly. The terms "slowly" and "quickly" must be interpreted in the context of the cycle time of the technical process and the reaction time required [7.243].

Self-Monitoring

A protective system must be self-monitoring; that is, it must be triggered not only when the system breaks down, but also by faults in its own system. This requirement is best satisfied by the *stored energy principle*, because, when this is applied, the energy needed to activate the safety device is stored within the system and any disturbance of or fault in the protective system will release that energy and switch off the plant or machinery. This principle can be used not only in electronic protective systems but also in mechanical, hydraulic and pneumatic systems.

The stored energy principle has been used in the valve shown in Figure 7.20. When the valve opens, the spring is compressed by the operating oil pressure. When the oil pressure reduces, the spring extends and the valve closes. Failure of the spring will not inhibit the closure of the valve because of the particular configuration used. The flow direction selected and the suspended configuration support the requirement of always functioning when danger arises.

A further example of the use of the stored energy principle in a hydraulic system is shown in Figure 7.21. In this protective system, pump 1 with a pressure-regulating valve 2 ensures a constant pre-pressure p_P. The protective system with the pressure p_S is connected to the pre-pressure system by means of an orifice 3. Under normal conditions, all outlets are closed, so that the quick-action stop valve 4 is held open

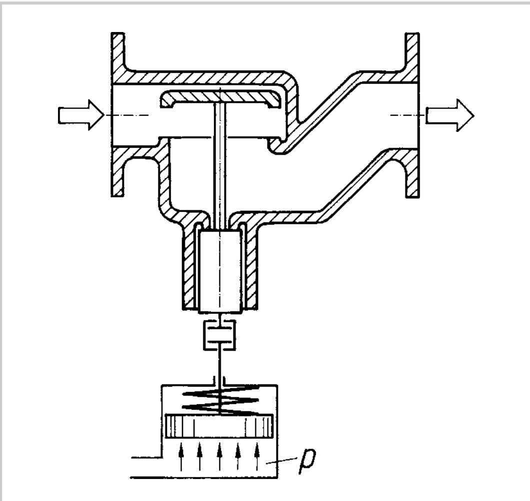


Figure 7.20. Layout of a quick-action valve. In the event of a drop in oil pressure p, the spring force, the flow pressure on the valve face and the weight of the valve act together to guarantee the rapid closure of the valve

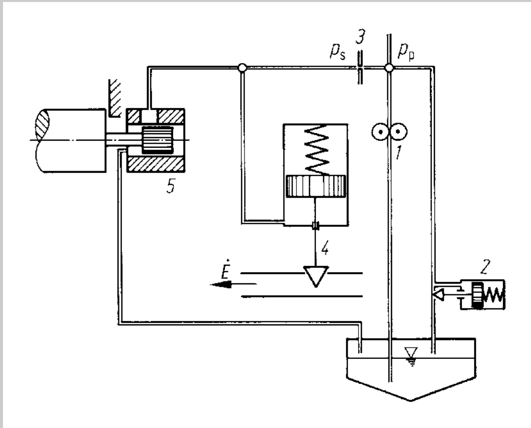


Figure 7.21. Hydraulic protection system employed to prevent incorrect axial shaft positions based on the stored energy principle

by the pressure p_S, allowing energy to be supplied to the machine. In the case of a faulty axial shaft position, the piston valve 5 at the end of the shaft opens, the pressure p_S drops, and further energy supplies are cut off by the quick-action stop valve 4. The same effect is produced by damage to the pre-pressure or protective system, for example by pipe fracture, lack of oil or pump failure. The system is self-monitoring.

A system operating on the *active energy principle*, where energy is only generated in the case of danger, cannot detect a failure in its own system. Therefore, this approach should only be used to provide the warning signals of a protective system when a monitoring system is also available and the system is checked regularly. The possibility that a protective system based on the stored energy principle can cause interruptions that are not caused by a dangerous situation but instead by the protective system itself should be met by increasing the reliability of the system elements, and not through application, for example, of the active energy principle.

Redundancy

The failure of a protective system or device should be seen as a real possibility. Because a single protective system may break down, its mere doubling or replication ensures greater safety: it is unlikely that all the systems will fail at once. A solution that is often applied in protective systems is redundancy based on two from three selection. Three sensors are used to detect the same danger signal (see Figure 7.17). Only when at least two sensors signal the critical value is the protective action—such as machine shutdown—initiated. Thus the failure of a single sensor does not reduce the protective cover, and its failure will not trigger an unnecessary protective action [7.179].

This is however only true provided that the replicated protective systems do not all fail due to a common fault. Safety is considerably increased if the double or multiple systems work independently of one another and are, moreover, based on different working principles (principle redundancy). In this case, common faults—for instance those due to corrosion—will not have catastrophic consequences: the simultaneous breakdown of all such systems is highly improbable.

Figure 7.22 illustrates protective devices employed to prevent excessive pressure in pressure vessels. Mere doubling would not protect against common failures such as corrosion or inappropriate materials. The use of different working principles, however, reduces the possibility of simultaneous failure.

When redundant configurations are linked in parallel or series, the values at which they are triggered should be carefully staggered within an appropriate range. In this manner, primary and secondary protection can be established. In the example in Figure 7.22, the configuration should be chosen such that the safety valve is activated at a lower excess pressure than the shear plate.

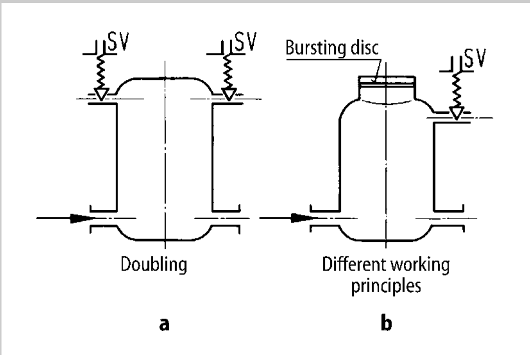


Figure 7.22. Protective devices employed to protect against excessive pressure build-up in pressure vessels: **a** two safety valves (not safe against common faults); **b** safety valve and shear plate (principle redundancy)

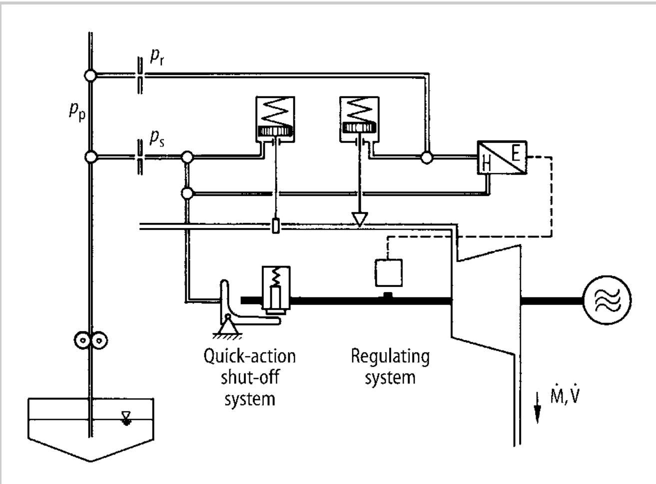


Figure 7.23. Stored energy protective system against overspeeding based on principle redundancy

In many cases the primary protection system can receive its signals from an existing control system, if it has the characteristics of a protective system. This requirement is met in the control of steam turbines shown in Figure 7.23 [7.272]. In the case of overspeeding, the energy supply is cut off by two systems that differ in principle. Increases in speed first invoke the regulating system, whose speed measurement and regulating valve are independent of, and different in principle to, the quick-action shut-off system.

Speed is measured by three identical but independent magnetic sensors. They take their measurements from a gear wheel on the turbine shaft (see Figure 7.24). Their primary purpose is to control the speed of the machine through electronics and hydraulics. In addition, each signal is compared with a reference signal in order to prevent excess speed. This comparison is based on the two from three

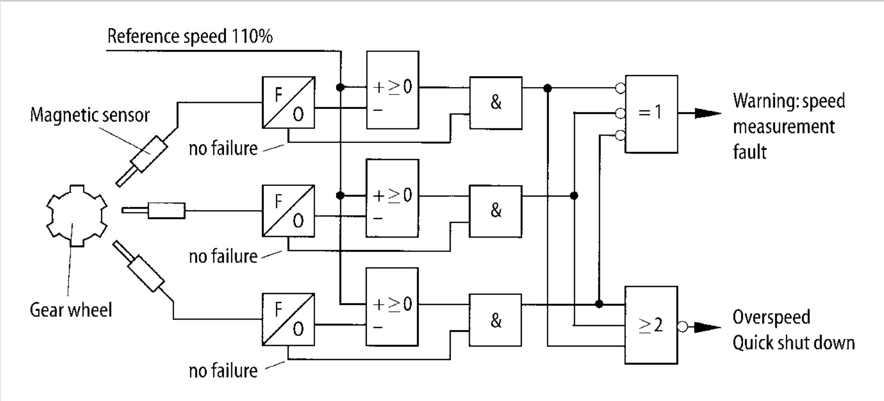


Figure 7.24. Electronic speed control and speed monitoring using a redundant layout based on the two from three principle (simplified representation). Safety is based on the stored energy principle, which is also applied to the quick-action shut-off system

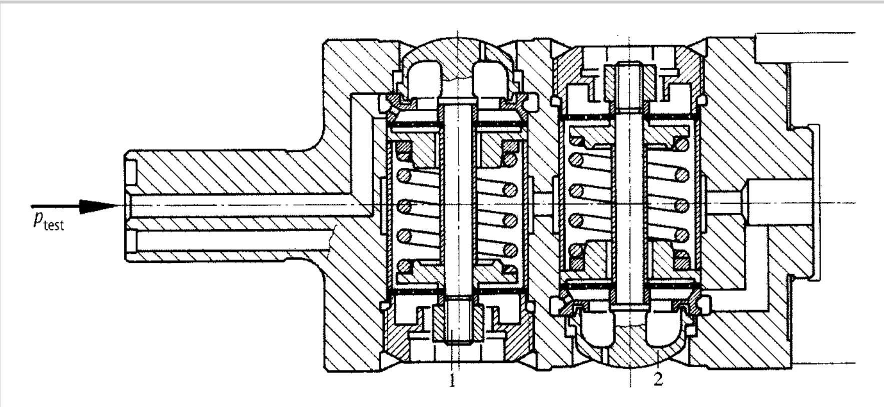


Figure 7.25. Stored energy protective system against overspeeding based on two triggering values

principle. Each measurement circuit is monitored separately, and any failures are signalled. If two fail, the quick-action shut-off system is activated immediately.

The measurement and the activation of the quick-action system, however, are based on a mechanical principle. Figure 7.25 shows quick-action pins that, in the case of excess speed, move out rapidly against their retaining springs and strike a trigger. This in turn activates the quick-action shut-off system hydraulically. The turbine is provided with two such bi-stable devices that trigger at 110% and 112% excess speed respectively (see Section 7.4.4).

A common hydraulic supply to the control and quick-action shut-off system based on the stored energy principle is acceptable because both are based on a common self-monitoring principle.

Bi-Stability

Protective systems and devices must be designed with a clearly defined triggering value. When this value is attained, the protective reaction must be initiated immediately and unambiguously. This can be achieved by using the bi-stable principle (see Section 7.4.4). Below the triggering value, the system is in a stable state. When the triggering value is attained, an unstable condition is created deliberately. This avoids intermediate states and transfers the system rapidly into its second stable state. This bi-stable characteristic must be realised without intermediate states occurring when the triggering value is reached in order to achieve clarity in the behaviour of the protective system or device.

Preventing System Restarts

After a protective system or device has been activated, that system should not automatically return a machine to normal operation, even if the danger recedes. The activation of a protective system is always triggered by an unusual situation. After shutdown, the situation should be checked and evaluated, and the subsequent restart should follow a clearly structured procedure. For example, the safety regulations covering protective systems and devices [7.256], as well as other machines used in production [7.334], prescribe procedures for restarting.

Testability

A protective system or device should allow its functioning to be tested without having to create a situation with real danger. However, it might be necessary to simulate a dangerous situation in order to trigger the protective system. During a simulation, the effects used must be similar to the real danger and all possible danger conditions checked.

In our speed control system example, this means a planned increase in speed up to the excess speed, at which point the protective system triggers. If this is not possible or it is not desirable, it is possible to simulate the centrifugal inertia force by using oil pressure to trigger the system. The machine does not have to be shut down for this simulation. Figure 7.25 shows the oil channel. The oil simulates an increase in the centrifugal inertia force on the quick-action shut-off pins so that they are triggered and their action tested without attaining an excess speed.

With redundant protective systems, it is possible to isolate individual systems from the machine to test them. Any other redundant protective systems can remain active and continue to monitor safety during the test. Care must be taken to ensure that the protective system automatically returns into its fully operational state after test procedures that only check part of the system.

From the previous paragraphs, the following points emerge:

- protection must be retained during testing
- testing must not introduce new dangers
- after testing, the parts tested should return automatically to their fully operational state.

Often a *start-up check* is useful, or even prescribed. This check permits the operation of a machine only after its functions have been tested by activating the protective system. Safety regulations, for example, often prescribe this type of start-up check for power tools with safety devices [7.256].

Protective systems and devices must be *tested regularly*, that is:

- before the first operation
- at regular predetermined intervals
- after every service, repair or modification.

The procedures should be described in operating manuals and the results documented.

Relaxing the Requirements

At this point, one may question whether it is necessary to meet the testability requirement as well as that of self-monitoring. However, even protective systems based on the stored energy principle include elements whose full functionality can only be assessed through testing. Examples include the operation of the quick-action pins in Figure 7.25, and sticking contacts in an electric switch.

Relaxation of the safety system requirements is only permissible when the probability of failure is so small and the consequences of any failure are so limited that the overall risk is acceptable. This will only be the case with redundancy requirements when system tests are easy and carried out regularly. This occurs when these tests are part of normal operation, for example when start-up checks are implemented. This often applies to protective systems associated with safety at work.

If human life is endangered or large-scale damage may occur, leaving out redundancy is neither justified nor economic. Which redundancy is applied, for example two from three selection, replication of the same principle, or principle redundancy, depends on the specific context and the level of risk.

Protective Barriers

The purpose of a protective barrier is to isolate people and objects from the source of danger, and to protect them from a variety of dangerous effects. DIN 31 001 Part 1 [7.58] and Part 2 [7.59] deal mainly with protection against physical contact with dangerous static and moving parts, and against objects and particles that break away. Elaborate illustrations and examples are given in [7.215].

The desired solution principles (see Figure 7.26) prevent contact by providing:

- full enclosure
- cover for a particular side
- fence, used to maintain a safe distance.

Safety distances play an essential role when it is possible to reach through or around fences or barriers. These distances are determined by body dimensions and ranges of reach. DIN 31 001 Part 1 [7.58] gives clear safety distances, depending on body dimensions and posture.

With respect to contact protection and protection against objects and particles that break away, DIN 31 001 Part 2 [7.59] only permits the use of those materials that can fulfil their protective function on the basis of their durability, shape stability, temperature resistance, corrosion resistance, resistance to aggressive substances, and their permeability to those aggressive substances.

4. Designing for Safety

The checklist in Figure 7.3 can prove a great help. Safety criteria must be scrutinised with respect to all the headings listed [7.303].

Function and Working Principle

It is important to establish whether or not the function is fulfilled safely and reliably by the chosen solution. Likely faults and disturbing factors must be taken

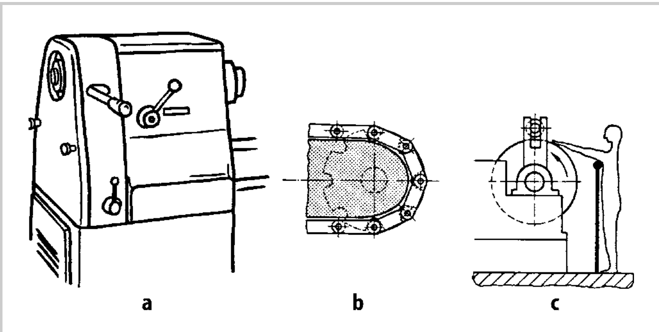


Figure 7.26. Examples of protective barriers: **a** full enclosure; **b** cover for a particular side; **c** fence used to maintain a safe distance

into account as well. The extent to which allowances must be made for exceptional, purely hypothetical, circumstances that could affect the function is not always clear, however.

The correct estimation of the scope and likelihood of a risk should be based on the successive negation of each of the functions to be fulfilled and on an analysis of the likely consequences (see Section 10.2). Sabotage need not necessarily be considered in this context, because measures to prevent human errors are likely to cover most possible circumstances.

What we have to consider and prevent first and foremost are failures due to possible disturbances of the structure, operation and environment of a machine, as well as those caused by operator error. Harmful effects that are not due to technological factors cannot be eliminated by the technical system itself, but the system must be able to survive them and, if possible, limit them.

A further question is whether the direct safety measures we have been discussing are adequate, or whether safety should be increased by additional protective systems and devices. Finally, we might also ask whether the whole project should be abandoned if it proves to be impossible to make adequate safety provisions in a particular case. The answer depends on the degree of safety that has been attained, on the probability of unpreventable damage or accident, and on the magnitude of the possible consequences. Objective standards are often lacking, particularly in the case of new applications. It has been argued that technical risks must be no greater than the risks humans must expect from natural causes [7.138]. However, this is always a matter for discretion. The final decision should, in any case, reflect a responsible attitude towards the human race.

Layout

External loads produce stresses in components. Through analysis we determine their magnitude and frequency (steady and/or alternating loads). The various types of stress produced can be determined by calculation or experiment. The calculated stresses in a component are then, using an appropriate failure hypothesis, converted into an *equivalent stress* σ_E, which should correctly represent the combined direct and shear stresses. The maximum equivalent stress should not exceed the *allowable stress* σ_A. When the two are equal, the material utilisation is 1.0. In general, the ratio of the equivalent stress divided by the allowable stress is smaller than 1.0, because the choice of dimensions is also influenced by standards and other embodiment considerations.

Materials technology provides designers with *material stress limits* σ_L or particular conditions (tension, compression, bending, shear and torsion), beyond which the material will fail or permanently deform. These values are usually obtained from test specimens and not from the components themselves. The strength of a component is also affected by uneven loading, and by its size, surface finish and shape. Only when these are taken into consideration can adequate durability be guaranteed. Thus the component stress limit is usually lower than the material stress limit.

The ratio of the material stress limit (or of the component stress limit) to the allowable stress is the *Safety Factor*, $(SF) = \sigma_L/\sigma_A$. This value must be greater than 1.0. Safety factors are provided in reference manuals for specific situations and types of materials, and the allowable stress σ_A in a component can easily be calculated using these.

The value of a safety factor depends on uncertainties in the determination of the material stress limits; on uncertainties in the load assumptions; on the calculation methods; on the production processes; on the (uncertain) influences of shape, size and environment; and also on the probability and importance of possible failures.

The determination of safety factors still lacks generally valid criteria. An investigation by the authors has shown that published recommended safety factors cannot be classified by type of product, branch of engineering or other criteria such as toughness of material, size of component, probability of failure, etc. Tradition, figures based on one-off and often inadequately explained failures, hunches and experiences are often the basis for numerical data from which no generally valid statements can be derived.

The figures that are given in the literature must therefore be treated with circumspection. Their application usually calls for a knowledge of the individual circumstances and of the special practices or regulations of the branch of engineering in question. In general, however, safety factors smaller than 1.5 should only be used when more precise calculation procedures have been used, experimental data are available, a sufficiently ductile material is used, or there is experience with the specific application. For brittle materials subject to stresses that lead to brittle fracture, the safety factor will be nearer to 2.0.

Toughness—that is, the ability to undergo plastic deformation before failure and thus relieve stress concentrations caused by unevenly distributed loads—is one of the most important safety features any material can have. The usual overspeed spinning tests of rotors with the correspondingly high stresses they set-up, and also the required overpressure tests of pressure vessels—provided that they are built of tough materials—are good examples of the direct safety method aimed at reducing stress concentrations in finished components.

Because toughness is a crucial safety-enhancing property of materials, it is not enough simply to aim at greater yield strength. Since, in general, the toughness of materials decreases with increasing yield strength, it is essential to ensure a minimum toughness, otherwise the benefits of plastic deformation are no longer guaranteed. Also dangerous are those cases in which the material turns brittle with time or for other reasons (for instance, due to radiation, corrosion, heat, or surface coatings). This is particularly true of synthetic materials.

If the safety of a component is calculated merely by the difference between the computed stress and the maximum permissible stress, a vital point is missed.

Of the utmost importance is the loading condition and the effect on the properties of the material due to ageing, heat, radiation, weathering, operating conditions and production processes, for instance welding and heat treatment. Residual stresses must not be underestimated either: brittle (fast) fractures without plastic deformation can occur suddenly and without warning. The avoidance of a build-up of additive stresses, of brittle materials, and of production processes that encourage brittle fractures, is therefore an essential requirement of direct safety.

If plastic deformation is monitored at a critical point, or can be used to impede the function in such a way that the danger can be noticed before humans or machines are endangered, it becomes fail-safe [7.206].

Elastic deformations must not be allowed to disturb the smooth functioning of a machine, for instance through loss of clearance. If this happens, the force transmission paths or the expansions can no longer be determined with certainty and overloading or fracture may ensue. This is just as true of stationary as it is of moving parts (see Section 7.4.1).

By *stability* we refer not only to the basic stability of a machine but also to its stable operation. Disturbances should be counteracted by stabilising effects, that is, by automatic return to the initial or normal position. Designers must ensure neutral equilibrium or that potentially unstable states do not lead to a build-up of disturbances that might get out of control (see Section 7.4.4).

Resonances produce increased stresses that cannot be accurately determined. They must be avoided unless the amplitudes can be sufficiently damped. This applies not only to the stability problem, but also to such associated phenomena as noise and vibration, which impair the efficiency and health of operators.

Thermal expansions must be taken into account under all operating conditions, in particular during unsteady processes, if overloading and impairment of the function are to be avoided (see Section 7.5.2).

Inefficient *seals* are a common cause of breakdown or trouble. Careful choice of seals, provision for pressure relief at critical sealing points and careful attention to fluid dynamics help to overcome these problems.

Wear and the resulting particles can also impede operational safety, and must therefore be kept within tolerable limits. In particular, designers should ensure that such particles do not damage or interfere with other components. They should be removed as near as possible to their point of origin (see Section 7.5.13).

Uniform *corrosion* reduces the designed thickness of components. Local corrosion, particularly of components subject to dynamic loading, may appreciably increase stress concentrations and lead to fast fractures with little deformation. There is no such thing as permanent stability under corrosion—the load capacity of components decreases with time. Apart from fretting corrosion and fatigue corrosion, stress corrosion can also be very serious for certain materials subject to tensile stresses in the presence of corrosive media. Finally, corrosion products can impede the functioning of machines, for instance by jamming valve spindles, control mechanisms, etc. (see Section 7.5.4).

Ergonomics

The application of ergonomic principles to industrial safety involves the careful scrutiny of sources and locations of danger as well as of human–machine relationships. Possible human errors and fatigue must also be included. Machines and products therefore have to be designed ergonomically (see Section 7.5.5).

Table 7.1. Harmful effects associated with various types of energy

Protect humans and environment against harmful effects Headings	 Examples
Mechanical	Relative movement of human and machine, mechanical vibrations, dust
Acoustic	Noise
Hydraulic	Jets of liquid
Pneumatic	Jets of gas, pressure waves
Electrical	Passage of current through body, electrostatic discharges
Optical	Dazzle, ultra-violet radiation, arcs
Thermal	Hot and cold parts, radiation, inflammation
Chemical	Acids, alkalis, poisons, gases, vapours
Radioactive	Nuclear radiation, X-rays

Table 7.2. Minimum industrial safety requirements in mechanical devices

In mechanical devices, protruding or moving parts should be avoided in areas where human contacts may occur
Protective equipment is required for the following, regardless of the operational speed: • for gear, belt, chain and rope drives • for all rotating parts longer than 50 mm, even if they are completely smooth • for all couplings • in cases of danger from flying parts • for potential traps (slides coming up against stops, components pushing or rotating against each other) • descending components (weights, counter-weights) • for slots, for example at material inputs. The gaps between parts must not exceed 8 mm; in the case of rollers, the geometrical relationship must be examined and, if necessary, special guards must be installed
Electrical installation must always be planned in collaboration with electrical experts. In the case of *acoustic*, *chemical* and *radioactive* dangers, expert advice must be sought for the requisite protection

A great many books and papers have been devoted to this subject [7.26, 7.65, 7.189, 7.255, 7.303]. In addition, DIN 31 000 [7.57] specifies the basic requirements of design for safety, and Parts 1, 2 and 10 of DIN 31 001 [7.58, 7.59] deal with protective equipment. Regulations by various professional bodies, factory inspectorates, etc., must be scrupulously observed in all branches of engineering, and so must a great deal of special legislation [7.115] (see also [7.334]). In this book it is impossible to examine every aspect of industrial safety.

Tables 7.1 and 7.2 provide a introductory guide to the sources of danger and the minimum requirements for industrial safety.

Production and Quality Control

Components must be designed in such a way that their qualities are maintained during production (see Chapter 10). To that end, special quality controls must be instituted, if necessary by special regulations. Through appropriate design measures, designers must help to avoid the emergence of dangerous weak spots in the course of production processes (see Sections 7.3.1, 7.3.2 and 7.5.8).

Assembly and Transport

The loads to which a product will be subjected during assembly and transport must be taken into consideration during the embodiment design phase. Welds carried out during assembly must be tested and, where necessary, heat treated. All major assembly processes should, whenever possible, be concluded by functional checks.

For safe transportation, firm bases, support points and handling points should always be provided and marked clearly. The weights of parts heavier than l00 kg should be marked where they can be seen easily. If frequent dismantling is called for, the appropriate lifting points must be incorporated.

Operation

Operation and handling must be safe [7.57, 7.58]. The failure of any automatic device must be indicated at once so that the requisite actions can be taken.

Maintenance

Maintenance and repair work must only be undertaken when the machine is shut down. Particular care is needed to ensure that assembly or adjusting tools are not left behind in the machine. Safety switches must ensure that the machinery is not started unintentionally. Centrally placed, easily accessible and simple service and adjustment points should be provided. During inspection or repair, safe access should be possible through the provision of handrails, steps, nonslip surfaces, etc.

Costs and Schedules

Cost and schedule requirements must not affect safety. Cost limits and delivery dates are ensured by careful planning, and by implementing the correct concepts and measures, not by cutting corners. The consequences of accidents and failures are generally much greater and graver than the effort needed to prevent them.

7.4 Principles of Embodiment Design

The general principles of embodiment design have been discussed at some length in the literature. Kesselring [7.148] set out principles of minimum production costs, minimum space requirements, minimum weight, minimum losses, and optimum handling (see Section 1.2.2). Leyer discussed the principle of lightweight construction [7.167] and the principle of uniform wall thickness [7.168]. It is obviously neither possible nor desirable to have all of these principles implemented in every technical solution—one of them might be crucial, the rest merely desirable. Which principle should be prioritised in a given case can only be deduced from the task and the company's facilities. By proceeding systematically, elaborating a requirements list, abstracting to identify the crux of the problem, and also by following the checklist given in Figure 5.3, designers transform these principles into concrete proposals that enable them to determine production costs, space requirements, weights, etc. These have to be consistent with the requirements list.

The systematic approach also highlights the question of how, with a given problem and a fixed solution principle, a function can be best fulfilled and by which type of function carrier. Embodiment design principles facilitate this part of the design process. In particular, they help with Steps 3 and 4, but also with Steps 7 to 9 as listed in Section 7.1.

Initially embodiment problems focus predominantly on issues of channelling, combining and storing. For the relatively common task of *transmitting* (channelling) forces or moments, it seems advisable to establish special "principles of force transmission". *Changing* the type or *varying* the magnitude of a force are primarily fulfilled by the appropriate physical effects, but designers must also apply the "principle of minimum losses" [7.148] for energy conservation or economic reasons, which they do by adopting a small number of highly efficient steps. This principle also applies to the efficient conversion of one type of energy into another, whenever this should be required. *Storing* energy involves the accumulation of potential and kinetic energy, be it directly or indirectly through the collection of material. The storage of energy, however, raises the question of the stability of the system, and the consequent application of the "principles of stability and bi-stability".

Often, several functions have to be fulfilled by one or several function carriers. Here the "principle of the division of tasks" may be useful to designers. Its application involves careful analysis of the functions and their assignment to function carriers. This analysis of functions is also helpful for the application of the "principle of self-help" when supplementary effects must be identified and exploited.

When applying embodiment design principles, designers may find that they run counter to certain requirements. Thus, the principle of uniform strength may conflict with the demand for minimum costs; the principle of self-help may conflict with fail-safe behaviour (see Section 7.3.3); and the principle of uniform wall thickness chosen for the purpose of simplifying the production process [7.168] may conflict with the demand for lightweight construction or uniform strength.

These principles represent many strategies that are only applicable under certain conditions. In using them, designers must strike a balance between competing demands. To that end, the present authors have developed what they consider to be important embodiment design principles, which will now be presented. Most are based on energy flow considerations and, by analogy, they apply equally well to the flow of material and of signals.

7.4.1 Principles of Force Transmission

1. Flowlines of Force and the Principle of Uniform Strength

The problems solved in mechanical engineering generally involve forces and/or motions and their connection, change, variation or channelling, and involve the conversion of energy, material and signals. The generally applicable function "channel forces" includes the application of loads to, the transfer of forces between, and the transmission of forces through components and devices. Guidelines are provided in [7.168, 7.278]. In general, designers should try to avoid all sudden changes of direction in the flowlines of force—that is, in the force transmission path—caused by sharp deflections and abrupt changes of cross-section. The idea of "flowlines of force" aids the visualisation of the force transmission paths (load paths) through components and devices, and is analogous to flowlines in fluid mechanics. Leyer [7.167, 7.168] has dealt with the transmission of forces at some length, so we can dispense with a detailed discussion of the problem. Designers are advised to consult these important texts. Leyer, moreover, emphasises the complex interaction between the functional, embodiment and production aspects. The concept of force transmission can be summarised as described below.

Force transmission must be understood in a broad sense; that is, it must include the application, transfer and transmission of bending and twisting moments. First, it is important to remember that *external loads* applied to a component produce axial and transverse forces as well as bending and twisting moments at every section. These set up *stresses* (direct and shear) that produce *elastic* or *plastic deformations* (longitudinal, lateral (Poisson), and shear strains, along with bending and twisting).

The section dimensions transmitting the forces are obtained by "mental dissection" of the components at the point under consideration. The sum of the stresses over these sections produces internal forces and moments which must be in equilibrium with the external loads.

The stresses, determined at the relevant section, are then compared with the material properties of tensile strength, yield strength, fatigue strength, creep strength, etc., with due regard being paid to stress concentrations, surface finish and size effects.

The *principle of uniform strength* [7.278] aims, with the help of appropriate materials and shapes, to achieve uniform strength throughout a mechanical device over its anticipated operational life. Like the principle of lightweight construction [7.167], it should be applied whenever economic circumstances allow.

This important consideration often misleads designers into neglecting the deformations (strains) associated with the stresses. It is, however, these very deformations that often throw light on the behaviour of components and tell us what we need to know about their integrity (see Section 7.4.1).

2. Principle of Direct and Short Force Transmission Path

In agreement with Leyer [7.168, 7.208] we consider the following principle to be of great importance:

- If a force or moment is to be transmitted from one place to another with the *minimum possible deformation*, then the shortest and most direct force transmission path is the best.

This principle, which leads to the minimum number of loaded areas, ensures:

- minimum use of material (volume, weight)
- minimum deformation.

This is particularly true if it is possible to solve a problem using tensile or compressive stresses alone, because these stresses, unlike bending and torsional stresses, produce smaller deformations. When a component is in compression, however, special attention must be paid to the danger of buckling.

If, on the other hand, we require a flexible component capable of *considerable elastic deformation*, then a design using bending or torsional stresses is generally the more economical.

The principle is illustrated in Figure 7.27—the mounting of a machine frame on a concrete foundation—where different requirements demand supports with different stiffnesses. This, in turn, has repercussions on the operational behaviour of the machine: different natural and resonant frequencies, modified response to additional loads, etc. The more rigid solutions are obtained with minimum material and space requirements by means of a short support under compression; the most flexible solution by means of a spring, which transmits the force in torsion. If we look at other design solutions, we find many examples of the same principle: for example, in the torsion bar springs of motor cars, or in flexible pipes that rely on bending or torsional deformations.

The choice of means thus depends primarily on the nature of the task; that is, on whether the force transmission path must be designed for durability with

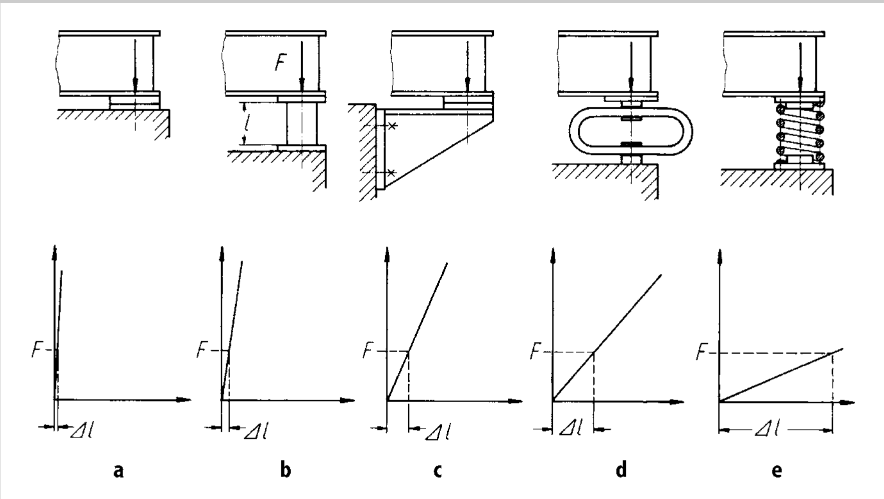


Figure 7.27. Supporting a machine frame on a concrete foundation: **a** very rigid support due to short force transmission path and low stress on the baseplates; **b** longer force transmission path, but still a rigid support with tubes or box sections under compression; **c** less rigid support with pronounced bending deformation (a stiffer construction would involve the greater use of materials); **d** more flexible support under bending stresses; **e** very flexible support using a spring, which transmits the load in torsion. This can be used to alter the resonance characteristics

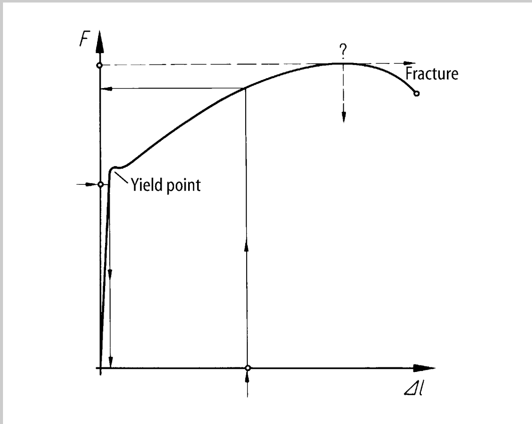


Figure 7.28. Force deformation diagram of tough materials. *Arrows* indicate the cause–effect relationships

maximum stiffness, or whether certain force–deformation relationships must be satisfied first and durability can be treated as a subsidiary problem.

If the *yield point is exceeded*, then the following have to be taken into consideration (see Figure 7.28):

- When a component is *loaded by a force*, it is invariably subjected to deformation. If the yield point is exceeded, then the linear-elastic relationship between the force and the deformation no longer holds. Relatively small changes in the force near the peak of the force–deformation curve may produce unstable conditions leading to fracture, because the load-bearing cross-section may be reduced more rapidly than the strength is increased due to strain hardening. Examples are tie rods, centrifugal inertia forces on a disc, and weights on a rope. The necessary safety precautions must always be taken.
- When a component is *deformed*, then a reaction force is set up. So long as the impressed deformation does not change, the force and the stress remain unchanged as well. If the peak is not reached, the component remains stable so that the yield point can be exceeded without danger. Beyond the yield point, a large change in deformation will lead to only a small change in the force. Admittedly, any preload must not be augmented with further operational loads in the same sense, otherwise the conditions described above will prevail. Further requirements are the use of tough materials and the avoidance of a build-up of multiaxial stresses in the same sense. Examples are highly distorted shrink-fits, preloaded bolts and clamps.

3. Principle of Matched Deformations

Designs matched to the flowlines of force avoid sharp deflections of the transmission path and sudden changes in cross-section, thus preventing the uneven distribution of stresses with high stress concentrations. A visualisation of the flowlines of force, though very graphic, does not always reveal the decisive factors involved. Here, too, the key is the deformation of the affected components.

The principle of matched deformations states that related components must be designed in such a way that, under load, they will deform *in the same sense* and, if possible, *by the same amount*.

As an example, let us take soldered or glued connections in which the solder or adhesive layer has a different modulus of elasticity from that of the material to be joined. Figure 7.29a illustrates the resulting deformation [7.181]. The deformations and the thickness of the solder or adhesive layers have been greatly exaggerated. The load *F*, which is transmitted across the junction of parts 1 and 2, produces distinct deformations in the overlapping parts, the adhesive layer being subjected to particularly marked deformation near the edges due to differences in the relative deformation of parts 1 and 2. While part 1 bears the full load *F* at the upper edge of the adhesive layer and is therefore stretched, part 2 does not yet bear a load. The relative shift in the adhesive layer sets up a local shear stress that exceeds the calculated mean value.

A particularly unsatisfactory result is shown in Figure 7.29b where, as a result of opposite and unmatched deformations of parts 1 and 2, the deformation in the adhesive layer is considerably increased. This example makes it clear why provision should be made for deformations to take place in the same sense and, if possible, to be equal in magnitude. Magyar [7.177] has made a mathematical study of the relationships between load and shear stress: the result is shown qualitatively in Figure 7.30.

The same phenomenon also occurs between nuts and bolts in bolted joints [7.328]. The nut (see Figure 7.31a) is in compression and the bolt is in tension, that is, they are deformed in the opposite sense. In the modified nut (see

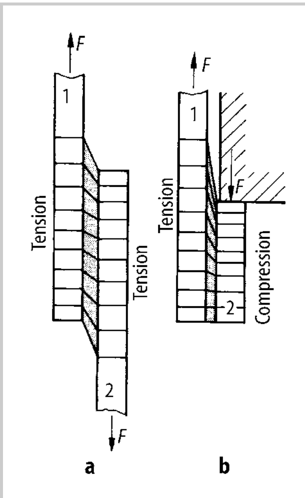


Figure 7.29. Overlapping adhesive or solder joint with strongly exaggerated deformation from [7.181]: **a** Parts 1 and 2 deformed in the same sense; **b** Parts 1 and 2 deformed in the opposite sense

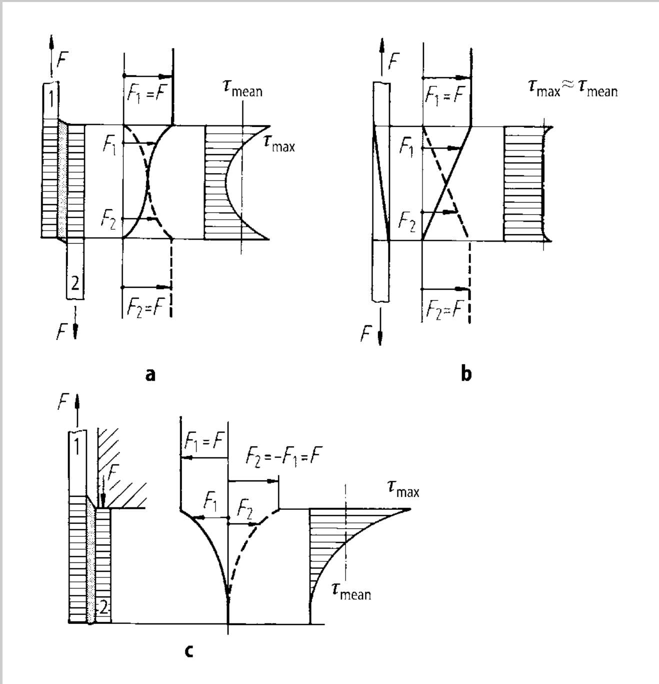


Figure 7.30. Distribution of forces and shear stresses in overlapping joints with layer of adhesive or solder, after [7.177]: **a** overlapped on one side (bending stress neglected); **b** spliced with linearly decreasing thickness; **c** pronounced "deflection of the flowlines of force" with deformations in the opposite sense (bending stress neglected)

Figure 7.31b) a deformation in the same sense is set up in the leading threads, which gives rise to a smaller relative deformation and hence a more even distribution of the load borne by individual threads. Wiegand [7.328] has been able to demonstrate this effect by showing that such nuts have a longer service life. Paland [7.214] has shown more recently that standard nuts are not as unsatisfactory as Maduschka [7.175] has suggested, because the moment $F \cdot h$ produces additional outward deformations of the nut at the contact surface and thus relieves the leading threads of their load. The load-relieving deformation of the nut due to this moment and also to the bending of the threads can be increased considerably by using material with a lower modulus of elasticity. If, on the other hand, the load-relieving deformations are resisted by a very stiff nut or a very small lever arm h, then the type of load distribution described by Maduschka would ensue.

As a further example, let us take a shaft–hub connection formed by a shrink fit. In essence, this too involves the deformation of two components [7.125]. In transmitting the torque, the shaft experiences a torsional deformation that decreases as the torque is transferred to the hub. The hub, for its part, is deformed in accordance with the transmitted torque.

Figure 7.32a shows that the maximum relative deformation occurs at A. In the case of alternating torques, this may lead to fretting corrosion; moreover, the right-

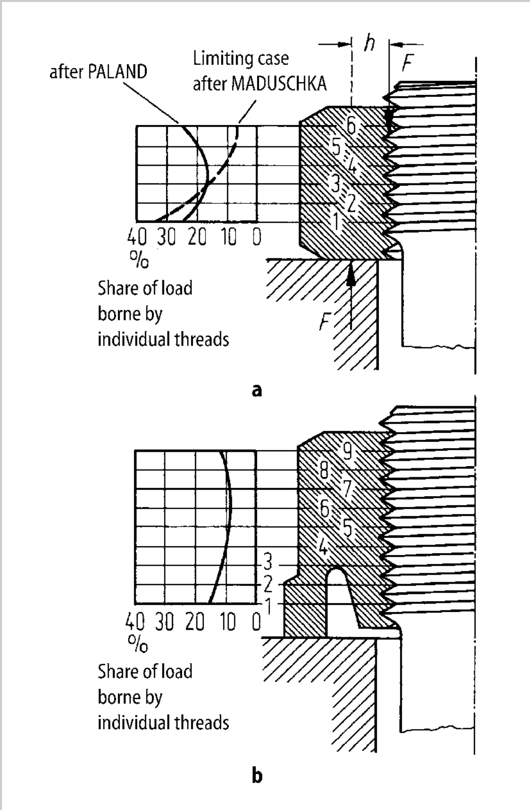


Figure 7.31. Nut shapes and load distribution, after [7.328]: **a** standard nut: limiting case after Maduschka [7.175] and case after Paland [7.214] allowing for deformation due to moment $F \cdot h$; **b** modified nut with matched deformations in the tension part

hand end, to all intents and purposes, contributes nothing to the transfer of the torque.

The solution shown in Figure 7.32b is much better because the resulting deformations are in the same sense. The best solution appears when the torsional stiffness of the hub is matched to that of the shaft. The transfer of torque then takes place along the whole length of the connection, ensuring uniform distribution of force flowlines and thus avoiding stress concentrations.

Even if the shrink fit were replaced with a keyed connection, the layout depicted in Figure 7.32a would, because the torsional deformations are in the opposite sense, set up very high contact stresses in the neighbourhood of A. The layout depicted in Figure 7.32b will, on the other hand, ensure an even contact stress distribution because the deformations are in the same sense [7.188].

The principle of matched deformations can also be applied to bearings, as in Figure 7.33. The embodiment of the bearings should ensure matched deformations between bearing and shaft, or provide for adjustment possibilities.

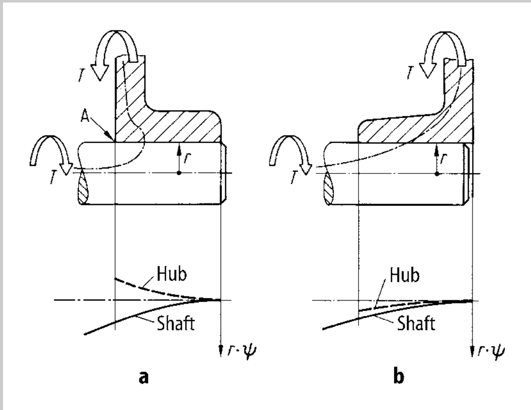


Figure 7.32. **a** Shaft–hub connection with strong "force flowline deflection". Torsional deformations of shaft and hub in opposite sense (ψ = angle of twist). **b** Shaft–hub connection with gradual "force flowline deflection". Torsional deformations of shaft and hub in the same sense

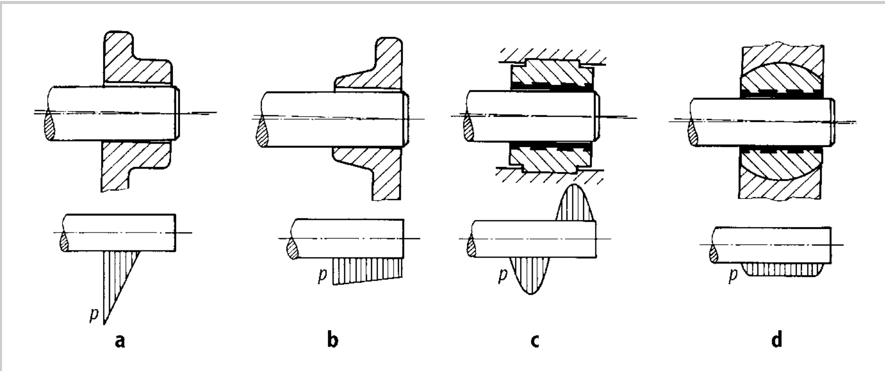


Figure 7.33. Force transmission in bearings: **a** edge compressing because of insufficient adaptation of the bearing to the deformed shaft; **b** more even bearing pressure because of matched deformations; **c** lacking adjustment to shaft deformation; **d** more even bearing pressure because of adaptability of bearing bush

The principle of matched deformations must be taken into account, not only in the transfer of forces from one component to another, but also in the division or combination of forces or moments. A well-known problem is the simultaneous propulsion of wheels that have to be placed at a considerable distance from one another, for instance in crane drive assemblies. In the layout shown in Figure 7.34a, the left side has a relatively high torsional stiffness due to the short force transmission path, and the right side a relatively low torsional stiffness because of its greater path length. When the torque is first applied, the left wheel will be set in motion, while the right wheel remains stationary until the right hand part of the shaft has twisted sufficiently to transmit the torque. The drive assembly has a tendency to run skew.

It is essential to provide the same torsional stiffness to both parts of the shaft so as to ensure an appropriate division of the initial torque. This can be achieved

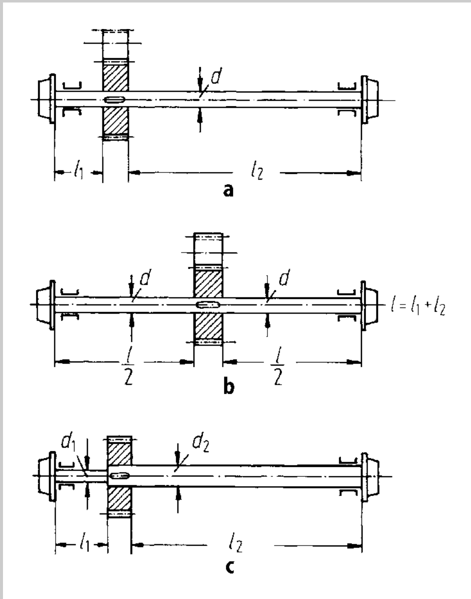


Figure 7.34. Application of the principle of matched—here equal—deformations in crane drives: **a** unequal torsional deformation of lengths l_1 and l_2; **b** symmetrical layout ensures equal torsional deformation; **c** asymmetrical layout with equal torsional deformation due to adaptation of torsional stiffnesses

in two distinct ways if the input torque is taken in one position only: either by symmetrical layout (see Figure 7.34b); or by adaptation of the torsional stiffness of the appropriate parts of the shaft (see Figure 7.34c).

4. Principle of Balanced Forces

Those forces and moments that serve the function directly, such as the driving torque, the tangential tooth force, and the load torque in a gearbox, can, in accordance with the definition of a main function, be described as *functionally determined main forces*.

In addition, there are many forces or moments that do not serve the function directly but that cannot be ignored, for instance:

- the axial force produced by a helical gear
- the force resulting from a pressure difference, for instance across the blades of a turbine or across a control valve
- tensile forces for producing a friction connection
- inertia forces due to linear acceleration or rotation of components
- fluid flow forces, inasmuch as they are not the main forces.

Such forces and moments accompanying the main ones are called *associated forces*, and may either produce a useful auxiliary effect or else appear merely as an unwanted effect that has be taken into account.

Associated forces place additional loads on the components and require an appropriate layout, or must be taken up by further surfaces and elements, such as stiffening members, collars, bearings, etc. As a result, weights are increased and further frictional losses may be incurred. For that reason, the associated forces must, whenever possible, be balanced out at their place of origin, thus obviating the need for a heavier construction or for reinforced bearing and transfer elements.

As has been shown in [7.204], this balance of forces is essentially ensured by two types of solution:

- balancing elements
- symmetrical layout.

Figure 7.35 shows how the associated forces can be balanced in a turbine, helical gears and a cone clutch, with the help of the principle of direct and short force

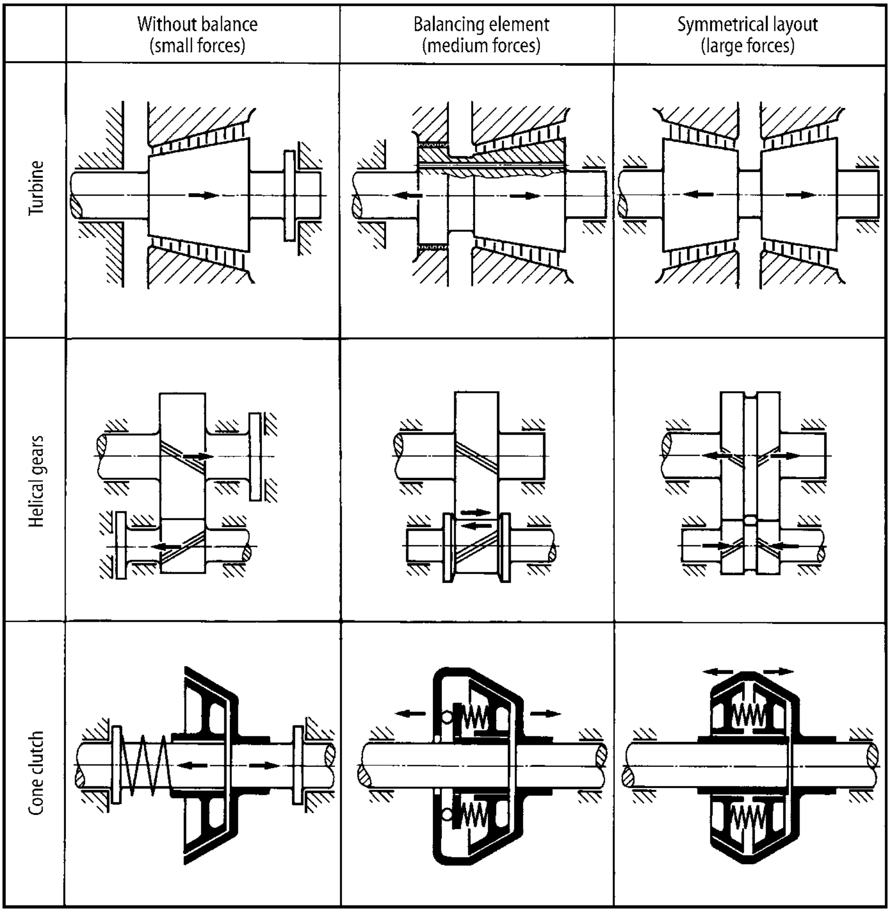


Figure 7.35. Fundamental solutions for balancing associated forces, illustrated via a turbine, helical gears and cone clutch

transmission path. As a result, no bearing position is loaded additionally and the designs are highly economical.

When it comes to the balancing of inertia forces, we find that a rotationally symmetrical layout is inherently balanced. The same solution principle is applied for reciprocating masses, as we know from automobile engineering. If the number of cylinders is too small to ensure a perfect balance, either special balancing elements, weights or shafts [7.228] are introduced, or cylinders are arranged symmetrically, as for instance in opposed cylinder engines.

As a general rule (which, however, can be ignored if there are overriding reasons for doing so), balancing elements should be chosen for relatively small or medium forces, and a symmetrical layout for relatively large forces.

5. Summary of Force Transmission Principles

Earlier we discussed the value of using the descriptive idea of flowlines of force when considering the transmission of forces during the embodiment of assemblies and components. The flowlines should fulfil the following criteria:

- the flowlines must always be closed
- the flowlines should, in general, be as short as possible, which can best be achieved by direct force transmission
- sharp deflections of the flowlines and changes in their "density" resulting from sudden changes in cross-section must be avoided.

In the case of complex force transmission situations, the definition or visualisation of a flowline envelope can be useful. This is the working zone outside of which the forces have no effect. The smaller the envelope, the shorter the force transmission paths. Figure 7.36 shows different concepts of a rotary bending test rig with the respective flowlines envelopes indicated.

The following principles complement the concept of flowlines:

- The *principle of uniform strength* which ensures, through the careful selection of materials and shapes, that each component is of uniform strength and contributes equally to the overall strength of a device throughout its service life.
- The *principle of direct and short force transmission path*, which ensures minimum volume, weight and deformation, and which should be applied particularly if a rigid component is needed.
- The *principle of matched deformations*, which ensures the matching of deformations of related components, so that stress concentrations are avoided and the function can be reliably fulfilled.
- The *principle of balanced forces*, which ensures, with the help of balancing elements or a symmetrical layout, that the associated forces accompanying the main ones are reacted as close as possible to their place of origin, so that material quantities and losses can be kept to a minimum.

In many situations, these principles cannot be applied to their full extent and often have to be applied in combination.

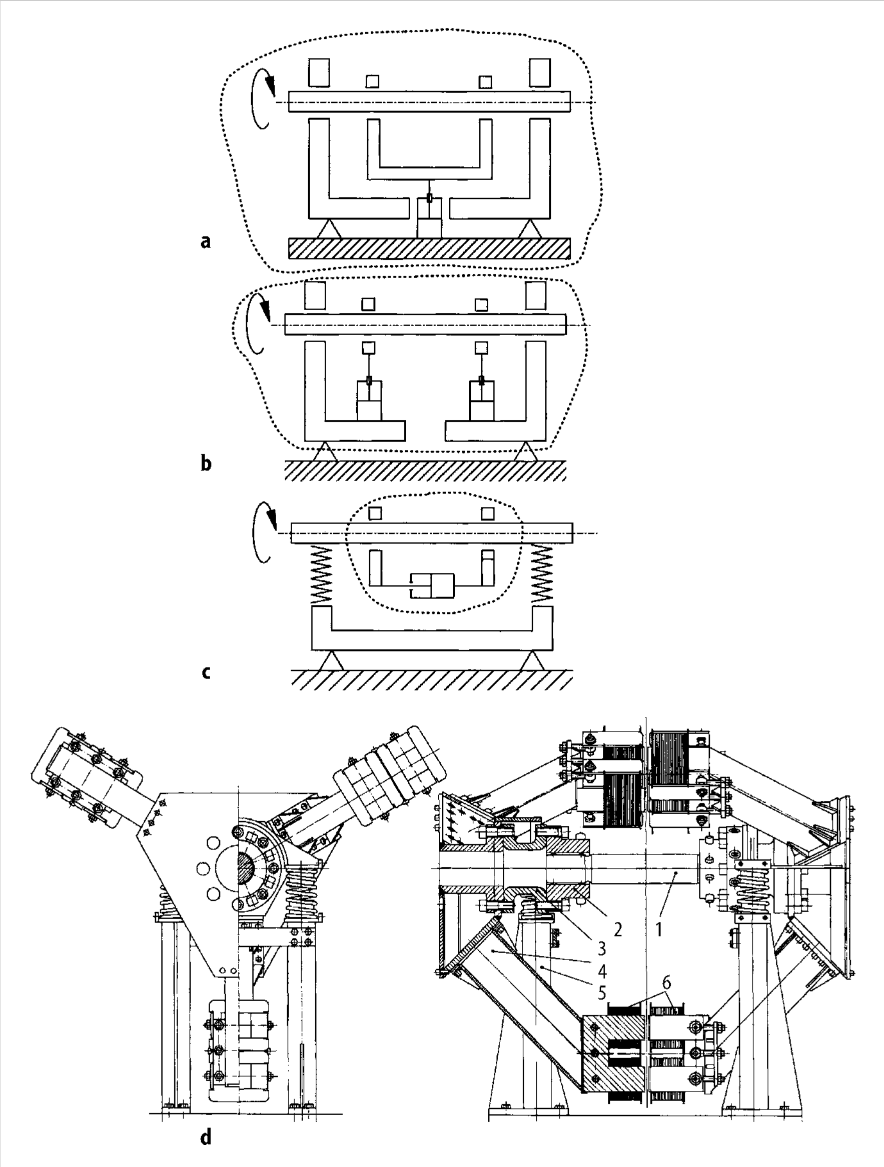


Figure 7.36. Force flow envelope (working zone of the forces) for a rotary bending test rig [7.330]. **a** Working zone includes the foundations; **b** working zone includes the supports; **c** working zone excludes the supports; **d** the test rig actually built using principle **c**, but with magnetic force excitation: 1 test shaft, 2 mounting flange, 3 connector, 4 support arm, 5 foundation supports, 6 magnet pair

7.4.2 Principle of the Division of Tasks

1. Assignment of Subfunctions

Even during the setting up and variation of the function structure, it is important to determine to what extent several functions can be replaced by a single one, or whether one function can be subdivided into several subfunctions (see Section 6.3).

These questions reappear in the embodiment phase, when the problem is to fulfil the requisite functions with the choice and assignment of suitable function carriers. We ask:

- Which subfunctions can be fulfilled with one function carrier only?
- Which subfunctions must be fulfilled with the help of several, distinct function carriers?

So far as the number of components and the space and weight requirements are concerned, a single function carrier fulfilling several functions would, of course, be the best. In terms of the production and assembly processes, however, this may prove disadvantageous, if only because of the complicated shape of the resulting component. Nevertheless, for economic reasons, an attempt should always be made to fulfil several functions with a single function carrier.

Numerous assemblies and components can fulfil several functions simultaneously or successively, as in the following examples:

- A shaft on which a gearwheel has been mounted transfers the torque and the rotating motion simultaneously, and, at the same time, takes up the bending moments and shear forces resulting from the normal tooth force. It also locates the gears axially and, in the case of helical gears, carries the axial force components from the teeth. In conjunction with the body of the gearwheel, it provides sufficient stiffness to ensure correct mating of the teeth.
- A pipe flange connection makes the connection and separation of the pipes possible, ensures the sealing of the joint, and transmits all forces and moments in the pipe resulting from residual tension, from thermal expansion and from unbalanced pipe loads.
- A turbine casing provides the appropriate inlet and outlet flow areas for the fluid, provides a mounting for the stationary blades, transmits the reaction forces to the foundation, and ensures a tight seal.
- A wall of a pressure tank in a chemical plant must combine a retaining with a sealing function and stave off corrosion, while not interfering with the chemical process.
- A deep groove ball bearing, apart from its centering task, transmits both radial and axial forces and occupies a relatively small volume.

The combination of several functions in a single function carrier may often prove economically advantageous, but may have certain drawbacks. These do not usually appear unless:

- the capacity of the function carrier has to be increased to the limit with respect of one or several functions
- the behaviour of the function carrier must be kept absolutely constant in one important respect.

As a rule, it is impossible to optimise the carrier of several combined functions. Instead, designers have recourse to the *principle of the division of tasks* [7.207], by which a special function carrier is assigned to every function. Moreover, in borderline cases, it may even be useful to distribute a single function over several function carriers.

The principle of the division of tasks:

- allows much better exploitation of the component concerned
- provides for greater load capacity
- ensures unambiguous behaviour, and hence fosters the basic rule of clarity (see Section 7.3.1).

This is because the separation of tasks facilitates optimum design in respect to every subfunction and facilitates more accurate calculations. In general, however, the constructional effort becomes correspondingly greater.

To determine whether the principle of the division of tasks can be usefully applied, the *functions must be analysed* with a view to determining if the simultaneous fulfilment of several functions in one carrier introduces constraints or mutual interferences. If it does, then it is best to settle for individual function carriers.

2. Division of Tasks for Distinct Functions

Examples from various fields illustrate the advantage of the division of tasks for distinct functions.

In large gearboxes, as found for instance between a turbine and a generator, it is advisable, because of thermal expansion of the foundations and bearings and also because of the torsional oscillations, to use a radially and torsionally flexible shaft whilst maintaining the shortest possible axial length on the output side [7.203]. However, because of the forces between the gear teeth, the transmission shaft must be as rigid as possible. Here the principle of the division of tasks leads to the following arrangement: the gearwheel is fitted to a stiff hollow outer shaft with the shortest possible distance between the bearings, while the radially and torsionally flexible component takes the form of an inner torsion shaft (see Figure 7.37).

Modern pressure-fed boilers are built with a membrane wall, as shown in Figure 7.38. The furnace must be gas-tight. Moreover, optimum heat transfer to the water demands thin walls with large surface areas. Beyond that, thermal expansion and pressure differences between the furnace and its environment must also be taken into consideration, and so must the weight of the walls. This complex problem is solved with the help of the principle of the division of tasks. The tubular walls with their welded lips constitute the sealed furnace. The forces resulting

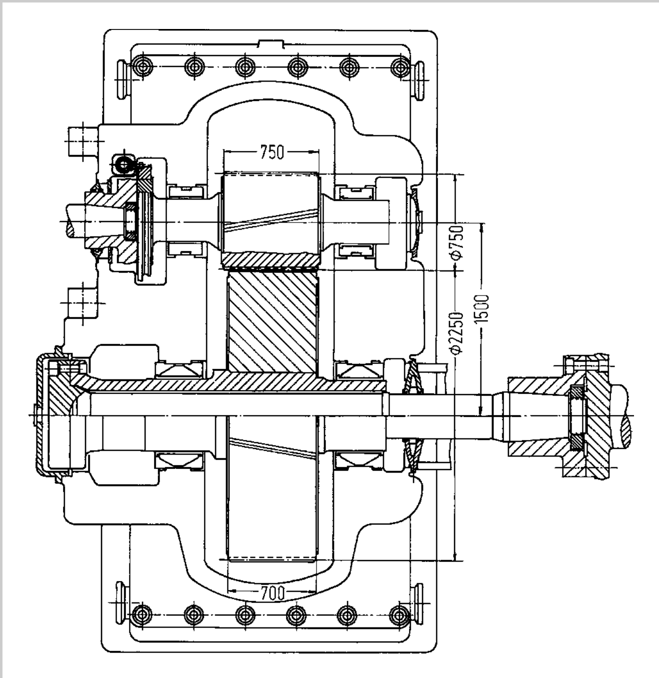


Figure 7.37. Large gearbox with an output torsion shaft; the bearing forces are transmitted over a stiff hollow shaft; the inner torsion shaft is radially and torsionally flexible, after [7.203] (Siemens-Maag)

from the pressure differences are transferred to special supports outside the heated area, which also carry the weight of the—usually suspended—walls. Articulated arms between the tubular wall and the supports allow for unimpeded thermal expansion. Thus every part can be designed in accordance with its special task.

The clamp connection in a superheated steam pipe shown in Figure 7.39 has also been designed based on the principle of the division of tasks. The sealing and load-carrying functions are assigned to different function carriers: the sealing function is performed by the welded membrane seal, which is axially loaded by the tension in the clamp. Tensile forces or bending moments should not be carried by the seal, whose function and durability would thereby be destroyed, so the load-carrying function is performed by the clamp which, in turn, is designed on the principle of the division of tasks. The clamp is made up of segments, which transmit forces and bending moments by means of a close-tolerance fit, and shrink rings hold the clamp segments together via friction in a simple and effective manner. Every part can he optimally designed for its particular task and is easily analysed.

The casings of turbines must ensure a tight seal under all operational and thermal conditions if they are to conduct the working fluid with minimum loss and turbulence. They must also provide an annular area and a support for the stationary blades. During temperature changes, sectioned casings with an axial flange have a particular tendency to distort and to lose sealing power due to

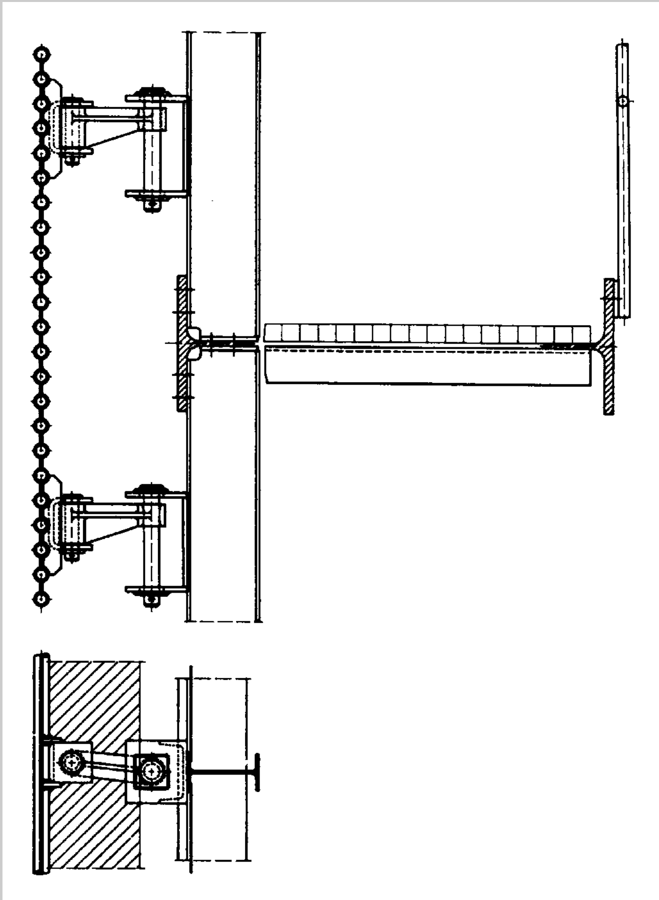


Figure 7.38. Section of boiler with membrane walls and separate supports (Babcock)

marked changes in shape at the inlet and outlet [7.224]. This effect can be offset by a separate blade carriers, that is, by a division of tasks. The annular area and stationary blade attachment can be designed regardless of the larger casing with its inlet and outlet sections. The outer casing can then be designed exclusively for durability and sealing (see Figure 7.40).

A further example is provided by the synthesis of ammonia, which involves feeding nitrogen and hydrogen into a container under high pressures and temperatures. If the hydrogen were allowed to come into direct contact with a ferritic steel container, it would penetrate into and decarbonise the latter, producing decomposition at the grain boundaries with the formation of methane [7.117]. The solution is again based on the division of tasks. The sealing function is provided by an inner casing of austenitic steel which is resistant to hydrogen, while support and strength are provided by a surrounding pressure chamber constructed from high-tensile ferritic steel, which is not resistant to hydrogen.

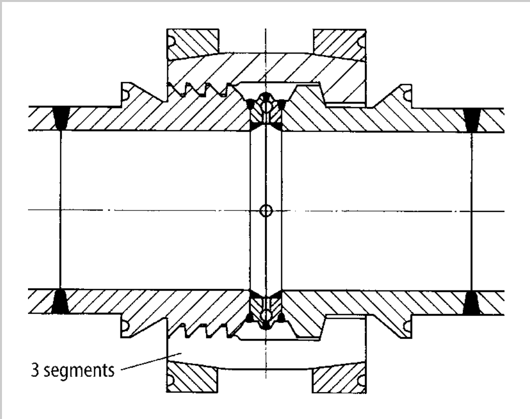


Figure 7.39. Clamp connection in a superheated steam pipe (Zikesch)

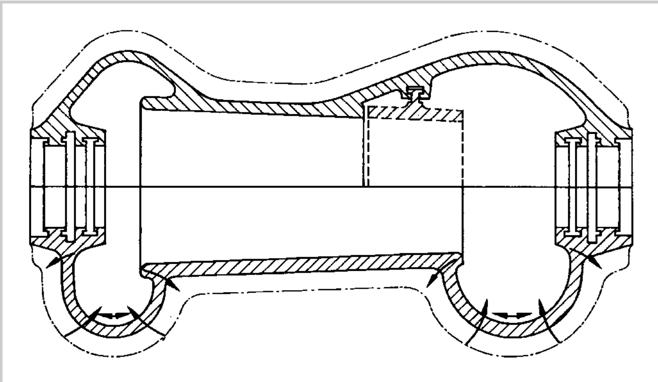


Figure 7.40. Axially divided turbine housing, after [7.224]: lower half conventional; upper half with separate blade carrier

In the electrical circuit-breaker illustrated in Figure 7.41, two or even three contact systems are provided. The breaker contacts 1 take the arcing current during the closing or opening of the switch, and the main contacts 3 carry the current under normal conditions. The breaker contacts 1 are subject to burning—that is, to wear and tear—and must be designed accordingly, while the main contacts must be designed to carry the full working current.

The division of tasks is also illustrated in Figure 7.42: the Ringfeder connectors carry the torque, while the corresponding cylindrical surfaces ensure the central location and seating of the pulley, which the Ringfeder connector cannot provide by itself when high accuracy is required.

A further example is provided by the design of rolling element bearings in which the service life of the locating bearing is increased by the clear separation of the transmission paths of radial and axial forces (see Figure 7.43). The outer race of the deep-groove ball bearing is not supported radially, and hence transmits axial forces only, while the roller bearing transmits radial forces only.

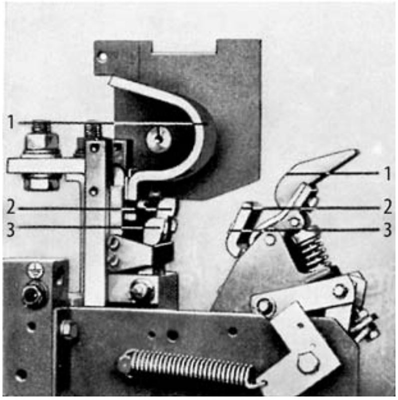


Figure 7.41. Arrangement of contacts in a circuit breaker (AEG): 1 breaker contacts; 2 intermediate contacts; 3 main contacts

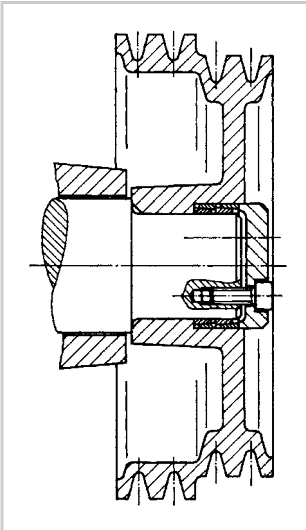


Figure 7.42. Ringfeder connector plus centralising surfaces

The principle of the division of tasks has been applied consistently to the construction of composite flat belts. They are made up, on the one hand, of a synthetic material capable of carrying high tensile loads and, on the other hand, of a chrome leather layer on the contact surface which provides a high coefficient of friction for the transfer of the load.

Yet another example is provided by the rotor blade attachment in a helicopter (see Figure 7.18).

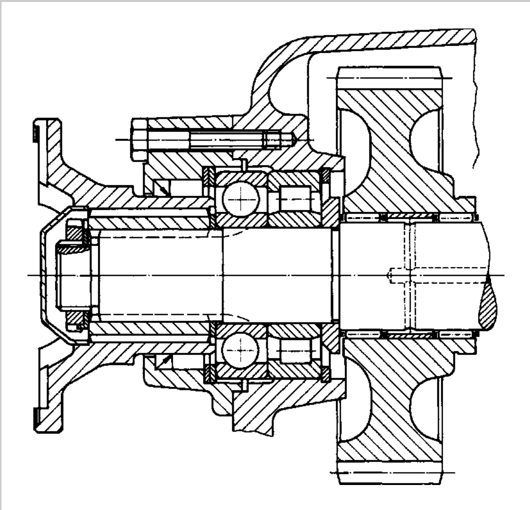


Figure 7.43. Locating bearing with separate transmission paths for radial and axial forces

3. Division of Tasks for Identical Functions

If increases in load or size reach a limit, a single function can be assigned to several, identical function carriers. In other words, the *load can be divided* and then recombined later. There are numerous examples of this.

The load capacity of a V-belt cannot be increased at will by increases in its cross-section (number of load-carrying strands per belt) because, for a given pulley diameter, an increase in the belt height h (see Figure 7.44) leads to an increase in the bending stress. As a result of the ensuing deformation, the rubber (which has hysteresis properties and is also a poor conductor of heat) becomes overheated and this reduces its life. A disproportionally wide belt, on the other hand, loses the stiffness needed to take up the normal forces acting on the wedge-shaped surfaces of the pulley. An increase in load-carrying capacity can, however, be obtained by dividing the overall load into part loads, each appropriate to the load limit and normal life of the individual belts (multiple arrangement of parallel V-belts).

The coefficient of thermal expansion of superheated steam pipes made of austenitic steel is approximately 50% higher than that of pipes made of the usual ferritic steel. Such pipes, moreover, are particularly stiff. At constant inner pressures and fixed material property limits, the ratio of outer to inner pipe diameter remains constant if the inner diameter is changed. However, while the throughput at constant flow velocities varies as the square of the inner diameter, the bending and torsional stiffnesses vary as its fourth power. The substitution of z pipe lines for a single large pipe would admittedly lead to increased pressure and heat losses for the same flow area, but would reduce the stiffness resisting thermal expansion by $1/z$. With four or eight pipelines, the individual reaction forces would then be no more than 1/4 or 1/8 of that present in a single pipe [7.29, 7.279]. In addition, the reduction in wall thickness leads to a reduction in thermal stresses.

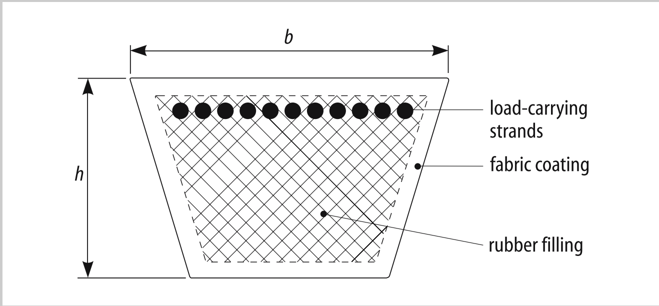


Figure 7.44. Cross-section of V-belt

Gearboxes, and epicyclic gearboxes in particular, make use of the principle of the division of tasks (or rather of forces) in the form of multiple meshing, which will increase the transmission capacity of the gearbox provided that the thermal effects can be kept within reasonable limits. In the symmetrical layout of epicyclic gearboxes based on the principle of balanced forces (see Section 7.4.1), even the bending moment in the shaft is eliminated because the forces produced by the gears cancel out. However, the torsional deformation is increased because of the greater load capacity (see Figure 7.45). In large gearboxes, this principle is applied to advantage in the form of multiple drives equipped with spur gears, which have external teeth only and hence are more easily produced. As Ehrlenspiel [7.96] has shown, it is possible to increase the load capacity with the number of force transmission paths, though not in direct proportion, because each step introduces a different flank geometry with a slightly greater flank loading. Basic arrangements are depicted in Figure 7.46.

One problem with the principle of the division of tasks is the uniform participation of all of the elements in the fulfilment of the function, that is, the provision of a *uniform distribution of forces or loads*. In general, this can only be achieved if:

- the participating elements adjust themselves automatically to balance out the forces
- appropriate flexibility is specially provided in the force transmission paths.

In the case of multiple V-belt drives, the tangential forces produce slight extensions of the belts which help to offset any dimensional errors in the lengths of the belts or in the pulleys, or any lack of parallelism in the shaft, and thus ensure equal load sharing.

In the case of the multiple pipeline discussed above, the individual pipe loss coefficients, the relationships between inflow and outflow, and also the geometry of the pipe layouts must be kept similar, or else the individual loss coefficients must be small and not greatly affected by the flow speeds.

In the case of multiple gears, either a strictly symmetrical arrangement must ensure equal stiffnesses and temperature distributions throughout the gearbox, or special flexible or adjusting elements [7.97] must ensure the equal participation of all of the components.

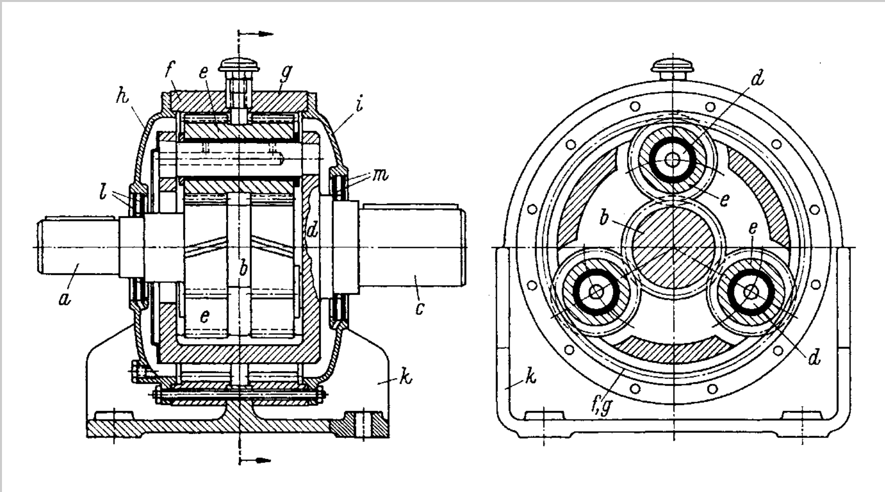


Figure 7.45. Epicyclic gearbox with balanced forces, after [7.97]

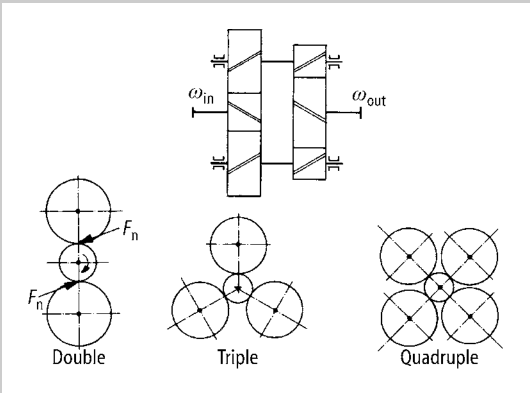


Figure 7.46. Basic arrangements of multiple gears, after [7.203]

Figure 7.47 illustrates a flexible arrangement. Further balancing components, such as elastic and articulated joints, are described in [7.97].

All in all, the principle of the division of tasks provides for increases in the maximum load capacity or for wider applications. By spreading tasks over several function carriers, we also gain a clearer picture of the relationship between forces and their effects, and, what is more, we can increase the output, provided only that a balanced division of forces is maintained by adjustable or self-regulating elements.

In supporting structures (such as bearing supports) where force transmission is divided, a more balanced load distribution can be achieved by adjusting the stiffness. During the stiffness analysis, the location and direction of the external forces have to be considered carefully, because they influence the deformation

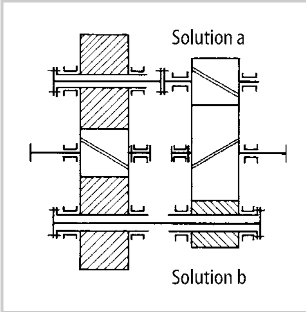


Figure 7.47. Balanced forces in multiple gears by means of flexible torsion shafts, after [7.203]

behaviour. This analysis can be facilitated by the use of Finite Element (FE) methods (see the principle of matched deformation in Section 7.4.1).

In general, the application of the principle of the division of tasks increases the number of components, which must be offset by greater overall economy or safety.

7.4.3 Principle of Self-Help

1. Concepts and Definitions

In the last section we discussed the principle of the division of tasks and showed how it could help to increase load capacity and provide a clearer definition of the behaviour of the components. To that end, we analysed the various subfunctions and assigned them to function carriers chosen such that they neither influence nor interfere with one another.

The same analysis can also be used in conjunction with the *principle of self-help* to achieve, through the appropriate choice of system elements and their arrangement, a mutual supportive interaction that improves the fulfilment of the function.

Under *normal conditions* (normal loading), self-help provides for greater effect by arranging the forces to work in the same direction as each other, or for relief by arranging the forces to offset each other. In *emergency situations* (overloading), self-help provides for greater protection and safety. In a self-helping design, the *overall effect* is made up of an initial effect and a supplementary effect.

The *initial effect* sets off the physical process required by the solution, but is insufficient on its own.

The *supplementary effect* is obtained from the functionally determined main forces (gearbox torque, sealing force, etc.) and/or from the associated forces (axial force produced by helical gears, centrifugal inertia force, force due to thermal expansion, etc.), provided, of course, that the two sets of forces are clearly correlated. A supplementary effect may also be obtained by appropriate changes to the type and distribution of the force transmission paths in order to increase load capacity.

The idea of formulating the self-help principle was first suggested by the Bredtschneider–Uhde self-sealing cover, which is particularly suitable for pressure vessels [7.237]. Figure 7.48 shows how it works. A relatively small force provided by the central bolt *2* suffices to press the cover *1* against the metal seal *5*. The initial effect of this force ensures that the parts make the proper contact. With increasing operational pressure, a supplementary effect is produced, which ensures that the sealing force between cover and tank is increased appropriately. The internal pressure thus provides the required sealing force automatically.

Inspired by this self-sealing solution, the principle of self-help was formulated in [7.206, 7.209] and further analysed and elaborated by Kühnpast [7.161].

It may be useful to specify the quantitative contribution of the supplementary effect S to the overall effect O in producing the degree of self-help:

$$\chi = S/O = 0 \ldots 1$$

The gain from self-help solutions can be expressed in terms of one or several technical characteristics: efficiency, service life, use of materials, technical limit, etc. The self-help gain is defined as:

$$\gamma = \frac{\text{technical characteristic with self-help}}{\text{technical characteristic without self-help}}$$

Whenever the application of the self-help principle calls for a greater effort on the part of designers, then it must bring clear technical or economic advantages.

Identical design approaches may turn out to be *self-helping* or *self-damaging*, depending on the layout. Take the case of an inspection cover (see Figure 7.49). So long as the pressure inside the tank is greater than the pressure outside, the layout shown on the left is self-helping, because the pressure on the cover (supplementary effect) increases the sealing effect (overall effect) of the initial tension-screw force (initial effect).

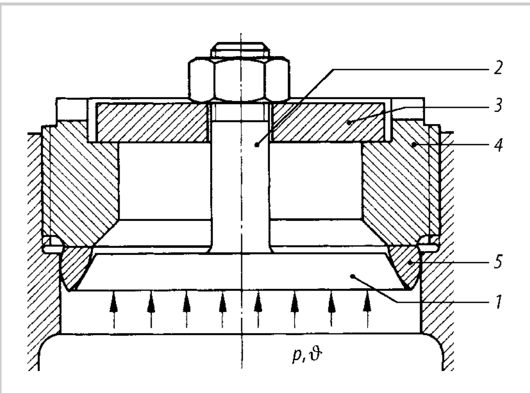


Figure 7.48. Self-sealing cover: *1* cover; *2* central bolt; *3* cross member; *4* element with sawtooth thread, *5* metal sealing ring; p = internal pressure, ϑ = temperature

The layout shown on the right, by contrast, is self-damaging because the pressure on the cover decreases the sealing effect *O* of the initial tension-screw force *I*. If, however, the tank were kept at below-atmospheric pressure, the left layout would be self-damaging, the right layout self-helping (see also Figure 7.50).

This example shows that the degree of self-help depends on the resultant effect: in the present case the effect on the sealing force resulting from the elastic forces, and not on the simple addition of the force exerted by the screw and the force acting on the cover. Figure 7.50 can also be considered to be a force–deformation diagram

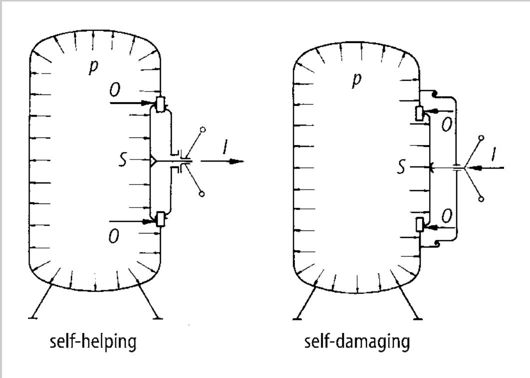


Figure 7.49. Layout of an inspection cover. I = initial effect; O = overall effect; p = internal pressure

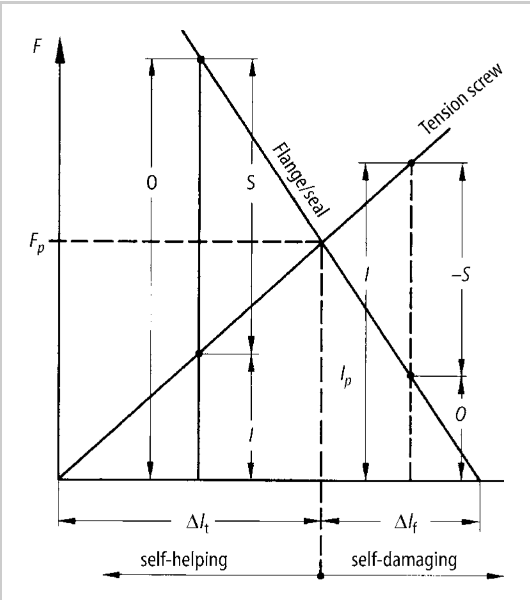


Figure 7.50. Force diagram for Figure 7.49: F = forces; F_p = preload; Δl = change in length; subscript t = tension screw; subscript f = flange/seal

Table 7.3. Summary of self-help solutions

	Normal load		Overload
Type of self-help	Self-reinforcing	Self-balancing	Self-protecting
Supplementary effect due to	Main and associated forces	Associated forces	Altered force transmission path
Important features	Main or associated forces act in the same sense as other main forces	Associated forces act in the opposite sense to main forces	Force transmission path altered by elastic deformation; limitation of function permissible

of a bolted connection with a preload and a working load. The conventional bolted flange connection may be called self-damaging inasmuch as, under operational conditions, the overall effect—that is, the flange sealing—becomes smaller than the preload. Also, the loading of the bolts is increased at the same time. If possible, therefore, only self-reinforcing arrangements that increase the overall effect while reducing the loading of the bolts should be chosen (Figs. 7.53a–d illustrate such arrangements).

For practical purposes, it is useful to classify self-helping solutions in accordance with Table 7.3.

2. Self-Reinforcing Solutions

In self-reinforcing solutions, the supplementary effect is obtained directly from a main or associated force and it adds to the initial effect to produce a greater overall effect.

This group of self-helping solutions is the most common. Under part-load conditions, it ensures greater service life, less wear, higher efficiency, etc., because the components are only loaded to an extent needed to fulfil the function at any particular moment.

As a first example, let us consider a continuously adjustable friction drive (see Figure 7.51).

The preload spring *a* presses the freely movable cup wheel *c* on the drive shaft *b* against the cone wheel *d*, thus providing the initial effect. Once a torque is applied, the roller follower *e* attached to shaft *b* is pressed against the cam *f* formed on the cup wheel *c*, where it produces a normal force F_n that can be resolved into a tangential force F_t and an axial force F_a, which, for its part, increases the contact force F_c applied to the cone wheel in a fixed proportion to the applied torque T:

$$F_a = T/(r \cdot \tan\alpha)$$

The force F_a represents the supplementary effect gained from the torque. The overall effect is obtained from the spring preload force F_p plus the axial force F_a,

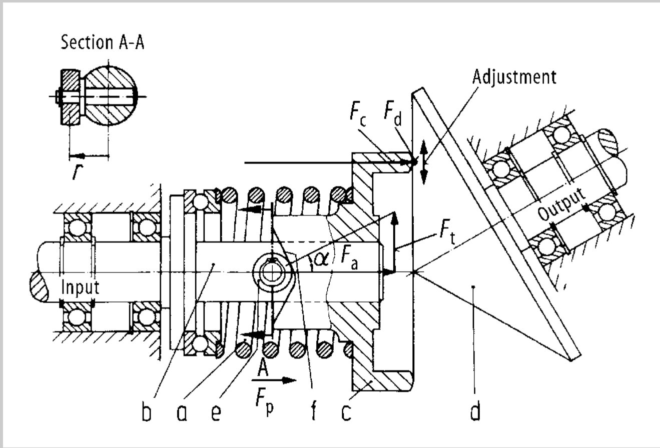


Figure 7.51. Continuously adjustable friction drive: *a* preload spring; *b* drive shaft; *c* cup wheel; *d* cone wheel; *e* roller follower; *f* cam formed on the cup wheel; *r* radius on which F_t and F_a act

which varies as the torque T (see Figure 7.52). The tangential driving force F_d on the cone, which determines the transmittable torque, is therefore:

$$F_d = (F_p + F_a) \cdot \mu$$

and the degree of self-help is:

$$\chi = S/O = F_a/(F_p + F_a)$$

It is obvious that the contact pressure between the wheels, which helps to determine the wear and the service life of the drive, must not exceed what is strictly necessary. A conventional solution (no self-reinforcement) would have demanded an axial force produced exclusively by the spring preload corresponding to the maximum torque, and would therefore have necessitated maximum pressure being applied to the contact area under all load conditions. As a result, the bearings would also have had to carry a considerably greater load, which would have led to a reduced service life or would have demanded a much heavier construction.

A rough calculation shows that if the actual loading is, say, 75% of the nominal maximum load, then the bearing load would be reduced by about 20% which, because of the exponential relationship of service life to load, can lead to the life of the bearings being doubled. In that case, with $n = 3$ the self-help gain with respect to the service life becomes:

$$\gamma_L = \frac{\text{Life with self-help}}{\text{Life without self-help}} = \left(\frac{C/0.8P}{C/P}\right)^n = 1.25^3 = 2$$

A typical example is provided by the SESPA drive [7.157].

Figure 7.53 shows various self-reinforcing layouts of contact surfaces loaded by bolts, in which the frictional forces are increased by the operational forces while the bolts themselves are off-loaded.

The application of the principle of self-help in the design of self-reinforcing brakes has been described by Kühnpast [7.161] and Roth [7.233]. Depending on the application, even self-damaging—and in this case self-weakening—solutions can prove interesting, inasmuch as they reduce the effect of variations of the coefficient of friction on the braking moment [7.107, 7.233].

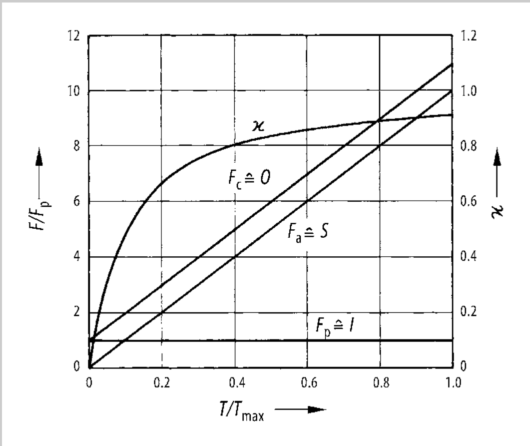


Figure 7.52. Degree of self-help (χ) and initial (I), supplementary (S) and overall (O) effect against the relative torque T/T_{max} for the friction drive (Figure 7.51)

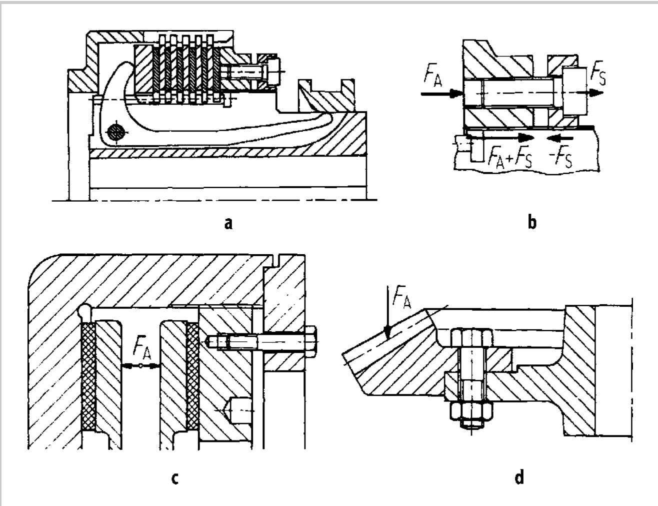


Figure 7.53. Self-helping bolted connections: **a** multiple disc clutch with adjustment ring; **b** force acting on the adjustment ring; **c** adjustable disc of two-disc friction clutch; **d** crown wheel attachment, symmetrical take-up of forces

Self-reinforcing seals (see Figure 7.54) provide us with further examples. In them, the operating pressure against which the seal has to be applied is used to produce the supplementary effect.

Finally, we must mention one case in which the supplementary effect is produced by an associated force. In hydrostatic axial bearings, the centrifugal inertia effect leads to an increase in oil pressure which, at high revolutions, will help to improve the load-carrying capacity, provided the heat can be removed (see Figure 7.55). The supplementary effect leads to an improvement in the load-carrying capacity due to the increased oil pressure resulting from the centrifugal effect alone; the overall effect is due to the load-carrying capacity of the combined static and dynamic pressures. According to Kühnpast [7.161], it should be possible at, say, 166 rev/s and $\chi = 0.38$, to obtain a gain in self-help of $\gamma = 1.6$ compared to static conditions.

The supplementary effect of another associated force, namely that caused by the effect of temperature on the shrink-fitted rings of a turbine, is discussed in [7.206].

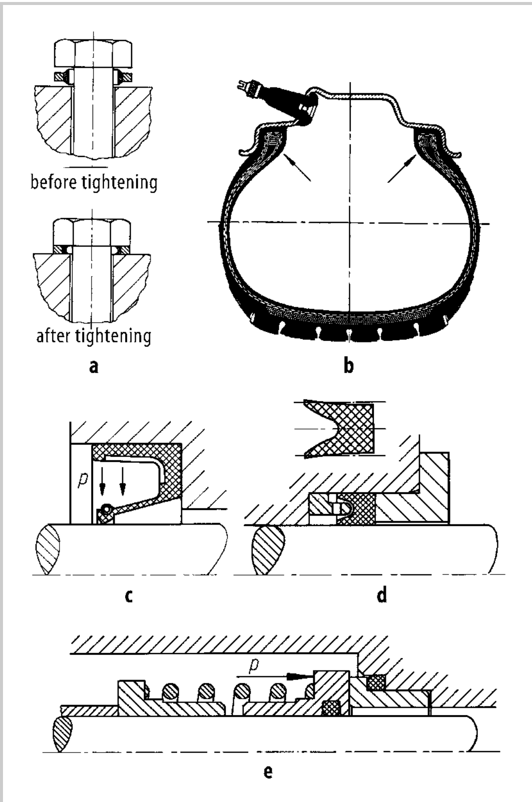


Figure 7.54. Self-reinforcing seals: **a** self-sealing washer; **b** tubeless tyre; **c** radial shaft seal; **d** sleeve seal; **e** sliding ring seal

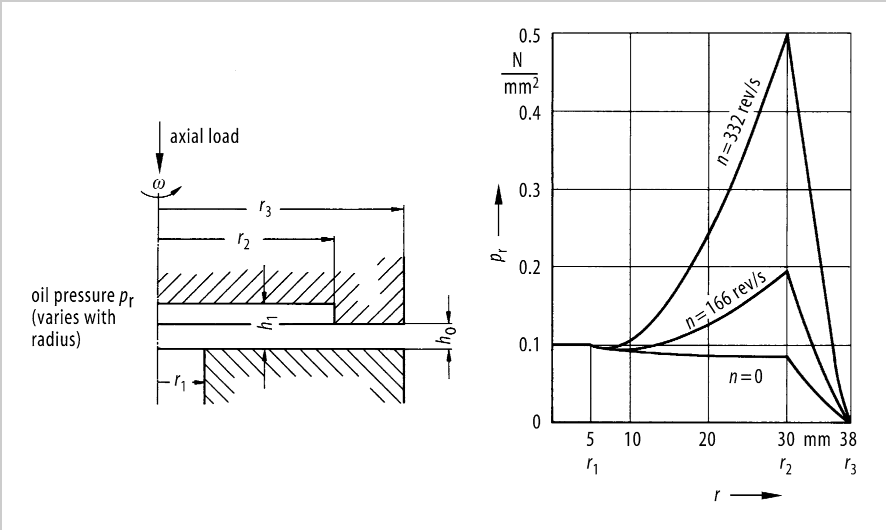


Figure 7.55. Self-help effect in hydrostatic axial bearings, after [7.161]

3. Self-Balancing Solutions

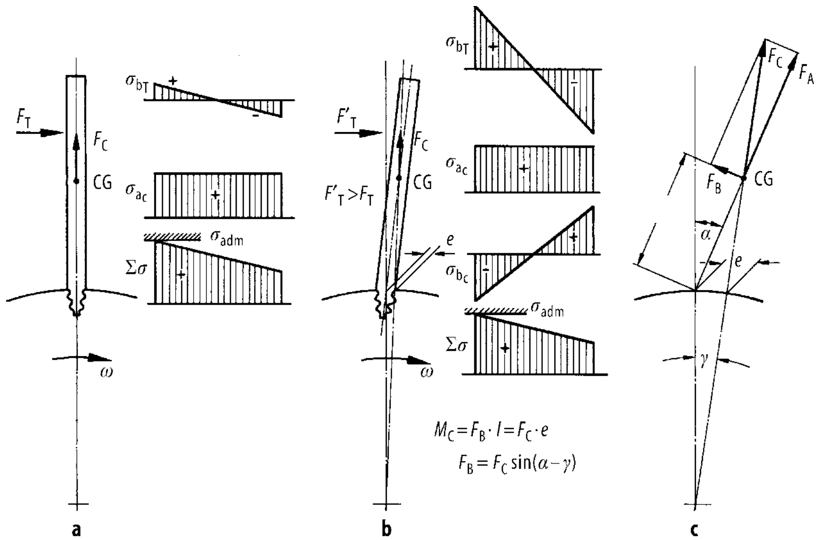
In self-balancing solutions, the supplementary effect is obtained from an associated force, and offsets the initial effect to produce an improved overall effect.

A simple example is provided by turbo-machines. A blade attached to a rotor is subject to a bending stress due to the tangential force acting upon it and also to an axial tensile stress due to the centrifugal inertia force. The two are additive and, because a certain stress must not be exceeded, the transferable tangential force is reduced (see Figure 7.56). If, however, the blade is attached at an angle, a supplementary effect is produced: an additional bending stress due to the centrifugal inertia force acting on the offset centre of gravity of the blade opposes the original bending stress and thus allows the application of a larger tangential force, that is, a greater overall effect. How far this balancing process can be carried depends on the aerodynamic and mechanical conditions.

A self-balancing effect can also be produced by allowing thermally induced forces (stresses) to oppose other forces (stresses), for instance, those resulting from excess or other mechanical loads (see Figure 7.57).

All of the examples we have given are intended to encourage the design of technical systems where:

- forces and moments with their resulting loads cancel out as far as possible, or
- additional forces or moments are produced in a clearly defined way so that it is possible to balance them out.



CG = Centre of gravity;
F_T = Tangential force; F_C = Centrifugal inertia force; σ_{bT} = Bending stress due to F_T; σ_{a_C} = Axial stress due to F_C;
σ_{b_C} = Bensing stress due to F_C; F_A = Axial component to F_C; F_B = Bending component of F_C

Figure 7.56. Self-balancing solution for turbine blades: **a** conventional solution; **b** leaning of the blade produces a balancing supplementary effect due to the additional bending stresses produced by the centrifugal inertia force (σ_{b_C}), which oppose the bending stresses caused by the tangential force (σ_{b_T}); **c** diagram of forces

4. Self-Protecting Solutions

In general, in the event of an overload, we do not want components to be destroyed, unless of course they have been deliberately designed as weak links. In particular, we try to protect components that are frequently subject to slight overloads. If special safety arrangements, for instance to limit the load, are not essential, then a self-protecting solution may prove advantageous. It will sometimes be simplicity itself.

Self-protecting solutions derive their supplementary effect from an additional different force transmission path that, in case of excess loading, is generally created after a given elastic deformation has taken place. As a result, the distribution of the flowlines of force is altered, which changes the nature of the loading and thereby increases the load-carrying capacity. Admittedly, in that case, the functional properties associated with normal conditions may become altered, limited or suspended.

The springs shown in Figure 7.58 have such self-protecting properties. In the case of excess loading, the spring elements, which are normally subject to torsional or bending stresses, will transmit the additional force directly by compressive stresses transmitted from coil to coil. The same effect may also be produced if the springs are shock-loaded (see Figure 7.58b).

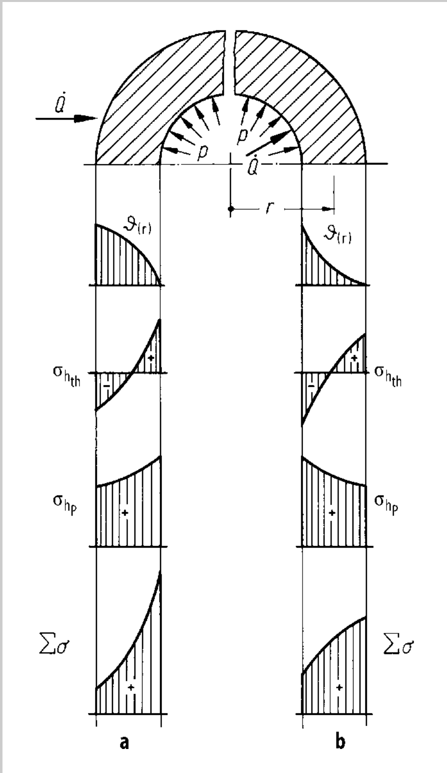


Figure 7.57. Hoop stresses in a thick-walled cylinder due to the internal pressure σ_{h_p}, and temperature differences at nearly steady heat flow $\sigma_{h_{th}}$: **a** nonbalancing solution, thermal stress is added to the maximum mechanical stress on the inner surface; **b** self-balancing solution, thermal stress opposes maximum mechanical stress on the inner surface

Figure 7.59 shows the layout of elastic couplings in which restriction of the spring movements provides additional and different force transmission paths with consequent loss of flexibility but with increased load-carrying capacity. The original springs are removed from the force transmission path. In Figure 7.59a, the load-carrying capacity of the bar springs is altered inasmuch as, besides the normal bending, a powerful shear force between the two halves of the coupling appears with overloads.

Figure 7.59b shows a coupling that, strictly speaking, may be considered a borderline case between a division of tasks and a self-protecting solution. The buffers will only take up forces in the case of overloading. In this case, the nature of the loading on the spring elements remains unchanged, although the force transmission path is altered after a given elastic deformation has taken place.

Kühnpast [7.161] also mentions cases in which there is an uneven stress distribution over a cross-section, and where plastic deformation can then be used for purposes of self-protection. In such cases, however, sufficiently tough materials and adequate dimensional stability are needed, and additive multiaxial stress situations are to be avoided.

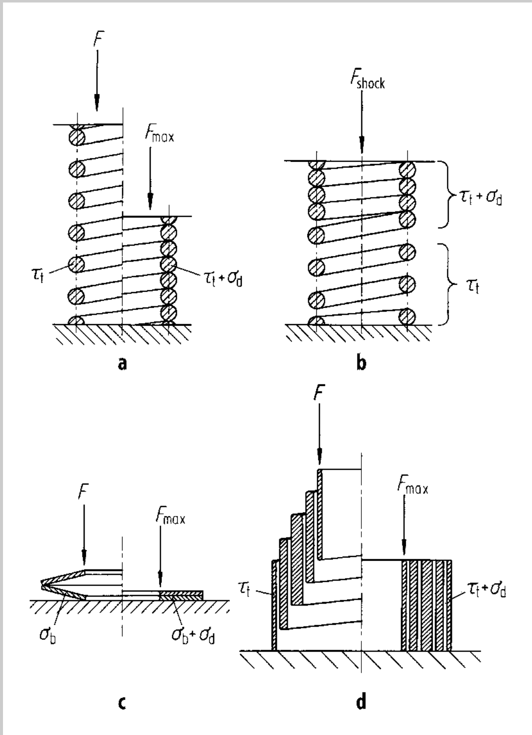


Figure 7.58. Self-protecting solution in springs: **a–d** force transmission path changed, the normal function is suspended or limited in the case of excess loading

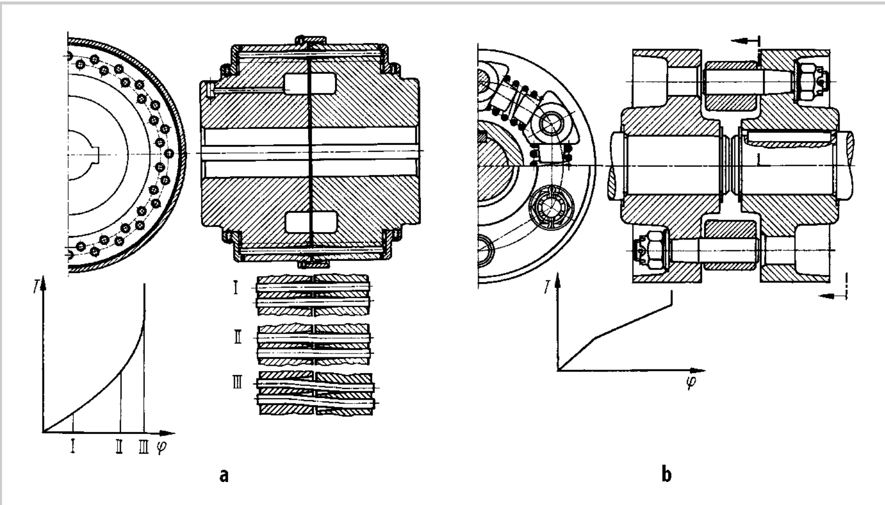


Figure 7.59. Self-protecting solution in couplings; change of force transmission paths with loss of elastic properties in case of overloading: **a** bar–spring coupling; **b** elastic coupling with coil springs and special buffers to take up the force in the case of overloading

It is hoped that the principle of self-help based on self-reinforcing, self-balancing and self-protecting solutions will encourage designers to examine every conceivable arrangement in an effort to arrive at an effective and economical solution.

7.4.4 Principles of Stability and Bi-Stability

We know the concepts of stable, neutral and unstable equilibrium from mechanics, as illustrated in Figure 7.60. When elaborating solutions, designers must always consider the effect of disturbances and try to keep the system stable by devising means whereby the disturbances can be made to cancel out, or at least to mitigate one another. If disturbances are self-reinforcing, we have unstable or bi-stable behaviour. This effect is desirable in certain solutions, where we speak of "planned instability".

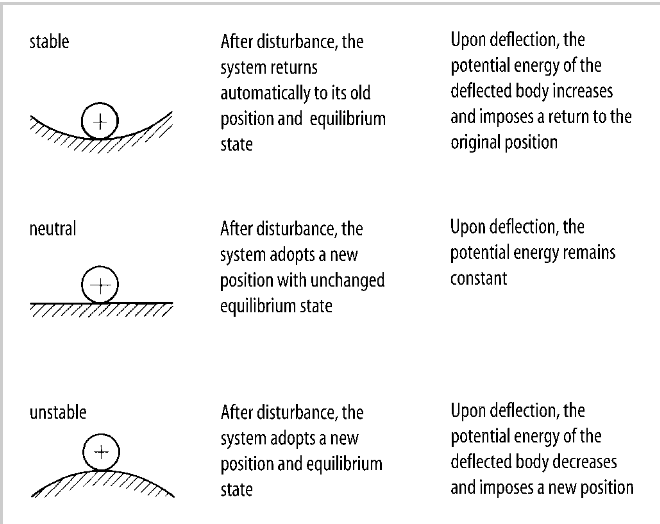


Figure 7.60. Characteristics of equilibrium states

1. Principle of Stability

By applying this principle, designers try either to ensure that disturbances cancel themselves out or to reduce their particular effects. Reuter [7.225] has discussed this subject at length and we shall now look at some of his examples.

In the design of pistons for pumps or regulating devices, the main objective is to achieve stable behaviour and minimum friction. Figure 7.61a shows the layout of a piston with unstable characteristics. Disturbances due to, say, inaccuracies in the cylinder bore can tilt the piston slightly and produce pressure distributions over the piston that encourage further tilting (unstable behaviour). Stable behaviour is

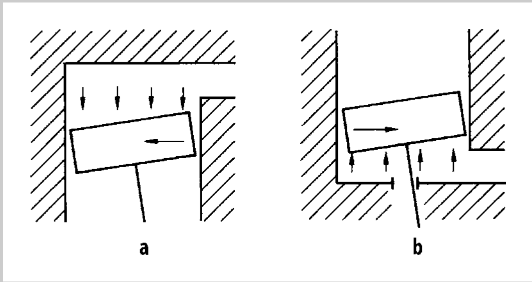


Figure 7.61. Piston in cylinder, tilted due to a disturbance, after [7.225]: **a** resulting pressure distribution produces an effect that increases the disturbance (unstable behaviour); **b** resulting pressure distribution produces an effect that opposes the disturbance (stable behaviour)

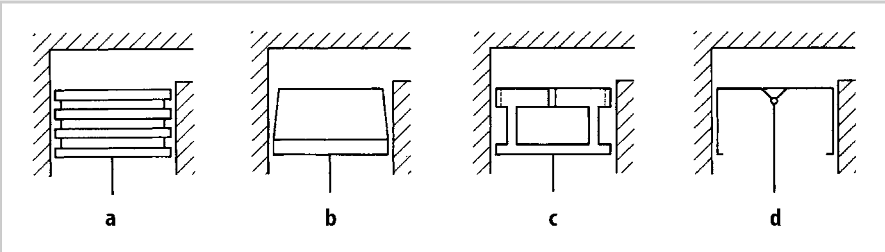


Figure 7.62. Measures for improving the resulting pressure distribution, after [7.225]: **a** unstable behaviour mitigated by pressure-equalising grooves; **b** stable behaviour through conical piston; **c** through pressure pockets; **d** through joint fitted above centre of gravity of the piston

ensured by the layout shown in Figure 7.61b, which, however, has a disadvantage: the piston rod inlet has to be sealed off on the pressure side.

According to [7.225], the layout shown in Figure 7.61a can be stabilised by the measures shown in Figure 7.62a-d. They ensure that a disturbance will itself initiate pressure distributions that tend to correct the misalignment.

Another example is the well-known case of hydrostatic bearings with oil pockets distributed around the periphery. When the bearing is loaded, the leakage path below the load is reduced, with the result that pressure builds up in the affected oil pocket and decreases in the opposite one. Thanks to the combined effect, the bearing can take up the load with very small shaft displacement.

The stuffing boxes and seals of turbomachinery must always be designed for thermostable behaviour [7.225]. The seal of a turbocharger shown in Figure 7.63 is a case in point. In the thermo-unstable layout (see Figure 7.63a), most of the frictional heat generated by contact forces will flow into the rotor, which will heat up further, expand, and hence increase the contact forces. In the stable arrangement (see Figure 7.63b), in contrast, the frictional heat will cause the contact forces to be reduced. A disturbance thus produces a self-limiting effect.

A similar approach is used in the design of taper roller bearings. Thus, in the layout shown in Figure 7.64a, heating of the shaft, by excessive loading for instance, will tend to increase the load even further because of the expansion of the shaft due to the increased frictional heat. The arrangement shown in Figure 7.64b, in contrast,

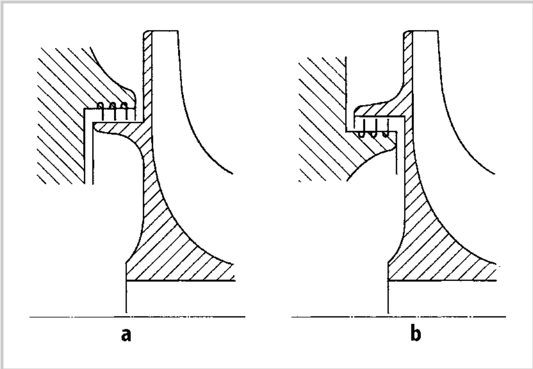


Figure 7.63. Seal in turbocharger, after [7.225]

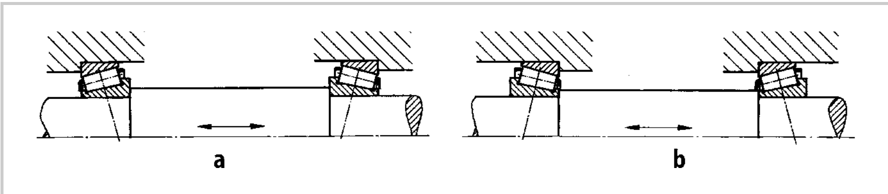


Figure 7.64. Taper roller bearings in which the shaft heats up more than the housing: **a** thermal expansion leads to increased loading and hence to unstable behaviour; **b** thermal expansion leads to reduced loading and hence to stable behaviour

will lead to a load reduction. In the case under consideration, this reduction must not, however, be allowed to reach the point where one of the bearings becomes unloaded, because the shaft at that point would then not be located radially and the bearings would be easily damaged.

Another interesting example of thermostable behaviour is provided by the double-helical gears used in marine gearboxes [7.322].

2. Principle of Bi-Stability

In some cases, unstable or bi-stable behaviour is positively welcome. This happens when, upon reaching a limit, a clearly distinct state or position is required and no intermediate state is acceptable. The requisite instability is initiated when a selected physical quantity reaches a limiting value and then introduces self-reinforcing effects which cause the system to jump into a second stable state. This bi-stable behaviour is required for switches and protective systems (see Section 7.3.3).

A well-known application of this is in the design of safety and alarm valves [7.225], which, upon reaching a limiting pressure, will spring from a completely closed to a completely open position. This avoids undesirable settings with a low flow rate or flutter and wear of the valve seat. Figure 7.65 illustrates the solution principle.

Up to the limiting pressure $p = p_1$, the valve remains closed under the preload of the spring. If this pressure is exceeded, then the valve head will lift off very slightly.

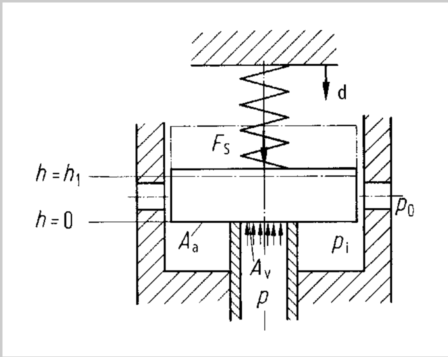


Figure 7.65. Solution principle for a valve with an unstable opening mechanism: d = precompression of spring; s = stiffness of spring; F_S = spring force; h = lift of valve head; p = pressure on valve; p_l = limiting pressure just sufficient to open the valve; p_i = intermediate pressure upon opening of valve; p' = pressure after opening of valve; p_0 = atmospheric pressure; A_v = surface area of valve opening; A_a = additional surface area.
Valve closed: $F_S = s \cdot d > p \cdot A_v$, $h = 0$
Valve just open: $F_S = s \cdot d \leq p_l \cdot A_v$, $h \approx 0$
Valve opening fully: $F_S = s(d + h) < p \cdot A_v + p_i \cdot A_a$, $h \to h_l$
Valve fully open: $F_S = s(d + h_l) = p'(A_v + A_a)$, $h = h_l$ (new equilibrium position)

The result is an intermediate pressure p_i, because the valve head throttles the outlet. This intermediate pressure acts on the additional surface A_a of the valve head and produces a supplementary opening force that offsets the elastic force of the spring F_S to such an extent that the valve head lifts rapidly. In the open state, a different intermediate pressure p' is set up and keeps the valve open. To close the valve, the pressure must be reduced considerably below the limiting opening pressure, because, the pressure is applied to a greater working surface area in the open state.

One application of this is the pressure switch for monitoring bearing oil pressure shown in Figure 7.66. If the bearing oil pressure drops below a certain value, the piston jumps open and the pressure inside the safety system is reduced with consequent shut-off of the endangered machinery.

The principle of bi-stability is also applied to the design of quick shut-off devices in which a striker pin under a spring preload has its centre of gravity slightly offset from the centre of rotation (see Figure 7.67). Once a limiting angular speed is reached, the striker pin begins to move against the spring preload. The resulting increase in the eccentricity of the centre of gravity leads to an increase in the centrifugal inertia force acting on the pin, which is flung out even without any further increase in the angular speed. For this to happen, however, the rate of increase in the centrifugal inertia force with x must be greater than that of the opposing spring force when the centre of gravity of the pin begins to move, see Figure 7.68. The forces must be equal in the limiting state ($\omega = \omega_l$). This can be achieved provided that:

$$\mathrm{d}F_c/\mathrm{d}x > \mathrm{d}F_s/\mathrm{d}x \quad \text{or} \quad m \cdot \omega_l^2 > s$$

Once it has been displaced to the outside, the pin strikes a catch which, in turn, activates the quick shut-off mechanism.

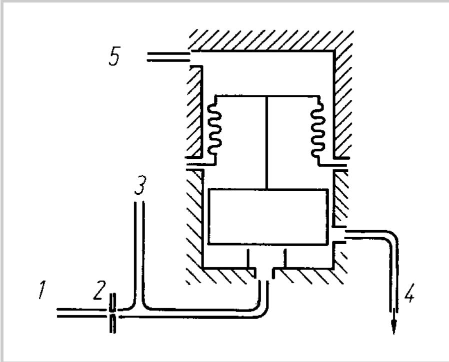


Figure 7.66. Diagrammatic sketch of a pressure switch used to monitor bearing oil pressure, after [7.225]. *1* Main oil system pressure: *2* orifice; *3* safety system activating quick shut-off valves; *4* drainage (no pressure); *5* bearing oil pressure

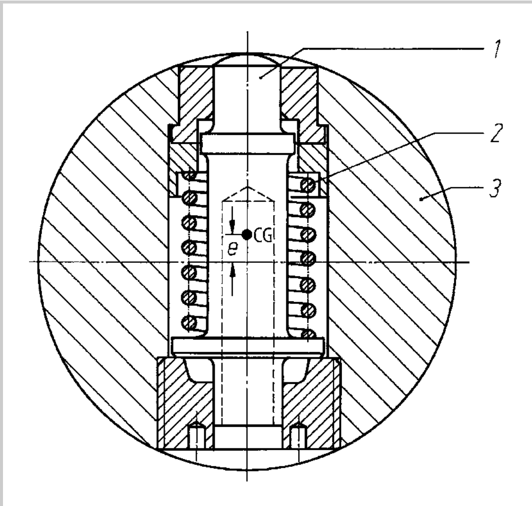


Figure 7.67. Quick shut-off pin *1* in shaft *3* with centre of gravity CG offset by *e*, and spring *2* holding the pin in the normal position, after [7.225]

7.4.5 Principles for Fault-Free Design

In high-precision products, in particular, but also for other technical systems, an embodiment should be sought in which the number of potential faults is minimised. This can be achieved by:

- designing a simple structure with simple components that have few close tolerances
- adopting specific design measures to minimise the causes of faults
- selecting working principles and working structures whose functions are largely independent of any disturbing effects, or which only have a low interdependency (see Section 7.3.1: basic rule of clarity)

- ensuring that any potential disturbing factors influence two parameters that compensate each other at the same time (see Section 7.4.1: principle of balanced forces).

Examples of this important principle [7.159,7.241,7.315] that result in simpler production and assembly and maintain product quality are: the elastic and adjustable

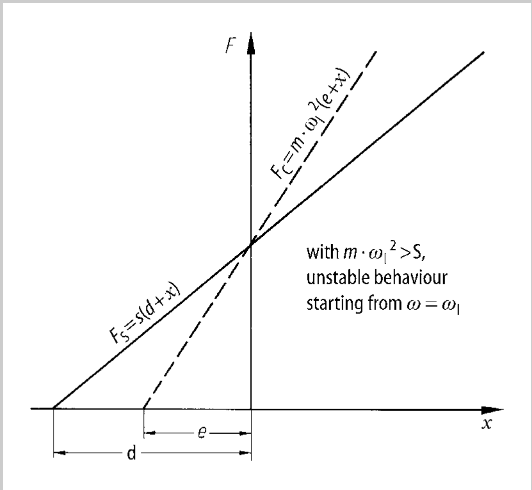


Figure 7.68. Graph of spring force and centrifugal inertia force against the displacement x of the centre of gravity of the quick shut-off pin (see Figure 7.67) . e = eccentricity of centre of gravity; d = spring precompression; ω_l = limiting angular speed beyond which the pin lifts off

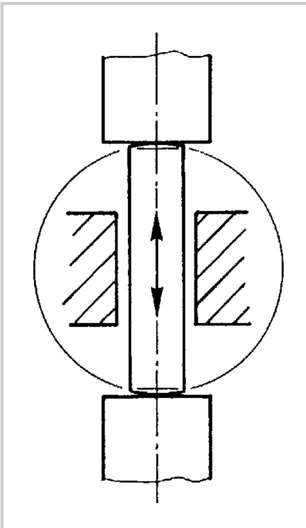


Figure 7.69. Link that is independent of play for the precise transfer of position [7.159]

configurations used in multigear gearboxes to balance out tooth tolerances (see Figures 7.45 and 7.47); the low stiffness of bolts and springs used to reduce the production tolerances in prestressed bolted connections and suspension systems; simple structures with few parts, low tolerances, and few toleranced joints; the possibility of adjusting and resetting to allow lower tolerances on individual components; the principle of stability (see Section 7.4.4).

Figure 7.69 shows a simple example: a compression link for the precise transfer of position. By making the ends of the link dome-shaped based on a shared spherical surface, the distance between the driving component and the receiving component remains the same despite any tilting of the plunger caused by any play in the guides [7.159].

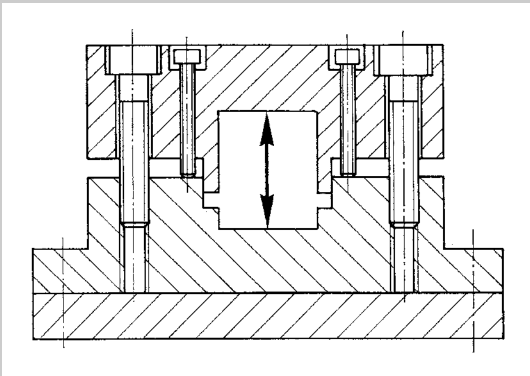


Figure 7.70. Continuous adjustment provided to maintain tight tolerances

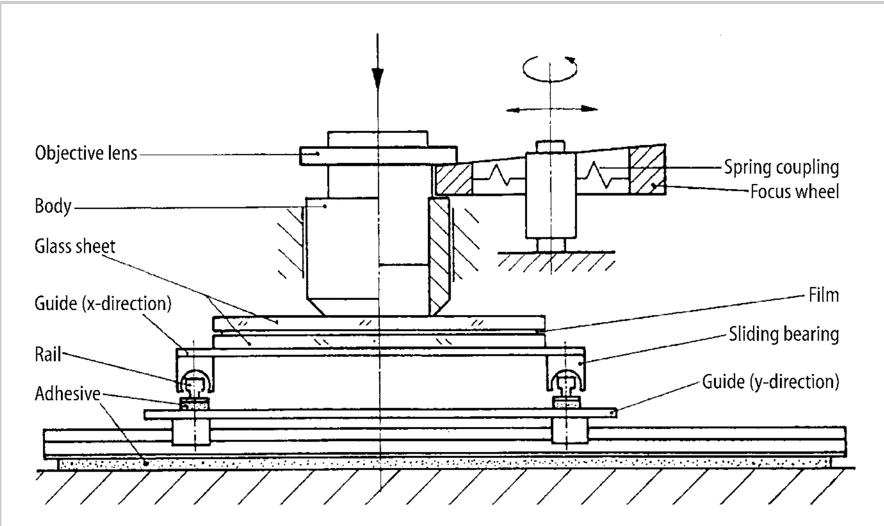


Figure 7.71. Automatically adjusting function chain in a microfiche reader

The example in Figure 7.70 illustrates how continuous adjustments can be incorporated to make it easier to maintain a volume with very tight tolerances in, for example, a split mould.

Figure 7.71 shows a further example. In a microfiche reader it is important to keep the objective lens perpendicular to the microfiche, which is held between glass plates. The usual solution is to mount the lens in a cylindrical body with tight tolerances, with its axis perpendicular to the glass surface. The solution in Figure 7.71, however, locates the cylindrical body directly on the glass plate and therefore automatically maintains it perpendicular to the surface of the glass.

7.5 Guidelines for Embodiment Design

7.5.1 General Considerations

In addition to the three basic rules of clarity, simplicity and safety derived from the general objectives (see Section 7.3), designers should also follow a number of embodiment design guidelines based on the general constraints set out in Section 2.1.7 and the checklist in Figure 7.3. These guidelines are internationally known as *Design for X*. They support the basic rules and help designers meet the specific requirements and constraints.

In what follows we cover the most important guidelines, without making any claims to completeness. Detailed discussions are dispensed with whenever summaries or special accounts have been published, to which the reader is referred.

This is the case for *design for durability* (stress requirements), and designers should refer to the literature covering the selection and design of machine elements [7.157, 7.165, 7.198, 7.275]. Special attention should be paid to changes in loading conditions with time and to the correct estimates of the level and type of the resulting stresses, as well as to the selection of the most suitable failure criteria. Damage-accumulation criteria help to improve service life predictions [7.16, 7.113, 7.116, 7.126, 7.247]. When determining stresses, stress concentrations and/or multiaxial stress conditions should be taken into account [7.193, 7.276, 7.284]. Assessments of durability should be based on the material properties and the appropriate failure criteria [7.192, 7.274, 7.276, 7.298, 7.299].

When *designing to allow for deformation, stability and resonance*, designers should refer to the appropriate calculations in mechanics and machine dynamics: mechanics and strength problems [7.17, 7.165]; vibration problems [7.155, 7.176]; stability problems [7.217]; and Finite Element methods [7.335]. In Section 7.4.1 we dealt briefly with the problems of designing with due allowance for the deformation caused by the transmission of forces.

This book discusses in some detail the following embodiment design guidelines. Design to allow for expansion and creep—that is, temperature phenomena—are discussed in Sections 7.5.2 and 7.5.3; design against corrosion in Section 7.5.4; and design to minimise wear in Section 7.5.5. Design for ergonomics is discussed in Section 7.5.6 and for aesthetics in Section 7.5.7; design for production and assembly, including quality control and transport, is dealt with at some length in Sections 7.5.8 and 7.5.9; and design for maintenance in Section 7.5.10. Design for recycling is discussed in Section 7.5.11; design for minimum risk in Section 7.5.12; and design to standards in Section 7.5.13.

7.5.2 Design to Allow for Expansion

Materials used in technical systems tend to expand when they are heated. The resulting problems must be taken into consideration, not only in the design of thermal devices in which higher temperatures must be expected as a matter of course, but also in high-performance engines and devices in which frictional heating can occur and special cooling is employed. As a result, several areas will be affected by local heating. Moreover, devices whose environmental temperature fluctuates significantly will only work properly if the physical effects of thermal expansion have been allowed for in the design [7.202, 7.206].

Apart from the thermal effects of linear expansion, designers must also consider the purely mechanical extension of parts subjected to heavy loading. In principle, the guidelines also apply to this type of change of length.

1. Expansion

Expansion has been the subject of a host of special studies. For solid bodies, the coefficient of linear expansion is defined as:

$$\alpha = \Delta l / (l \cdot \Delta\vartheta_{\mathrm{m}})$$

where Δl = change in length (expansion) due to a temperature rise of $\Delta\vartheta_{\mathrm{m}}$, l = the length of the component under consideration, and $\Delta\vartheta_{\mathrm{m}}$ = mean temperature difference to which the body is subjected.

The coefficient of linear expansion defines the expansion of a solid along one coordinate axis only, while the coefficient of cubical expansion defines the relative change in volume per degree of temperature rise. For homogeneous solids, its value is three times that of the coefficient of linear expansion. Coefficients of expansion should be understood as mean values over a particular temperature range; they depend not only on the material but also on the temperature. At higher temperatures, the coefficient usually increases.

Figure 7.72 gives the coefficients of linear expansion for distinct groups of engineering materials. It shows that with commonly used combinations of metals, for example 35C carbon steel with austenitic (10C/18% Cr-Ni-Nb) steel, or grey cast iron with bronze or aluminium, great care must be taken to allow for relative expansions because of the significant differences in the coefficients of thermal expansion between the materials. With large dimensions, even relatively small differences between, say, 35C carbon steel and 13% chromium steel (10C/13% Cr) can cause serious problems.

Metals with a low melting point, such as aluminium and magnesium, have greater coefficients of thermal expansion than metals with a high melting point, such as

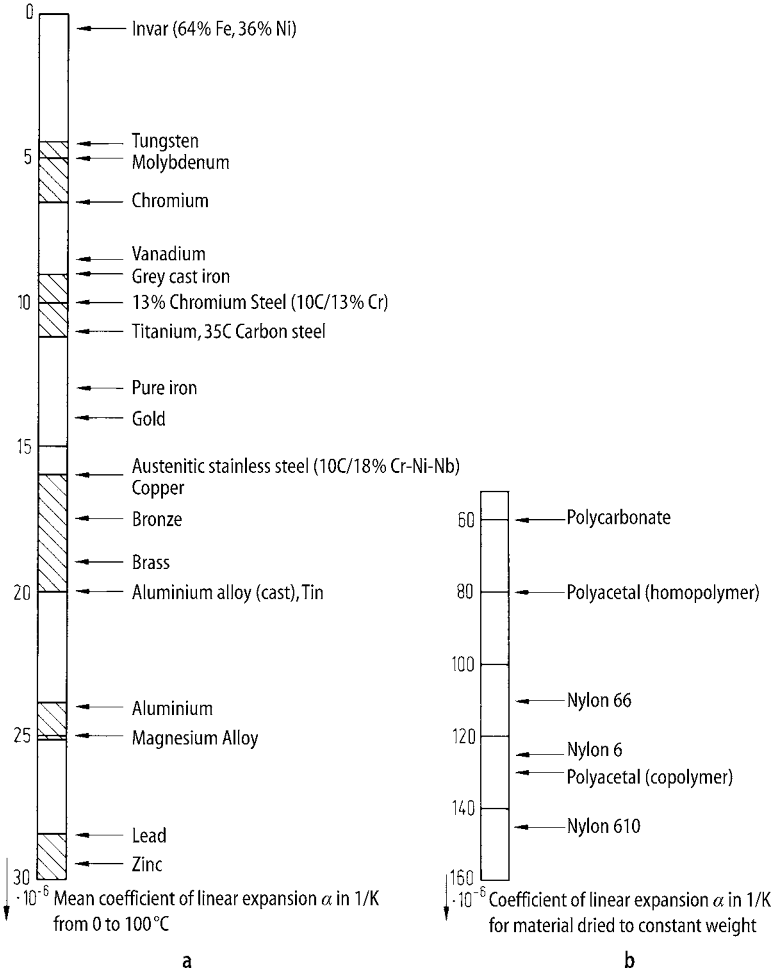


Figure 7.72. Mean coefficients of linear expansion for various materials: **a** metallic; **b** synthetic

tungsten, molybdenum and chromium. Nickel alloys have different coefficients depending on their nickel content. Very low values occur in the range of 32–40% by weight, with 36% Ni-64% Fe, known as "Invar", having the lowest coefficient. Synthetic materials have significantly higher coefficients of expansion than metals.

2. Expansion of Components

To calculate changes in length Δl, designers must know the temperature distribution (position and time) in the component and hence the mean temperature change with respect to the initial value. If the temperature distribution does not change with time, we speak of a *steady* or fixed expansion. If the temperature distribution changes with time, we speak of an *unsteady* or fluctuating expansion.

In the case of steady expansion, the physical quantities upon which the expansion of a component depends is obtained from the basic equations:

$$\Delta l = \alpha \cdot l \cdot \Delta\vartheta_{\mathrm{m}} \qquad \Delta\vartheta_{\mathrm{m}} = \frac{1}{l}\int_0^l \Delta\vartheta(x)\,\mathrm{d}x$$

The change in length Δl is therefore dependent on:

- the coefficient of linear expansion α
- the length l of the component
- the mean temperature change $\Delta\vartheta_{\mathrm{m}}$ over this length.

The value thus determined has a direct bearing on the design: every component must be clearly located and must only have as many degrees of freedom as are necessary for its proper functioning. In general, a point is fixed and the requisite translational and rotational movements are set by appropriate guides, for example slides, bearings, etc. A body in space (a satellite or helicopter) has three translational degrees of freedom in the x, y and z directions and three rotational degrees of freedom about the x, y and z axes. A sliding pivot (for example the nonlocating bearing of a shaft) provides two degrees of freedom: one translational and one rotational. A body clamped at one point (for example a built-in beam), on the other hand, has no degrees of freedom. Layouts based on these considerations alone do not, however, allow for expansion automatically, as we shall now demonstrate.

Figure 7.73a shows a body clamped at one point with no degrees of freedom. Upon thermal expansion it can expand freely from this point along the various axes. Figure 7.73b shows a plate that can be rotated about the z axis and thus has one degree of freedom. As shown in Figure 7.73c, this single degree of freedom can be simply removed by means of a slide. Were this plate to expand under uniform temperature increases, it would have to rotate about the z axis, for the slide does not lie in the direction of the expansion that results from the change of length in the x and y directions. If the slide allowed only translational movement and did not also act as a pivot, then jamming would occur. By fitting the slide in the direction of one of the coordinates (see Figure 7.73d), it is possible to avoid the rotation of the component.

After deformation due to thermal expansion, geometric similarity will only be maintained if the following conditions are met:

- The coefficient of expansion α must be constant throughout the component (isotropy), which can be taken for granted in practice provided that only one kind of material is used and that the temperature differences are not too great.
- The thermal strains ε along the x, y, z axes must be such that:

$$\varepsilon_{\mathrm{x}} = \varepsilon_{\mathrm{y}} = \varepsilon_{\mathrm{z}} = \alpha \cdot \Delta\vartheta_{\mathrm{m}} \text{ [7.196]}\ .$$

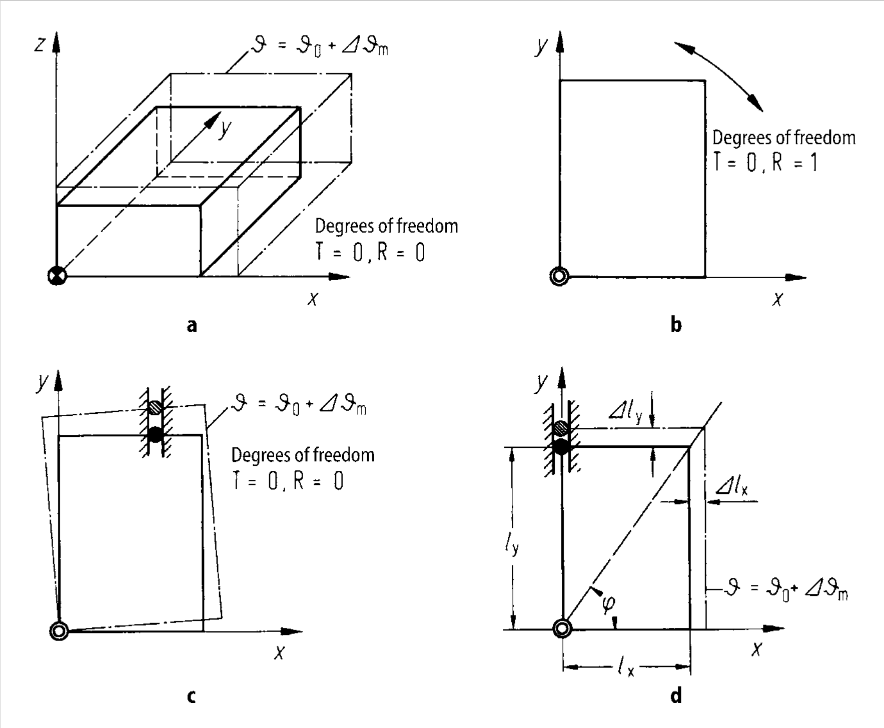


Figure 7.73. Expansion due to steady uniform temperature distribution. *Continuous line*: initial state; *broken line*: higher temperature state. **a** Body attached to a fixed point; **b** plate can rotate about the *z* axis, that is, it has one degree of freedom; **c** plate as in **b** but with single degree of freedom removed by an additional sliding pivot; **d** plate as in **b** but allowing for expansion without rotation. It would also be possible to use simple slides which might equally well be arranged along the *x* axis as along a line through the *z* axis inclined at $\tan\varphi = l_y/l_x$

If α is constant throughout a component, then the mean temperature increase must be the same for all three axes, so that we have:

$$\Delta l_x = l_x \cdot \alpha \cdot \Delta\vartheta_m$$
$$\Delta l_y = l_y \cdot \alpha \cdot \Delta\vartheta_m$$
$$\Delta l_z = l_z \cdot \alpha \cdot \Delta\vartheta_m$$

and for the *x* and *y* axes:

$$\tan\varphi = \frac{\Delta l_y}{\Delta l_x} = \frac{l_y}{l_x} \qquad \text{(See Figure 7.73d)}$$

- The component must not be subjected to additional thermal loads, which will not happen if, for instance, it is completely surrounded by a source of heat [7.183].

As a rule, however, different temperatures are measured in a single component. Even in the simplest case, with the temperature distribution changing linearly along the x axis (see Figure 7.74a), a change in angle is produced which, again, can only be taken up by a guide with a sliding as well as a pivoting movement. A simple slide, which allows translational movement with one degree of freedom, can only be used if the guide lies along the line of symmetry of the deformation (see Figure 7.74b). If this condition is not fulfilled, a further degree of freedom must be allowed.

Hence we obtain the rule that guides that take up thermal expansion and have one degree of freedom must only lie on a line through the fixed point, and this line must be the line of symmetry of the deformed state. The deformed state can be caused by load-dependent and temperature-dependent stresses, in addition to the expansion itself.

Since the stress and temperature distribution also depend on the shape of the component, the required symmetry line of the deformed state should, in the first instance, be sought both along the symmetry line of the component and also along that of the superimposed temperature field. However, as Figure 7.74b shows, this line of symmetry may not be easily identifiable from the component shape and the temperature distribution, so that the ultimate state of deformation must also be taken into account. That state, as we said earlier, may also be caused by external loads. To that extent, our remarks also apply to guides for components subject to large mechanical deformations. An example can be found in [7.8].

The following examples serve as further illustrations. Figure 7.75 is the plan view of a device whose temperature decreases from the centre to the periphery. It is supported on four feet. In Figure 7.75a, one of the feet is chosen as the fixed point. If the device is not to rotate or jam, the guide may only be placed along the line of symmetry of the temperature field, that is, on the opposite foot. Figure 7.75b shows a method of providing guides along lines of symmetry without a designated fixed point. The intersection of the lines through the guides constitutes an imaginary fixed point from which the device can expand evenly in all directions. In that case, two guides, for example *1* and *2*, could be omitted.

Figure 7.76 shows the location of inner casings in outer casings when a common centre must be maintained, as occurs, for instance, in turbines. If the deformed

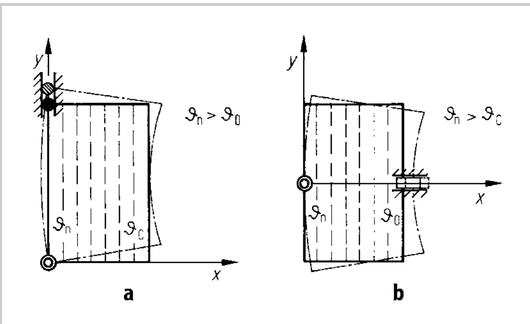


Figure 7.74. Expansion under nonuniform temperature distribution, here decreasing linearly along the x axis: **a** plate corresponding to Figure 7.73d, nonuniform temperature distribution produces deformation shown by *broken line*, sliding pivot required; **b** guide placed on symmetry line of deformed state so that a simple slide can be used

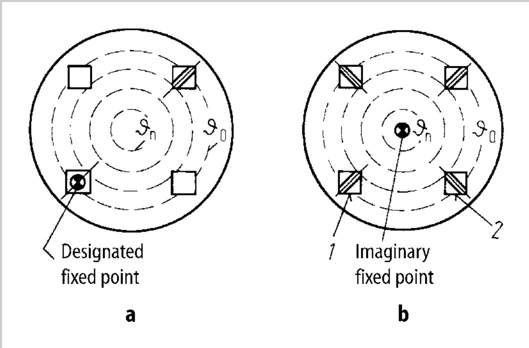


Figure 7.75. Plan view of a device mounted on four feet, whose temperature decreases from the centre to the periphery: **a** designated fixed point on one foot; simple slide along a line that is also the symmetry line of the temperature field; **b** imaginary fixed point in the centre of the device formed by the intersection of the lines of expansion

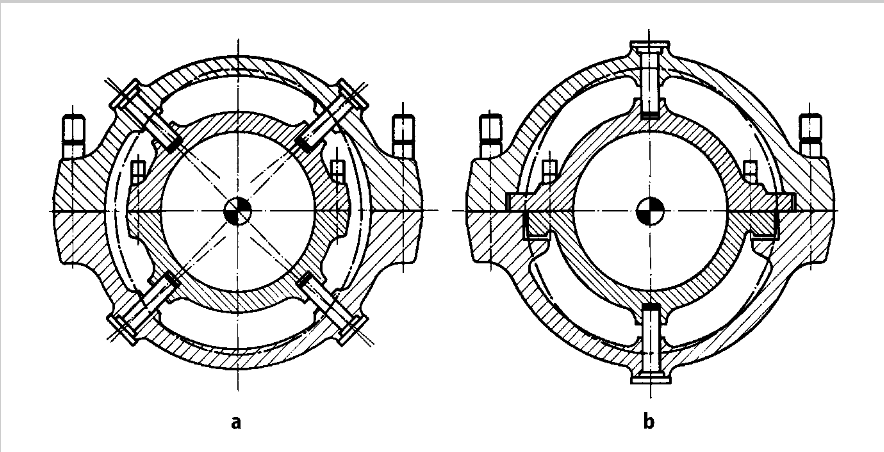


Figure 7.76. Location of inner casings in outer casings: **a** arrangement of guides does not allow for expansion: oval deformation of the housings can cause guides to jam; **b** arrangement allowing for expansion: guides lie along symmetry lines, no jamming with oval deformation

shape of these components is not completely rotationally symmetrical, then the guides must be placed on the lines of symmetry to prevent jamming of the guides due to, say, oval deformation of the casings (see Figure 7.76b). Such oval deformation is caused by temperature differences in the housing wall and flange, especially during the warm-up phase. The imaginary fixed point lies on the longitudinal axis of the casing or shaft.

Figure 7.77 shows an austenitic steel high-temperature steam inlet pipe *a* which must be fitted into a ferritic steel outer casing *b* while protruding into a ferritic steel inner casing *c*. Because of marked differences in the two coefficients of expansion and also because of the considerable temperature differences between the components, particular attention must be paid to relative expansion. An imaginary fixed

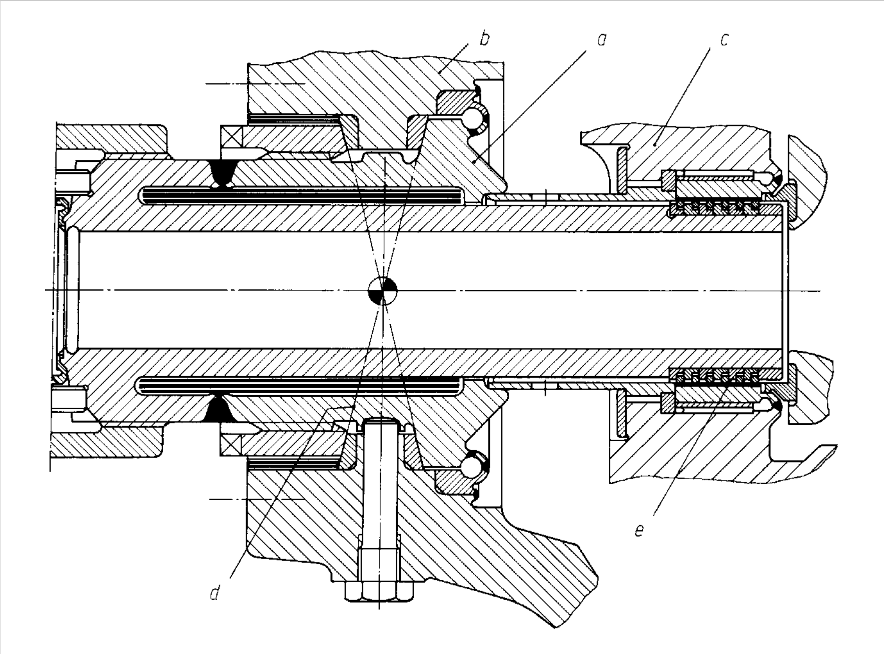


Figure 7.77. Inlet pipe *a* of a steam turbine made of austenitic steel that takes the steam through the ferritic steel outer casing *b* to the inner casing *c*. Expansion planes through guideways *d* determine an imaginary fixed point. Piston ring seals at *e* permit the axial and radial expansion of the end of the inlet pipe (BBC)

point is provided by the rotationally symmetrical guides *d*, an arrangement ensuring the unimpeded expansion of the austenitic component along any line through the imaginary fixed point. Because the temperature distribution at that point is fairly uniform, the respective radial and axial expansions produce an expansion along the indicated lines.

By contrast, the insertion of the inlet pipe into the inner casing must allow independent expansion along two axes, because the fixed point of the inlet pipe and the fixed point of the inner casing are not identical and no definite temperature distributions can be assigned to the components. The double degree of freedom is obtained with the help of the piston-ring seal *e*, which permits independent axial and radial movements of the inlet pipe.

3. Relative Expansion of Components

So far we have considered expansion in a relatively stable environment. Very often, however, the relative expansion of two (or more) components has to be taken into account, especially in the case of mutual loadings or when certain clearances must be maintained. If in addition the temperature varies with time, then designers are faced with a very difficult problem. The relative expansion of two components is:

$$\delta_{\mathrm{rel}} = \alpha_1 \cdot l_1 \cdot \Delta\vartheta_{\mathrm{m}_1(\mathrm{t})} - \alpha_2 \cdot l_2 \cdot \Delta\vartheta_{\mathrm{m}_2(\mathrm{t})}$$

Steady-State Relative Expansion

If the relative mean temperature difference does not vary with time, and if the coefficients of linear expansion are identical, then all that has to be done to minimise the relative expansion is to even out the temperature or else to select materials with different coefficients of expansion. Often both are necessary.

This can be seen in the case of a flanged connection consisting of a steel stud and an aluminium flange [7.200]. Because the aluminium has a higher coefficient of expansion, a temperature rise will increase the load on the stud, which may lead to failure (see Figure 7.78a). This can be prevented, on the one hand, by increasing the length of the stud and using a sleeve and, on the other hand, by using components with appropriate coefficients of expansion (see Figure 7.78b). If relative expansion is to be avoided altogether, then we must have:

$$\delta_{rel} = 0 = \alpha_1 \cdot l_1 \cdot \Delta\vartheta_{m_1} - \alpha_2 \cdot l_2 \cdot \Delta\vartheta_{m_2} - \alpha_3 \cdot l_3 \cdot \Delta\vartheta_{m_3}$$

With $l_1 = l_2 + l_3$ and $\lambda = l_2/l_3$, the relative length of sleeve to flange becomes:

$$\lambda = \frac{\alpha_3 \cdot \Delta\vartheta_{m_3} - \alpha_1 \cdot \Delta\vartheta_{m_1}}{\alpha_1 \cdot \Delta\vartheta_{m_1} - \alpha_2 \cdot \Delta\vartheta_{m_2}}$$

With steady-state expansion, $\Delta\vartheta_{m_1} = \Delta\vartheta_{m_2} = \Delta\vartheta_{m_3}$, and with steel ($\alpha_1 = 11 \times 10^{-6}$), Invar ($\alpha_2 = 1 \times 10^{-6}$) and aluminium alloy ($\alpha_3 = 20 \times 10^{-6}$) as the chosen materials (see Figure 7.78b), we have $\lambda = l_2/l_3 = 0.9$.

Designers will be familiar with the complicated expansion problems associated with the pistons of internal combustion engines. Here, the temperature distribution over and along the piston differs even in the near-steady

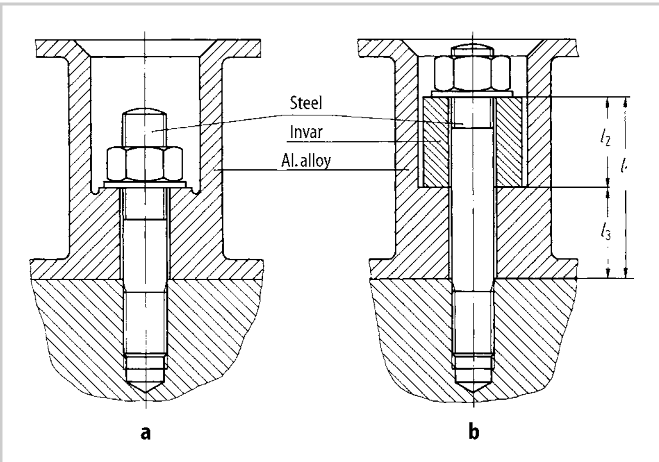


Figure 7.78. Connection by means of a steel stud and aluminium flange [7.200]: **a** stud endangered because aluminium flange has greater expansion; **b** incorporation of Invar expansion sleeve with a coefficient of expansion close to zero helps to balance the relative expansion of flange and stud

state and, what is more, differences in the coefficients of expansion of piston and cylinder must also be taken into account. One solution is the use of an aluminium–silicon alloy with a relatively small coefficient of expansion (smaller than 20×10^{-6}); of expansion-inhibiting inserts that are also good heat conductors; and of a flexible piston skirt. The bimetallic effect provided by steel inserts also helps to match the shape of the piston skirt to that of the cylinder [7.178] (see Figure 7.79). A further possibility is to make the piston oval-shaped.

If, on the other hand, the choice of materials is restricted in practice, then designers must rely on temperature adjustments. In high-power generators, for instance, large lengths of insulated copper rod must be embedded in the steel rotors. For insulation purposes alone, the absolute and relative expansions must be kept as small as possible. Here the only solution is to keep the temperature to a minimum by cooling [7.163, 7.317]. However, if these fast-running rotors have large dimensions, thermal imbalances may occur even though the temperature distribution is relatively uniform. The rotor, because of its complicated structure and the various materials that have gone into it, may not always (and at every point) display the same temperature-dependent behaviour. This can only be remedied if the expansions are kept under control by the carefully planned introduction of appropriate cooling or heating.

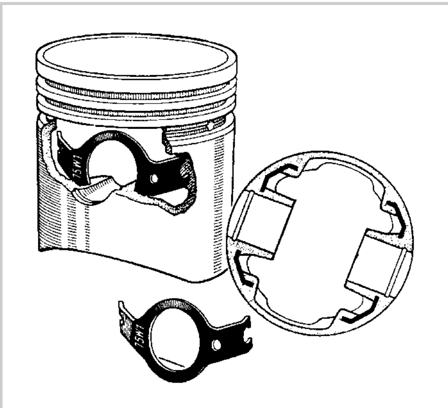


Figure 7.79. Piston of internal combustion engine made of aluminium–silicon alloy with steel inserts which inhibit circumferential expansion; moreover the bimetallic effect ensures optimum adaptation of the piston skirt to the cylinder (Mahle), after [7.178]

Unsteady Relative Expansion

If the temperature changes with time, for instance during heating or cooling processes, we often obtain a relative expansion that is much greater than that found in the final steady state. This is because the temperatures of the individual components can differ considerably. In the common case, where the components are of equal length and have equal coefficients of expansion, we have:

$$\alpha_1 = \alpha_2 = \alpha \text{ and } l_1 = l_2 = l$$
$$\delta_{\text{rel}} = \alpha \cdot l \left(\Delta\vartheta_{\text{m}_1(\text{t})} - \Delta\vartheta_{\text{m}_2(\text{t})}\right)$$

The heating of components has been examined by, among others, Endres and Salm [7.99, 7.236]. No matter whether we assume a step or linear change in temperature in the heating medium, the heating curve will be characterised by a time constant. If, for instance, we consider the temperature change $\Delta\vartheta_{\text{m}}$ of a component during a sudden temperature increase $\Delta\vartheta^*$ of the heating medium, then, under the admittedly approximate assumption that the surface and mean temperatures of the components are equal—which, in practice, is approximately true only for relatively thin walls and high thermal conductivity—we obtain the curve shown in Figure 7.80, with:

$$\Delta\vartheta_{\text{m}} = \Delta\vartheta^* \left(1 - \text{e}^{-\text{t}/\text{T}}\right)$$

Here t is the time and T is the time constant such that:

$$T = \frac{c \cdot m}{h \cdot A}$$

where:

c = specific heat of the component

m = mass of the component

h = heat transfer coefficient of the heated surface of the component

A = heated area of the component.

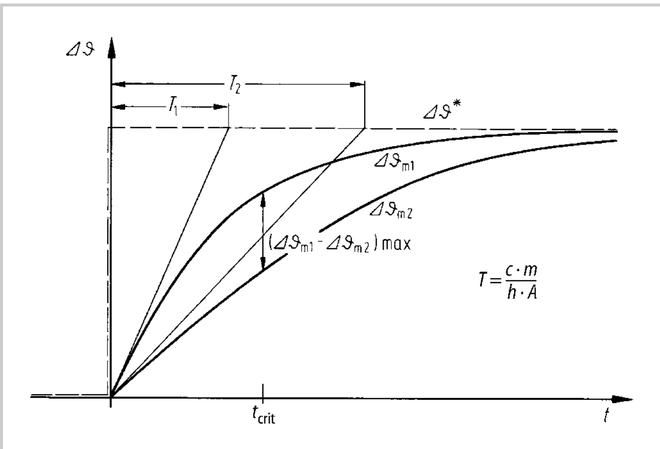


Figure 7.80. The effects on two components with different time constants of a step change in temperature $\Delta\vartheta^*$ in the heating medium

Despite the simplification involved, this approach may be considered to be fundamental. With two components that have different time constants, we obtain temperature curves that, at a given critical time, will have a maximum difference. At this point we have maximum relative expansion, and must provide clearances to accept the expansion or run the risk of excessive stresses beyond the yield point. Two identical temperature curves appear if the time constants of the two components can be equalised. In that case, there is no relative expansion. This objective cannot always be achieved, but in order to render the time constants approximately equal—that is, to reduce the relative expansion—the following relationship:

$$T = c \cdot \varrho \cdot \frac{V}{A} \cdot \frac{1}{h}$$

where V = volume of the component and ϱ = density of the component, can be used by designers to:

- adapt the ratio of the volume V to the heated surface area A, or
- adjust the heat transfer coefficient h by means of, say, lagging or selecting different cooling airflow rates.

Figure 7.81 gives the relationship V/A for a number of simple but representative bodies.

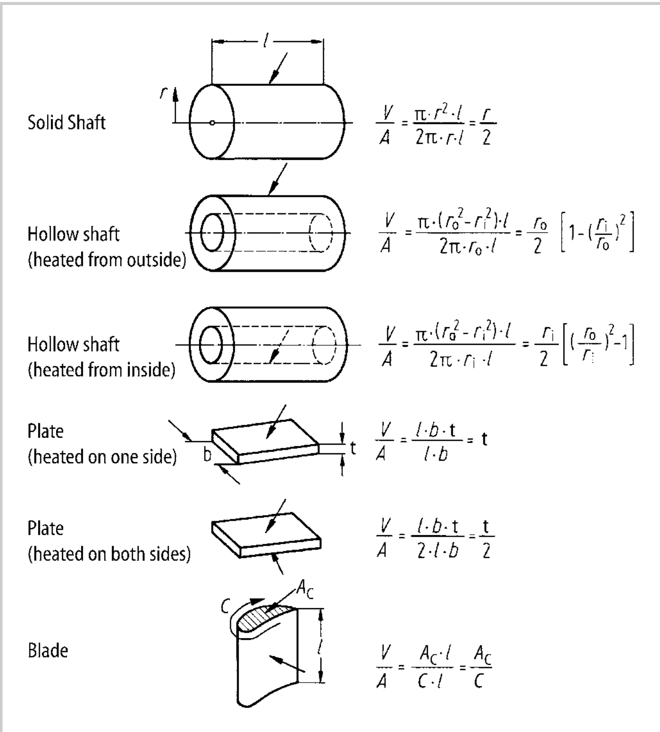


Figure 7.81. Volume–surface area relationships for various geometrical bodies; *arrows* point to heated surfaces

An example is shown in Figure 7.82. Here, the problem is to ensure adequate clearance for a valve spindle so that it can move safely and smoothly in its sleeve, even during temperature changes. In Figure 7.82a, the sleeve has been incorporated into the housing. When heated, the spindle will quickly expand radially, while the sleeve, which transfers its heat readily to the housing, remains cooler for a longer time. As a result, the clearance between the spindle and the sleeve will diminish dangerously.

In Figure 7.82b, the sleeves are sealed axially but can expand freely radially. Moreover, the volume-to-area ratio of the sleeves is such that the spindle and sleeves have the approximately equal time constants. As a result, the clearance remains more or less uniform at all temperatures and can therefore be kept small. The surface of the valve spindle and the inner surfaces of the sleeves are heated by steam leaks, so that we have:

$$(V/A)_{\text{spindle}} = r/2$$

$$(V/A)_{\text{sleeve}} = \left(r_o^2 - r_i^2\right)/2r_i$$

with $r_i = r$ and $(V/A)_{\text{spindle}} = (V/A)_{\text{sleeve}}$, we have

$$r/2 = (r_o^2 - r^2)/2r, \text{ and so}$$

$$r_0 = r \cdot \sqrt{2}$$

Figure 7.83 shows various steam turbine housings. With appropriate design, it is possible to adapt the volume-to-area ratios of the housings, the heat transfer coefficients and sizes of the heated surfaces to the time constants of the shafts and thus keep the blade clearances approximately constant when starting (heating) the

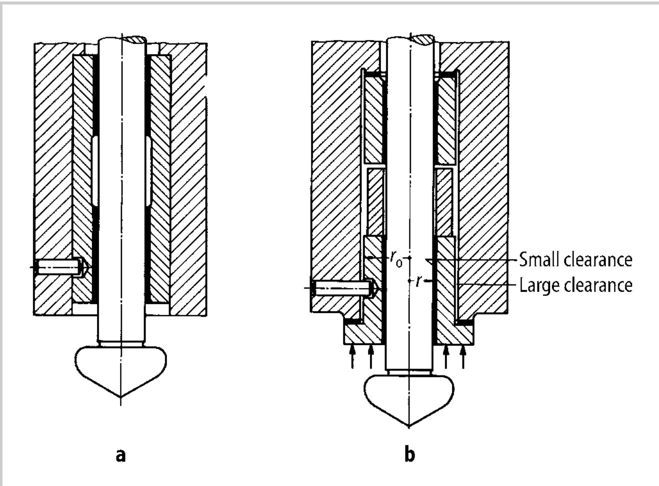


Figure 7.82. Spindle seals of steam valves: **a** fixed sleeve requires relatively large spindle clearance because it has not been designed to allow for expansion; **b** radially free and axially sealed sleeves permit small spindle clearance because spindle and sleeves have been designed to have the same time constant

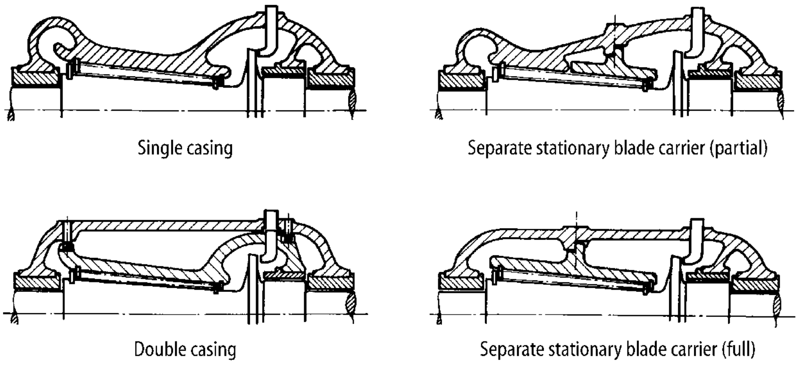


Figure 7.83. Steam turbine housings with different time constants

turbines. Another approach is to ensure that the relative expansion is such that the clearance increases rather than decreases during start-up.

There are several well-known methods for reducing the heat transfer coefficient of a component (for example by insulation), and thus for slowing down the heating and reducing the relative expansion.

The ideas we have just put forward are applicable wherever temperatures change with time, and particularly wherever relative expansion goes hand-in-hand with clearance reductions that are likely to endanger the functioning of turbines, piston engines and machines operating in hot environments.

7.5.3 Design to Allow for Creep and Relaxation

1. Behaviour of Materials Subject to Temperature Changes

When designing components subject to temperature changes, we must take into account not only the expansion effect but also the creep properties of the materials. The temperatures involved need not necessarily be very high, although they usually are. However, there are some materials that will, even at temperatures well below 100°C, behave in much the same way as metals do at very high temperatures.

Beelich [7.4] has examined this subject at some length, and in what follows we shall base ourselves largely on his findings.

Materials in common use, pure metals as well as alloys, have a polycrystalline structure and a temperature-dependent behaviour. Below a *critical temperature*, the stability of the intercrystalline bonds is largely independent of time, and the yield point can be used to determine the strengths of components. Components at temperatures above the critical temperature are strongly influenced by the time-dependent behaviour of the material. In this temperature range, materials will, under the influence of load, temperature and time, experience a gradual plastic deformation that, after a given period, may lead to fracture. The ensuing time-dependent fracture stress is much lower than the 0.2% proof stress at the same temperature determined by short-term experiments (see Figure 7.84). Critical temperature and creep strength depend largely on the materials used and both must be taken into consideration. With steels, the critical temperature lies between 300°C and 400°C.

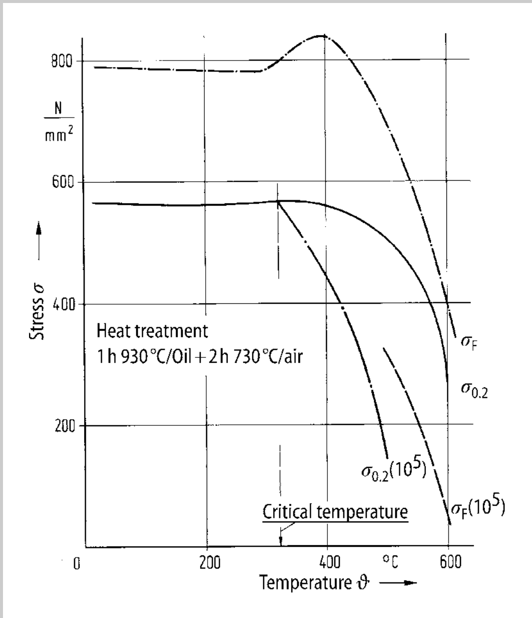


Figure 7.84. Characteristic values determined by high-temperature tensile strength and creep experiments with 21C/1.5% Cr-Mo-V steel at various temperatures; the critical temperature is the intersection of the curves of 0.2% proof stress and stress for 0.2% creep strain in 10^5 hours

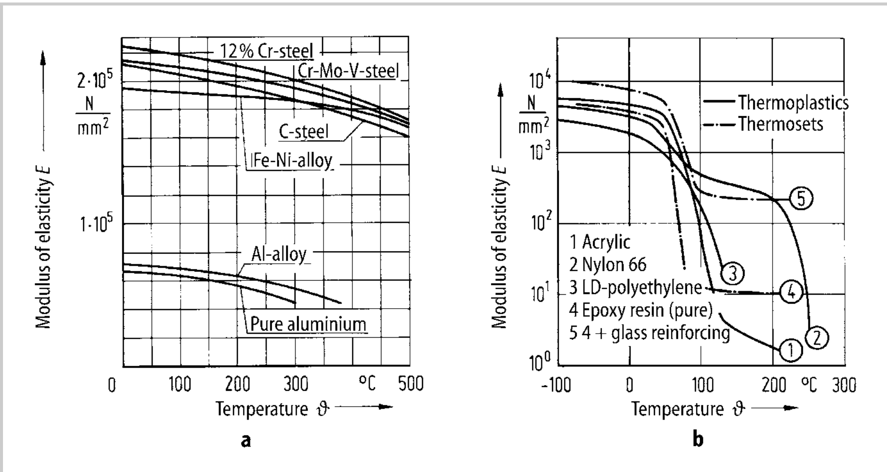


Figure 7.85. Relationship of modulus of elasticity to temperature for various materials: **a** metals, **b** synthetic materials

When working with synthetic materials, designers must allow for their viscoelastic behaviour, even at temperatures below 100°C.

In general, the modulus of elasticity changes inversely with the temperature (see Figure 7.85a). The smallest changes occur with nickel alloys. As the modulus of elasticity drops, so does the stiffness of the components—synthetic components in particular (see Figure 7.85b). In this case, designers must know the temperature at which the modulus of elasticity suddenly drops to relatively low values.

2. Creep

Components that are put under loads for long periods at high temperatures will, in addition to the strain given by Hooke's Law ($\varepsilon = \sigma/E$), also experience plastic deformation (ε_{plast}) with time. This property of materials, which is known as *creep*, depends on stress, the effective temperature ϑ and time.

We say a material creeps if the strain of a component increases under constant load or stress [7.4]. The creep curves of various materials are well known [7.110, 7.136].

Creep at Room Temperature

Before we can design components loaded to near the yield stress, we must know how they react in the transition region between the elastic and the plastic states [7.136]. With persistent static loads in this transition region, we can expect primary creep in metals even at room temperature (see Figure 7.86). The resulting plastic deformations are small and merely affect the dimensional stability of a particular component. In general, steels show little creep when subject to stress $\leq 0.75 \cdot \sigma_{0.2}$ or $\leq 0.55 \cdot \sigma_F$, whereas, in the case of synthetic materials, a reliable assessment of the mechanical behaviour can only be made by considering the temperature and time-dependent characteristics.

Creep Below the Critical Temperature

Previous studies [7.136, 7.147] of metals have shown that the customary calculations, based on high-temperature yield strength as the maximum permissible stress for short-term loads, additional thermal loads and load variations, suffice up to the critical temperature.

With components that must have high dimensional stability, however, the characteristics of the material determined by creep experiments must also be taken into account, even at moderately high temperatures. Unalloyed and low-alloy boilermaking steels and even austenitic steels show varying degrees of creep depending on length of operation and working temperature.

Synthetic materials experience structural changes, even at slightly elevated temperatures. These transformations may lead to a marked temperature and time dependence of the properties of the materials, which is not the case with metals. In specific cases these changes are irreversible and referred to as thermal ageing [7.156, 7.185].

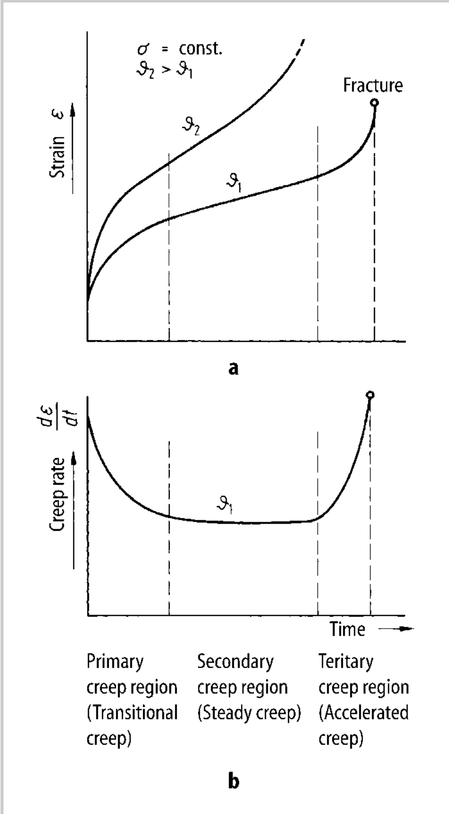


Figure 7.86. Strain **a** and creep rate **b** with duration of load (schematic representation); characteristics of the various creep phases

Creep Above the Critical Temperature

In this temperature region, mechanical loads will cause deformations in metals at far below the appropriate high-temperature yield strength, that is, the materials will creep. This creep leads to gradual deformation of components and can lead to loss of function and possible failure. In general, this process can be divided into three phases [7.136, 7.147] (see Figure 7.86). For components affected by temperature changes, the beginning of the tertiary creep phase must be considered dangerous. This region begins at approximately 1% permanent strain. Figure 7.87 shows the 10^5-hour creep strengths $\sigma_{1\%/10^5}$ at 500°C for various steels.

3. Relaxation

In loaded systems (springs, bolts, tension wires, shrink fits), the necessary preload produces an overall strain ε (elongation Δl). Because of creep and settling of the material due to plastic flow at the bearing surfaces and split lines, the ratio of

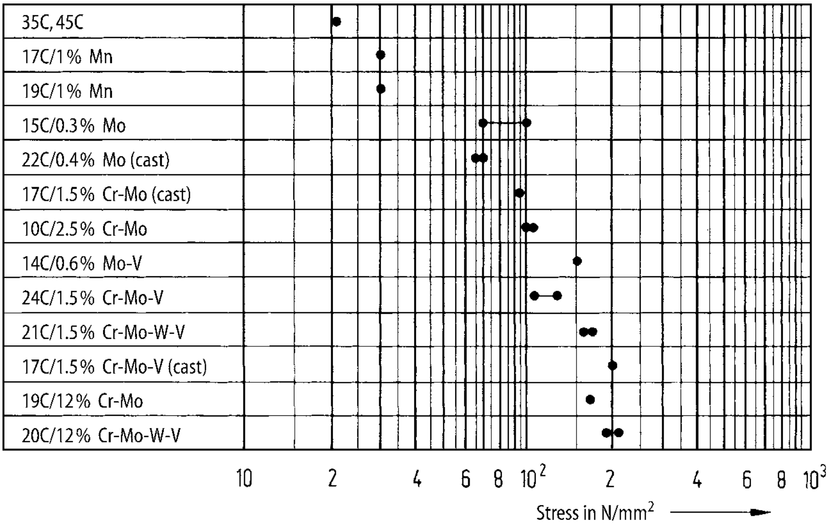


Figure 7.87. Stresses corresponding to a 1% permanent strain for various steels after 10^5 hours at 500°C [7.213]

plastic to elastic deformation gradually increases. The phenomenon of decreasing elastic strain at constant overall strain is called *relaxation* [7.100, 7.326, 7.327].

Loaded components are usually preloaded at room temperature. Because the modulus of elasticity varies with the temperature (see Figure 7.85), the preload decreases at higher temperatures, even without a change in length of the loaded system.

The preload remaining at operational conditions, though reduced, will lead to creep at high temperatures and hence to a further drop in the preload (relaxation). The residual clamping force is also affected by production and operation determined factors; for instance by the assembly preload, the design of the loaded system, the nature of the contact surfaces, and the influence of superimposed stresses (normal or tangential to the surface). Studies of the relaxation of bolted flanges [7.100, 7.326, 7.327] have shown that plastic deformation also occurs at the split lines and bearing surfaces (settlement) and in the threads (creep and settlement).

To sum up, we can say that, with metallic components:

- The drop in preload depends on the relative stiffness of the parts loaded against each other. The more rigid the connection, the greater the drop in the preload due to plastic deformation (creep and settlement).
- Although settlement can be appreciably offset during the tightening of bolted flanges or the assembling of shrink fits, designers should, where possible, provide for few but accurately machined surfaces (split lines, bearing surfaces).
- There is a temperature limit beyond which the material cannot be properly used. In addition, designers should always choose materials in which the ap-

propriate high-temperature yield point is not reached, even with superimposed operational stresses.

- In the short term, high initial preloads (initial clamping forces) give rise to higher residual clamping forces. In the longer term, the residual clamping forces become relatively independent of the initial preload.
- Joints that have already undergone relaxation can be tightened up if the toughness of the material permits. As a rule, creep of about 1%, which leads to the tertiary creep region, must not be exceeded.
- If joints are subjected to an alternating load in addition to the static preload, then, as experiments have shown, the amplitudes tolerated during relaxation-dependent decreases in the mean stress are considerably greater than those tolerated at constant mean stress. However, relaxation-dependent decreases in the mean stress will often lead to a loosening of the joint.

When using bolted joints made of synthetic materials, designers try to take advantage of their low electrical and thermal conductivity, their resistance to corrosion, their high mechanical damping, their small specific weight, etc. In addition, such joints must, of course, have the appropriate strength and toughness. Special attention must also be paid to preload decay, otherwise the functioning of the joints can be seriously impaired. Special studies [7.190, 7.191] have shown that in synthetic (unlike in metallic) materials:

- The preload remaining after a given time and at room temperature is determined by the material itself and its tendency to absorb moisture.
- Continual changes in the absorption and release of moisture have a particularly deleterious effect.

4. Design Features

In order to increase the potential life of components subject to long-term loads, designers must familiarise themselves with the behaviour of the materials involved over time. According to [7.136], it is dangerous to use short-term values to predict load responses for periods of 10^5 hours or longer.

It is impossible to avoid thermal stresses in all components by specifying the use of highly alloyed materials. Appropriate design features are often more useful than changing the materials.

The design must enable creep to be kept within permissible limits, which can be done by means of:

- a high elastic strain reserve, which helps to minimise additional loads due to temperature fluctuations (see Figure 7.88)
- insulation or cooling of components, as in double-casing steam turbines and gas turbines (see Figure 7.89)
- the avoidance of mass concentrations which, in unsteady processes, may lead to increased thermal loading

- the prevention of creep in unwanted directions, which can cause functional failure (for instance the jamming of valve spindles) or dismantling problems (see Figure 7.90).

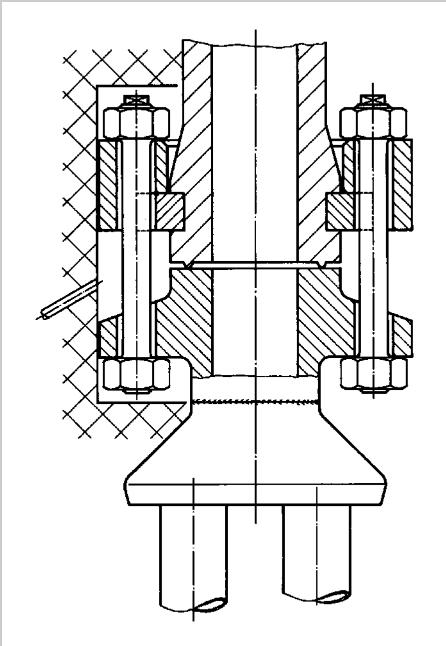


Figure 7.88. Austenitic–ferritic steel flanged joint intended for operating temperatures of 600°C [7.265]

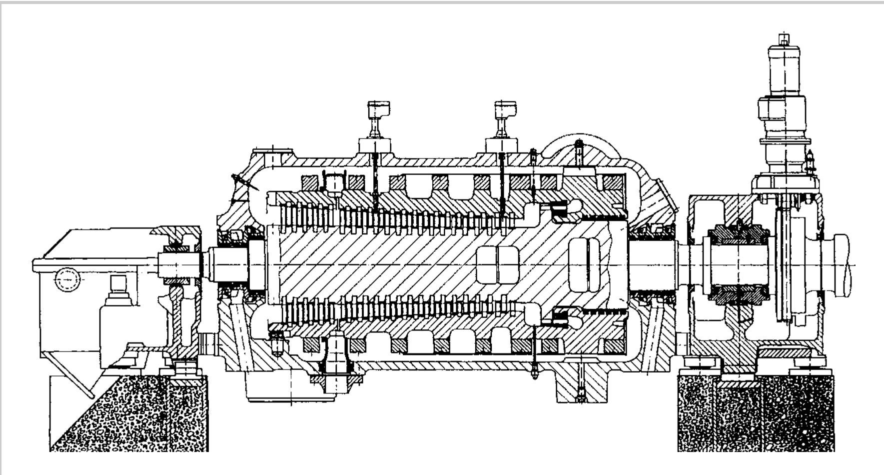


Figure 7.89. Double-casing steam turbine with shrink rings that hold the inner casing together. Relaxation of the shrink rings is reduced by cooling with exhaust steam. As the machine increases its output, the shrink rings exert an increasing pressure thanks to growing temperature difference between the steam inlet and outlet. The shrink rings are seated on heat-inhibiting segments which, with the help of shims, permit the original shrink fit to be restored after relaxation (ABB)

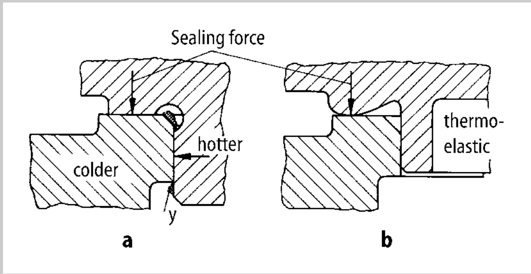


Figure 7.90. Centering and sealing of a cover [7.206]. **a** Dismantling is impeded because the material creeps into the relief groove and at y; **b** convex sealing edge provides a better seal with smaller sealing force. Creep does not impede dismantling thanks to improved design

In Figure 7.90a, the material of the cover creeps into the relief groove. The cover, which heats up more quickly, presses against the centering surface and also creeps at point y. The cover shown in Figure 7.90b is a better design since, despite the creep, it can be dismantled easily. In addition, the cover has been made hollow so that it cannot exert a significant radial force on the centering surface. In other words, the part which is moved during dismantling should not project axially beyond the fixed part [7.206].

7.5.4 Design Against Corrosion

It often happens that corrosion can only be reduced, not completely avoided. Rubo [7.235] emphasises the use of components with the same corrosion resistance in a machine. The use of corrosion-proof materials throughout may not be economic, in which case suitable embodiments can be used to retain functionality despite corrosion. This suggests a shift from focusing on corrosion protection to designing machines and their components to be corrosion tolerant. It follows that designers must tackle corrosion with appropriate concepts or special embodiment design features. The measures they take will depend on the type of corrosion anticipated. An extensive description of the types of corrosion and many useful design features are provided in the guidelines on design against corrosion in [7.158]. Spähn, Rubo and Pahl [7.212, 7.261] describe various types of corrosion and their remedies, and the following remarks are largely based on their findings. In order to provide a systematic categorisation from a design viewpoint, these are set out slightly differently from DIN 50900 [7.80, 7.81].

1. Causes and Effects of Corrosion

While the formation of metal oxide layers in dry environments and at higher temperatures tends to increase chemical resistance to corrosion, relatively weak electrolytes are formed in conditions below the dew point, and these generally lead to electrochemical corrosion [7.260]. Corrosion is also fostered by the fact that different components have contacting surfaces with different properties, for instance due to the inclusion of various noble or base metals, to differences in crystalline structure, and to residual stresses set up, for instance, by heat treatment and welding. In addition, wherever the design calls for slits or holes, local differences in electrolyte concentration appear, even in the absence of clear differences in electric potential, due to the use of different materials.

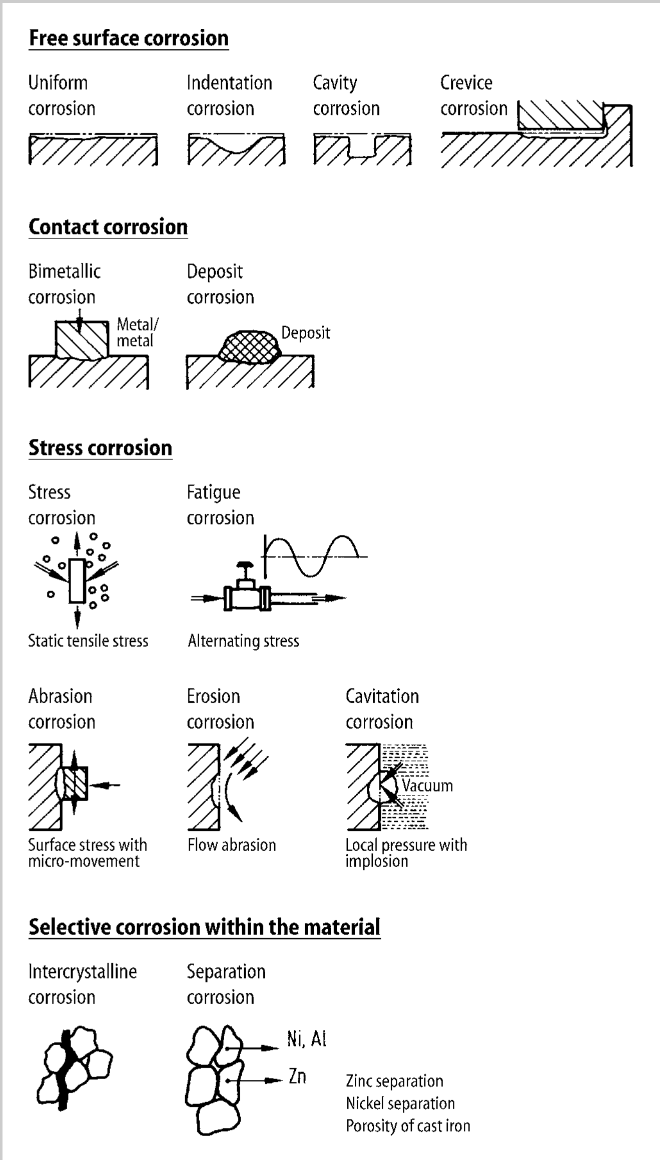


Figure 7.91. Types of corrosion

According to [7.80, 7.212] (see Figure 7.91) we must distinguish between:

- free surface corrosion
- contact corrosion
- stress corrosion
- selective corrosion within the material.

The preventive measures depend on the respective causes and effects. Various examples are given in the following sections.

2. Free Surface Corrosion

The corrosion of free surfaces can be uniform or locally concentrated. The latter is particularly dangerous because, in contrast to uniform corrosion, it leads to high stress concentrations and is often difficult to predict. It is, therefore, necessary to pay particular attention right from the start to potential danger zones.

Uniform Corrosion

Cause:

The presence of moisture (weak electrolytes) combined with oxygen from the air or the contacting medium, particularly below the dew point.

Effects:

Extensive uniform corrosion of the surface—in steel, for instance, approximately 0.1 mm per annum in a normal atmosphere. Sometimes more pronounced locally, especially in zones frequently kept below the dew point and hence subject to moisture concentration. Uniform corrosion is fostered by a more aggressive medium, higher flow velocity, and local heat transmission.

Remedies:

- Provide uniform service life by means of appropriate wall thicknesses and materials.
- Select a concept that obviates corrosion or makes it economically acceptable (see Example 1 below).
- Use small and smooth surfaces involving geometrical shapes with a maximum volume-to-surface area ratio (see Example 2 below).
- Avoid moisture traps (see Figure 7.92).
- Avoid temperatures below the dew point by good insulation and prevent hot or cold bridges (see Example 3 below).
- Avoid flow rates greater than 2 m/s.
- Avoid areas of high and differing thermal loads on heated surfaces.
- Apply a protective coating [7.82], possibly in conjunction with cathodic protection.

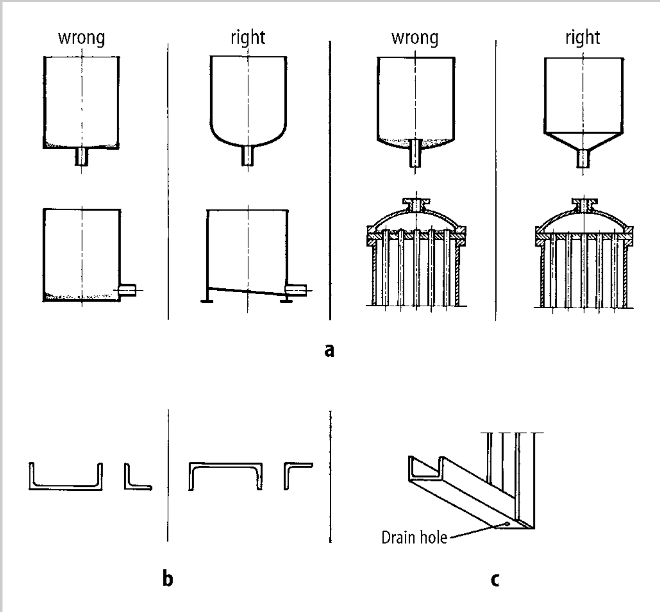


Figure 7.92. Drainage of components susceptible to corrosion: **a** design of bases encouraging and impeding corrosion; **b** wrong and right arrangement of steel sections; **c** brackets made of channel section with drain-hole

Indentation Corrosion

This type of corrosion is not uniform over the surface.

Cause:

There are components [7.81] with anodic and cathodic areas that cause differences in the rate of corrosion. These differences are usually caused by inhomogeneous material, by a medium with varying concentrations, and by local influences such as temperature and radiation.

Remedies:

- Remove inhomogeneity and varying influences.
- Provide a protective coating. Damage to this coating, however, will cause strong local corrosion (see cavity corrosion).

Cavity Corrosion

Cavity corrosion is concentrated on small surfaces with relatively deep indentations, with the depth being at least as great as the width. A clear distinction between indentation and cavity corrosion is not always possible.

Cause:

Similar to indentation corrosion, but its occurrence is more localised.

Remedies:

Basically the same as for indentation corrosion, although particular attention should be paid to reduction and prevention.

Crevice Corrosion

Cause:

Most often, the accumulation of acidic electrolytes (moisture, aqueous medium) following the hydrolysis of corrosion products in crevices etc. In rust and acid-proof steels, there is a breakdown of passivity due to depletion of oxygen in a crevice. Typically this type of corrosion is caused by insufficient ventilation.

Effects:

Increased corrosion in hidden areas. Increased stress concentrations in areas that are, in any case, under greater stress. Danger of fracture or separation without prior warning.

Remedies:

- Provide smooth, crevice-free surfaces and connections.
- Provide weld seams without permanent crevices; use butt seams or through-welded fillet seams (see Figure 7.93).
- Seal crevices, for instance by providing protruding parts with moisture-proof sleeves or coatings.
- Enlarge crevices so that throughflow prevents the accumulation of moisture.

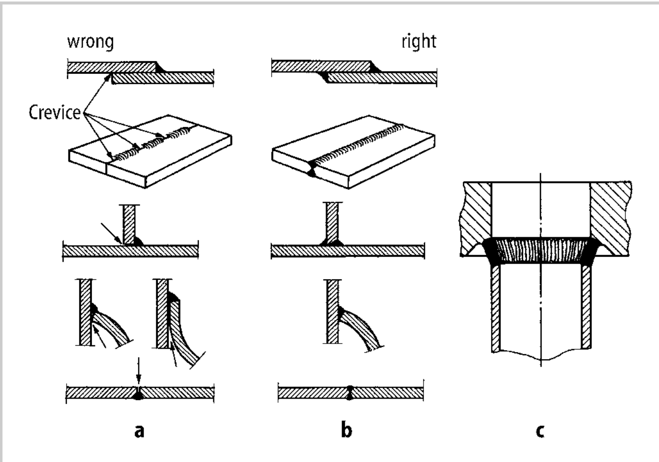


Figure 7.93. Examples of welded joints: **a** susceptible to crevice corrosion; **b** correct design, after [7.260]; **c** crevice-free welding of pipes, also improves resistance to stress corrosion cracking

3. Contact Corrosion

Bimetallic Corrosion

Cause:
The contact of two metals with different potentials in the presence of an electrolyte, that is, a conductive fluid or vapour [7.259].

Effects:
The baser of the two metals will corrode more rapidly than the nobler round the contact area, and this will occur more quickly for a smaller surface area (galvanic corrosion). Once again, the stress concentration is increased and corrosion products may be deposited. Such deposits have secondary effects of various kinds; for instance the production of sludge, contamination of the medium, etc.

Remedies:

- Use combinations of metals with small potential differences and hence a small contact current.
- Prevent action of electrolytes on the contact area by providing local insulation between the two metals.
- Avoid electrolytes altogether.
- If necessary, resort to planned corrosion by introducing still baser materials in the form of sacrificial anodes.

Deposit Corrosion

Cause:
Unwanted materials become deposited on the surface or in crevices and cause potential differences at particular locations. These deposits can come from existing corrosion, the surrounding medium, vaporisation residues, excess sealing material, etc.

Remedies:

- Avoid, filter, or collect the deposits.
- Prevent water traps, aim at smooth flow, maintain reasonable speed and self-drainage (see Figure 7.92a).
- Rinse or clean the components.

Transition Zone Corrosion

Cause:
Changes in the state of the medium or its components from the liquid to the gaseous phase and vice versa tend to increase the danger of corrosion of metallic surfaces in the transition zone. That danger may be increased further by encrustations in the transition zone [7.260].

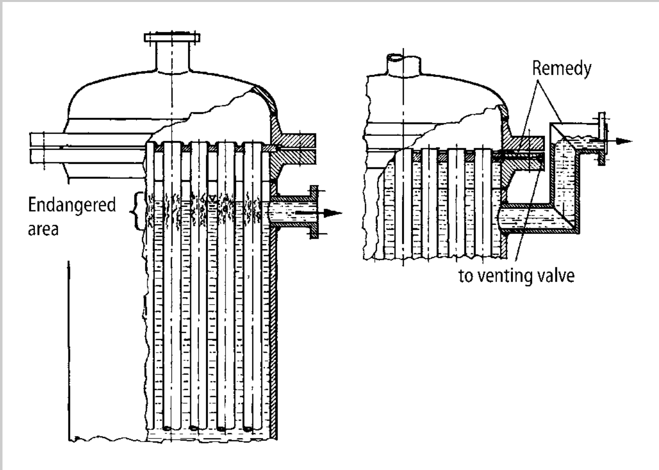


Figure 7.94. Increased corrosion at the transition from the gaseous to the liquid state, after [7.260] due to concentration of the medium in the region of the water line of a vertically arranged condenser. This can be remedied by raising the water level

Effects:

This type of corrosion is concentrated in the transition zone and is more pronounced with more sudden changes of state and more aggressive media [7.234].

Remedies:

- Gradually supply and remove heat using a heating or cooling element.
- Reduce turbulence, and hence heat transfer coefficients at the inlet of the affected medium, for instance by means of guide vanes.
- Provide corrosion-resisting jackets at critical points (see Examples 3 and 4).
- Avoid transition zone problems by appropriate design features (see Figure 7.94).
- Continuously change fluid level, for example by stirring.

4. Stress Corrosion

Components susceptible to corrosion are often mechanically loaded, either statically or dynamically. The mechanical stresses produced by these loads can cause several serious corrosion phenomena.

Fatigue Corrosion

Cause:

Corrosive attacks on a component subjected to mechanical fatigue loading appreciably reduce its strength. The greater the loading, the more intense the corrosion and the shorter the life of the component.

Effects:

Fracture without distortion, as in fatigue failure. Because the corrosion products, especially in slightly corrosive media, can only be seen under a microscope, this type of corrosion is often mistaken for normal fatigue failure.

Remedies:

- Minimise alternating mechanical or thermal stresses and especially avoid oscillatory stresses due to resonance phenomena.
- Avoid stress concentrations.
- Provide compressive stresses on the surface by shotblasting, roller burnishing, nitriding, etc., to increase the working life.
- Avoid contact with corrosive media (electrolytes).
- Provide surface coating (for example rubber, baked enamel, hot dip galvanisation, aluminium, etc.).

Stress Corrosion

Cause:

Certain sensitive materials tend to develop transcrystalline or intercrystalline cracks if static tensile stresses are combined with a specific trigger.

Effects:

Depending on the medium [7.260], various very fine and rapidly developing transcrystalline or intercrystalline cracks appear in the component. Adjacent parts are not affected.

Remedies:

- Avoid sensitive materials, which may not, however, be possible because of other requirements. These materials are: unalloyed carbon steels, austenitic steels, brass, magnesium, aluminium alloys and titanium alloys.
- Substantially reduce or completly avoid tensile stresses on the attacked surfaces.
- Introduce compressive stresses on the surface, for instance by shrink fits, by preloaded multilayer materials, or by shotblasting.
- Reduce residual tensile stresses by annealing.
- Apply cathodic coatings.
- Avoid corrosive influences by lowering the concentration and temperature.

Strain-Induced Corrosion

Cause:

Under repetitive large extensions or compressions, any protective outer layer cracks and opens repeatedly. This removes the protection and local corrosion will occur.

Remedy:
Reduce the magnitude of any extensions and compressions.

Erosion and Cavitation Corrosion

Corrosion may accompany erosion and cavitation, in which case the breakdown of the material is accelerated. The basic remedy is the avoidance or reduction of erosion and cavitation by hydrodynamic means or special design features. Only when this is not possible should such hard surface treatments such as metal spraying or hard chrome coating be considered.

Abrasion Corrosion

Cause:
Abrasive corrosion can be caused by relatively small movements between two surfaces subject to contact stresses (see also Section 7.4.1). Abrasion spots can appear, for instance, as a result of thermal expansion, or of pipes vibrating against their guides, etc. In either case, the oxidic protection layer on the surfaces of the rubbing parts may become damaged. Exposed metallic areas have a more negative electrochemical potential than those covered with a protective layer. If the fluid medium is an electrolyte, these relatively small exposed areas will be broken down electrochemically unless the protective layer can be regenerated.

Effects:
The affected surfaces form hard oxidation products (so-called abrasion rust) that speed up the process. At the same time, stress concentrations increase.

Remedies:
The most effective remedy is the removal of the abrasive movement, for example through elastic suspensions or hydrostatic bearings.
If the abrasive movement cannot be removed, the following measures should be adopted:

- Reduce the vibration of the pipes by reducing the flow velocity inside them and/or change the distances between the guides.
- Increase the gaps between the pipes and their guides so that no rubbing contact takes place.
- Increase the wall thicknesses of the pipes, thus increasing their stiffness and the tolerable corrosion rate.
- Use pipe materials that readily accept protective coatings.

5. Selective Corrosion within a Material

In the case of selective corrosion, only certain interfaces in the material matrix are affected. Of importance are:

- intercrystalline corrosion of stainless steels and aluminium alloys
- so-called “spongiosis”—graphite corrosion of cast iron when iron particles separate out
- dezincification of brass (zinc separation).

Cause:
Many material constituents or intercrystalline areas are less corrosion-resistant than the bulk material matrix.

Remedy:
Suitable selection of materials and their processing, such as adopting welding procedures which avoid producing a corrosion-sensitive material structure. Designers need to consult a materials expert when this type of corrosion is thought to be likely.

6. General Recommendations

In general, designers should aim at ensuring maximum and uniform lives for all components [7.234,7.235]. If it should prove economically impossible to meet these requirements with the appropriate choice of materials and layout, then designers must provide for the regular monitoring of all areas and components particularly prone to corrosion. This can done by visual inspection and regular measurements of wall thicknesses, directly by mechanical or ultrasonic methods and/or indirectly by means of corrosion probes that can be scrutinised and replaced at regular intervals.

Corrosion should never be allowed to proceed to the point where it threatens safety (see Section 7.3.3).

Finally, the reader is referred back to the principle of the division of tasks (see Section 7.4.2), with can enable even difficult corrosion problems to be solved. Thus, one component might provide protection against corrosion and provide a seal, while another provides support or transmits forces. As a result, the combination of high mechanical stresses with corrosion stresses is avoided, and the choice of materials for any one component becomes easier [7.207].

7. Examples of Design against Corrosion

Example 1

Lye is used to absorb CO_2 from a gaseous mixture under pressure, and the CO_2-enriched lye is then forced to surrender much of its CO_2 by expansion (regeneration). The position of the expansion chamber in a gas-washing plant is determined by the following factors.

If the lye were expanded immediately behind the washing tower (see Figure 7.95, point *A*) the pipework to *B* would have to withstand lower pressures and would therefore permit a saving in wall thickness. However, because of the release of

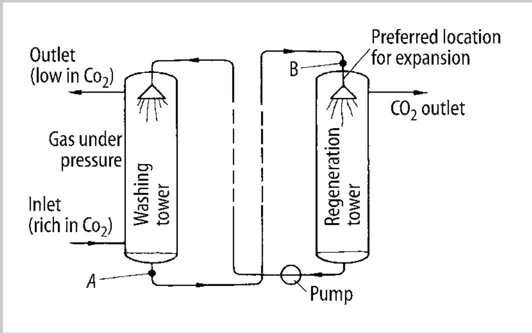


Figure 7.95. Influence of the point chosen for the expansion of CO_2-enriched lye on the choice of material for the pipework from A to B

CO_2, the aggressiveness of the lye permeated with CO_2 bubbles would increase to such an extent that the cheap unalloyed pipe steel commonly used would prove inadequate and hence have to be replaced with a more expensive rust- and acid-proof material. For that reason, it is far better to keep the CO_2-enriched lye under pressure until it enters the regeneration tower (point *B*).

Example 2

In this example, designers have to choose between two methods of storing compressed gases (see Figure 7.96): (a) 30 cylindrical containers, each with a capacity of 50 litres and a wall thickness of 6 mm; and (b) one spherical container with a capacity of 1.5 m^3 and a wall thickness of 30 mm. Solution (b) is less prone to corrosion for two reasons:

- The surface exposed to corrosive attack is approximately 6.4 m^2, which is about five times smaller than that in (a). In other words, less material is lost through corrosion to the same depth.

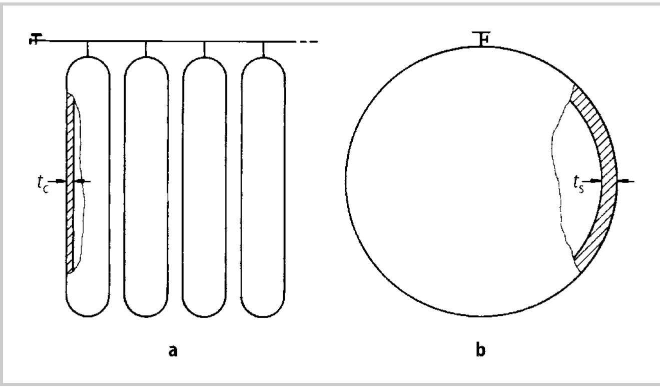


Figure 7.96. Influence of container shape on corrosion [7.234] for gases stored at 200 bar: **a** in 30 cylinders with a capacity of 50 litres each; **b** in a sphere with a capacity of 1.5 m^3

- For an anticipated corrosion depth of 2 mm in ten years, the loss of strength in (a) is such that the walls of the containers must be increased to a thickness of 8 mm, while corrosion to a depth of 2 mm in the 30 mm wall of container (b) is relatively insignificant. The spherical container can be dimensioned by considering strength requirements only and is therefore the better design of the two.

Example 3

Figure 7.97a shows a container holding a mixture of superheated steam and CO_2 [7.234]. The outlet is not insulated and cooling leads to the formation of a condensate with strong electrolytic properties. Corrosion will attack at the transition zone between the condensate and the gases, with the result that the outlet may break away.

Figure 7.97b shows a solution using insulation and Figure 7.97c one using separate components made of more durable materials.

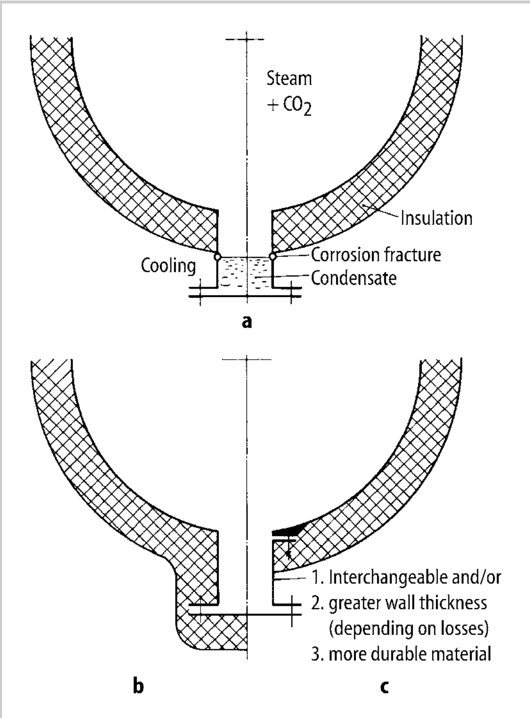


Figure 7.97. Outlet of a container for superheated steam and CO_2 under pressure: **a** original design; **b** insulated outlet avoiding condensation; **c** other corrosion-resistant variants with separate components

Example 4

In a heated pipe carrying moist gases, the inlet to the heated area is particularly prone to corrosion (see Figure 7.98a). A less sudden transition (see Figure 7.98b) or an extra protective sleeve (see Figure 7.98c) offer remedies.

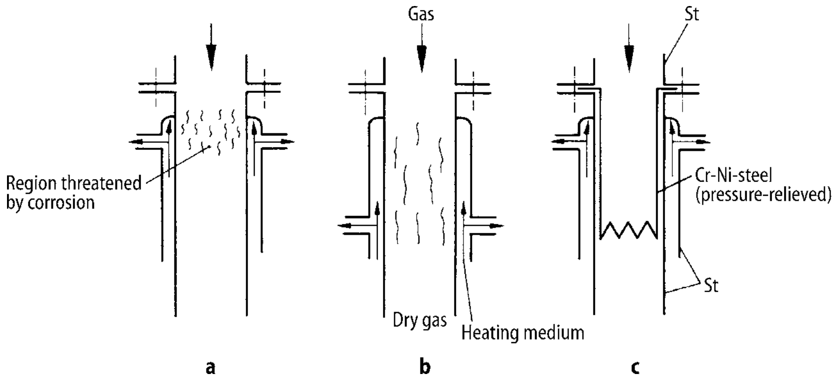


Figure 7.98. Corrosion in a heated pipe [7.234]: **a** severe corrosion at the inlet due to sudden transition; **b** sudden transition avoided; **c** protective sleeve covers critical zone and mitigates sudden transition

7.5.5 Design to Minimise Wear

1. Causes and Effects

The causes and effects of wear are many and complex. For a deeper understanding see the following literature: [7.28,7.121,7.153,7.258,7.314]. DIN 50320 [7.79] defines the types of wear and wear mechanisms. The main consequences of wear are shorter component lives, reduced functional performance, and higher losses. The most common and fundamental wear mechanisms affect component surfaces, in particular at the micro level. These mechanisms are described below.

Adhesive Wear

Adhesive wear is caused by high loading between two moving surfaces, which leads to microwelds (localised atomic binding) that are continuously broken by the relative movement between the surfaces. This results in surface damage and wear particles.

Abrasive Wear

Abrasive wear between components is caused by hard particles in the surface of one component (or in the medium) that micromachine (grind) the surface of the other component. This results in grooves and scoring in the direction of the relative movement. Mild abrasive wear can lead to a smoother surface and better surface mating; stronger wear leads to unacceptable surface damage.

Surface Disruption Wear

Surface disruption wear is caused by alternating mechanical stresses in the surface layers of the components. The effects are cracks, pitting, tears and wear particles.

Tribo-Chemical Wear

Tribo-chemical wear is caused by a chemical reaction between two components involving elements of the lubricant and/or the environment activated by friction (temperature increase). The effects are surface changes, such as hardened zones or wear particles. The latter in turn again increase the wear.

2. Design Features

Designing to minimise wear involves the application of tribological measures (system: material, working geometry, surface, lubricant/fluid) or material-related measures to minimise wear between loaded components subject to relative surface movements.

As with other effects, such as corrosion, the first step is to try to avoid the causes of the particular wear mechanism (*primary measures*); for example, by applying tribological measures to provide fluid friction between the moving surfaces and avoid dry or mixed friction. The elastohydrodynamic effect can, for example, provide fluid friction for sliding movements with the appropriate conditions for fluid viscosity, sliding speed and surface loading. If the layout or operating constraints do not allow this approach, a hydrostatic or magnetic solution might be chosen. In the case of small relative movements, the use of elastic joints should be considered.

When primary measures to remove the cause are not possible, *secondary measures* involving the materials and lubrication have to be applied to reduce the rate of wear. To reduce the wear rate, the local energy input due to the friction power per unit area, $p \cdot v_R \cdot \mu$, should be minimised by reducing the surface pressure (stress) p, the relative velocity v_R, and/or the coefficient of friction μ. Friction coefficients and wear coefficients for many common combinations of materials are provided in [7.28]. The wear coefficient is defined as:

$$\text{Wear coefficient} = \frac{\text{Sliding displacement} \times \text{Wear volume}}{\text{Normal force}}$$

When wear cannot be avoided, the following measures can prove helpful:

- Filter wear particles out of the fluid flow to avoid particle build-up and increased wear.
- Use the principle of the division of tasks (see Section 7.4.2) for structures with working surfaces that are in danger of wear; that is, the wear zones should be easy and economical to replace or be made out of a wear-resistant material.
- Allow the wear rate to be measured by using wear indicators and hence ensure operational safety and timely maintenance (see 7.5.10).

7.5.6 Design for Ergonomics

Ergonomics deals with the characteristics, abilities and needs of humans and, in particular, the interfaces between humans and technical products. A knowledge of ergonomics can lead to an embodiment that [7.173, 7.300]:

- adapts technical products to humans
- matches humans to products or activities by selection based on education and experience.

The range of technical products also includes domestic products and those used for hobbies and leisure.

The emphasis of ergonomic research is moving its focus from conventional physical activities in production facilities to working conditions in electronic industries and the design of user-friendly human–machine interfaces [7.56, 7.311]. This has, among other results, led to software tools for ergonomic workplace assessment and design [7.164].

1. Fundamentals

The starting point is the human being, where he or she is the operator, user or recipient. Humans can work with or be affected by technical products in many different ways (see Section 2.1.6). In this context it is helpful to address biomechanical, physiological and psychological issues.

Biomechanical Issues

The operation and use of products requires specific *body postures and movements*. These result from the spatial situation resulting from the embodiment of a product (for example the position and movement of controls) combined with the *body dimensions* [7.67]. This relationship can be represented and evaluated using templates of body dimensions [7.70] (see Figure 7.99).

The maximum forces humans can exert are given in [7.71]. To find the acceptable forces for a particular situation, however, also requires knowledge of frequency, duration, age, gender, experience and fitness, as well as knowledge of the methods used to calculate these influences [7.25, 7.127].

Physiological Issues

Body postures and movements resulting from the operation and use of technical products involve static and dynamic muscle actions. Muscle action requires the circulatory system to supply blood to the muscles based on the external loading. For static muscle action (for example when supporting a load), the blood throughput is throttled and recovery of the muscle is postponed. For this reason, large loads can only be sustained for short periods.

From an ergonomic point of view, it is important to distinguish between *loads, stresses and fatigue*. Loads are external influences. Loads produce stresses related to individual characteristics, such as age, gender, fitness, health, and training. The result of stress is fatigue, which depends on the intensity and duration of the stress. Recovery is achieved through *relaxation*. Fatigue-like situations, such as *monotony*, however, are not recoverable through relaxation but require a change of activity.

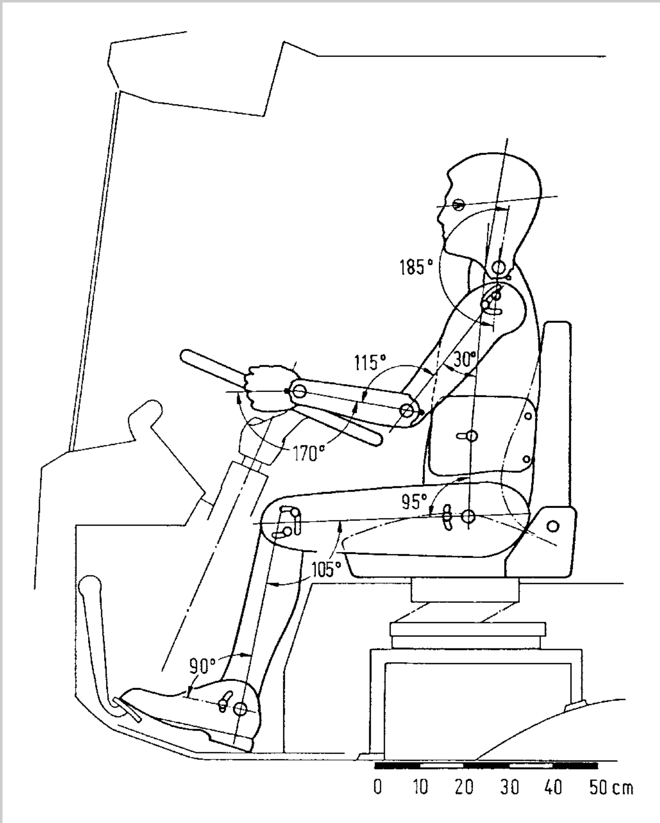


Figure 7.99. Application of a body template to evaluate the sitting position in a truck, after [7.70]

A further physiological requirement for human life and work is a normal body temperature of between 36°C and 38°C. Despite external *hot* and *cold situations*, and continuous heat generation within the body (increased during heavy work), the body temperature in the brain and other parts remains nearly constant because of the heat transferred by the blood. Working requirements and climatic influences have to be matched through technological measures, for example ventilation or organisational changes such as work breaks [7.68].

The *senses* also play an important role in work and leisure activities. Physiological variables involved in vision, for example, are minimum, optimum and maximum light density and light contrasts [7.44,7.45,7.69]. The variables related to hearing are noise level and noise differences [7.306], and these must be taken into account when designing acoustic warning signals in a noisy environment [7.69]. The relevant signals must be based on the sensor characteristics of human beings. No clear models exist for the processing of these signals in the nervous system and the brain. However, it is known that humans filter inputs to each of the sensors according to experience, interest, etc.

Psychological Issues

Several psychological issues have to be considered in the design of technical products. The use of sensors, for example, implies that the processing of the signals involves a series of steps that can be influenced in a variety of ways. Examples include optical illusions, not hearing or seeing unimportant things, and different interpretations. Guiding attention is therefore an important embodiment design guideline. This is true for the embodiment of control rooms [7.54], as well as for the placing of indicators and signs on products.

The process of sensing, deciding and acting usually proceeds undisturbed. When this process, which is partially unconscious, is disturbed, conscious thinking is used to bring certainty back into the process of perceiving, deciding and acting. In products where the structure and functionality cannot be seen from the outside, the cause of and remedy for unusual phenomena, such as disturbances, cannot be clarified by thinking. It is therefore necessary to convey the required information through sufficient and clear signs and through operating manuals. A well-designed product should minimise the thinking required for its operation so that thinking capacity can focus on the actual task. The requirement is for an obvious configuration; that is, one which during operation avoids thought processes that can be easily disturbed or are susceptible to errors. For example, the relation between the movement of a control and the resulting response should be obvious and simple.

Perception and thought focus on the actual action. Learning is defined as storing successful actions and knowledge for later use. For the operation and use of products, for example, one has to take into account that a series of actions learnt earlier may be reintroduced out of habit. Subsequent versions of a similar product should, therefore, avoid introducing unnecessary changes in operation or use; in particular, opposite movements or different positions for similar control actions should be avoided. Such changes must never be introduced if the consequences of an error could lead to direct or indirect safety risks.

Directing and constraining human activities excessively using technical or organisational systems can have a negative effect on motivation and behaviour, especially over a long period. All such activities should therefore leave space for free actions.

2. Human Activities and Ergonomic Constraints

Humans can be involved or affected by technical processes, either actively or passively. In an active relationship they can act and are deliberately involved in the technical product. That is, they execute certain functions such as activating, controlling, monitoring, loading, removing, registering, etc. In general, the following *repetitive* activities are undertaken in an activity cycle:

- Preparing for the activity, e.g. going to work.
- Gathering and processing information, e.g. observing and orienting, drawing conclusions, deciding on an action.

- Undertaking the activity, e.g. activating, connecting, separating, writing, drawing, talking, giving signs.
- Checking results, e.g. identifying status, checking measured values.
- Stopping the activity or starting a new one, e.g. cleaning, closing, going away, starting a new activity cycle.

When the involvement of human beings is functional—in other words, deliberate—then this involvement should be planned carefully and suitable arrangements made. This should start early in the design process, even when clarifying the task (see Chapter 5). It is often necessary to represent this involvement in the function structure (see Section 6.3).

Active Human Involvement

Whether it is sensible and useful to involve humans in technical systems has to be assessed from the viewpoints of *effectiveness, efficiency and humanity* (dignity and appropriateness). This initial and basic consideration influences and determines, to a large extent, the involvement of humans and thereby the solution principle. The following ergonomic aspects can be useful in the generation of solutions and as evaluation criteria [7.300] (see Table 7.4):

- Is human involvement necessary or desirable?
- Will the involvement be effective?
- Is involvement easy to achieve?
- Can the involvement be sufficiently precise and reliable?

Table 7.4. Ergonomic aspects for the requirements list and the evaluation criteria [7.300]

Active human involvement in a technical system intended to fulfil a task:

- necessary, desired
- effective
- simple
- fast
- precise
- reliable
- error-free
- clear, sensible
- learnable

Active or passive involvement through disturbing effects and side-effects on humans:

- tolerable stress
- low fatigue
- low annoyance
- no physical danger, safe
- no health risk or loss
- stimulation, change, holding attention, no monotony
- personal development

- Is the activity clear and sensible?
- Can the activity be learnt?

Only when the answers to these questions are positive should the involvement of humans in technical systems be considered.

Passive Human Involvement

Not only those actively involved, but also those passively involved will experience *disturbing effects* and *side-effects* from technical systems (see terminology in Section 2.1.6). The effects of energy, material and signal flows and the environment, such as vibrations [7.292], light [7.43–7.45], climate [7.68] and noise [7.306] are very important. These effects have to be identified early on so that they can be considered during the selection of the working principle and the development of the embodiment. The following questions can be useful and can also serve as evaluation criteria (see Table 7.4):

- Are distresses tolerable, and is the emerging fatigue recoverable?
- Has monotony been avoided, and is stimulation, change and attention ensured?
- Are annoyances or disturbances few or nonexistent?
- Has physical danger been avoided?
- Has health risk or loss been excluded?
- Does the work allow for personal development?

When these questions cannot be answered satisfactorily, then another solution should be selected, or the existing solution considerably improved.

3. Identifying Ergonomic Requirements

In general it is not easy for designers to immediately find satisfactory answers to the questions listed above. As described in Guideline VDI 2242 [7.300], the problem of identifying the most important influences and suitable measures can be approached in two ways, as discussed below.

Object-Based Approach

In many cases the technical system (object) that has to be ergonomically embodied is known and documented, e.g. a control panel, a driver's seat, a piece of office equipment, or an item of protective clothing. In such cases it is useful to apply the checklist in Part 2 of Guideline VDI 2242 [7.301]. It is also important to be sensitive to the particular requirements of the system under consideration and to make use of Table 7.5. Just reading the guidelines can be very instructive and can help clarify the issues. Concrete design features can be based on the insights acquired or obtained from the literature listed below.

Table 7.5. Characteristics used to identify ergonomic requirements [7.300]

Characteristics	Examples
Function	Division of functions, type of functions, type of activities
Working principle	Type and intensity of the physical or chemical effects, consequences such as vibration, noise, radiation, heat
Embodiment	
• Type	Type of elements, configuration, type of operation
• Form	Ergonomic overall form and elements, division based on symmetry and proportion, aesthetically pleasing
• Position	Configuration, arrangement, distance, direction of effect and visibility
• Size	Dimensions, working area, contact surfaces
• Number	Amount, division
Energy	Adjustment force, adjustment direction, resistance, damping, pressure, temperature, moisture
Material	Colour and surface finish, contact properties such as safe to touch, easy surface to hold
Signals	Labelling, text, symbols
Safety	Free of danger, avoiding danger sources and spots, inhibit dangerous movements, protective measures

Effect-Based Approach

In new situations—that is, when no system has been defined—it is useful to adopt the following approach instead. The effects related to existing and thus known energy, material and signal flows of technical systems are identified and compared with the ergonomic requirements. When there are limitations, intolerable loads or even dangers to safety, other solutions must be sought. Effects such as mechanical forces, heat and radiation are derived from the individual types of energy and the forms in which they appear. The material flow has to be checked to identify whether the suggested materials are flammable, easy to ignite, poisonous, cancer-causing, etc. For this purpose, Guideline VDI 2242 Part 2 [7.301] provides a checklist of effects, which gives an indication of existing problems and refers to literature with possible solutions.

The following literature are also useful:

Design of work space	[7.65, 7.72, 7.127, 7.172, 7.243, 7.300]
Work physiology	[7.53, 7.231]
Illumination	[7.20, 7.37, 7.43–7.45, 7.55]
Computer workplace	[7.52, 7.83, 7.84]
Climate	[7.68, 7.246]
Operation and handling	[7.24, 7.65–7.67, 7.70, 7.71, 7.78, 7.140, 7.195]
Vibration and noise	[7.31, 7.306, 7.310]
Monitoring and control	[7.69, 7.73, 7.74].

7.5.7 Design for Aesthetics

1. Aims

Technical products should not only fulfil the required technical functions as defined by the function structure (see Section 6.3) but also be aesthetically pleasing to their users. A considerable change has occurred recently in user expectations and in the way that products are judged.

VDI Guideline 2224 [7.296] focuses on the aesthetics of products. Starting with a technical solution, the guideline provides rules for the external form or shape; for example, it should be compact, clear, simple, unified, in line with function, and compatible with materials and with production processes.

In many products nowadays, aesthetics are as important as technical functionality. This is particularly true for products aimed at large markets and used directly by users in their daily lives. In such cases the emphasis is not only on aesthetics and use, but also on factors such as prestige, fashion and lifestyle. The forms—or better the embodiments—of consumer products are determined primarily by industrial designers, artists and psychologists. While ensuring the technical functionality, they select the forms, shapes, colours and graphics—that is, the overall appearance—based on human feelings and values. Expression and style play an important role; for example a military appearance may be applied to radio products, a space age look to lights, a safari image to cars, or a nostalgic feel to telephones. The body of a car, for example, is strongly based on artistic and psychological criteria and not only on technical criteria such as low air resistance and transportation efficiency.

It is clear that all of the requirements regarding function, safety, use and economy have to be fulfilled. The aim of designers, however, is to create products that appeal to customers. Given this aim, industrial design lies between engineering and art, and has to address ergonomic and visual issues in the same way as engineering design has to address function and safety issues. In addition, the company image has to be promoted in order to underline the individuality of its products. Such complex requirements suggest that the involvement of industrial designers should not be left until the end of the design process. They should be part of the design team and involved from the beginning of the task clarification phase. In special circumstances they can even help formulate the task or undertake preliminary design studies.

The result of this approach is a design process that proceeds from "outside to inside". Continuous collaboration between industrial designers and engineering designers is required to ensure that the requirements of appearance, expression and impression still allow the technical functions to be fulfilled within the forms and shapes created.

In this collaboration, engineering designers should not try to replace industrial designers, but should focus on developing the technical and economic aspects of the product. In the same way that technical solutions are developed, visual variants have to be proposed and evaluated, and models and prototypes made to decide on the final appearance of the product. When searching for solutions, the same methods as those described for the engineering design process can be used, such as brainstorming, stepwise development of variants through sketches, and systematic variation of configuration, form and colour.

Tjalve [7.280] gives a very clear example of such a development (see Figure 7.100). This clarity is evident throughout his book and illustrates the way in which form

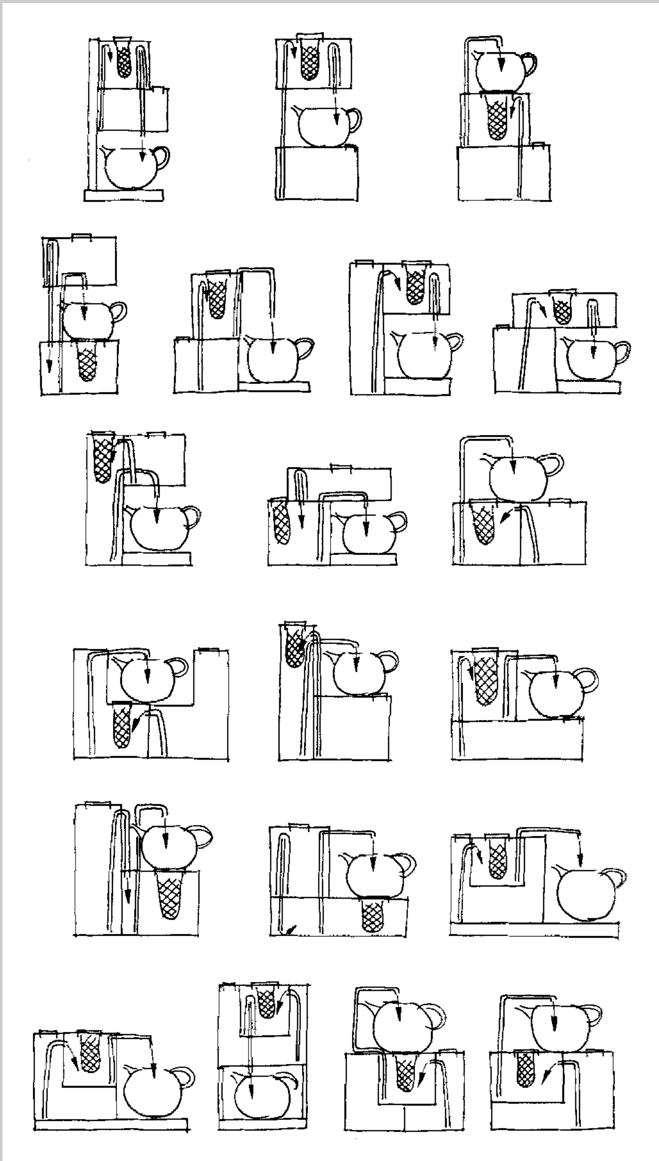


Figure 7.100. Systematic variation of the structure of an automatic teamaker (after [7.280]), investigating the configuration of the water kettle, the tea container and the teapot

and embodiment can be varied. He emphasises that the following factors influence each other and determine the appearance of the product:

- engineering (purpose, function, construction structure)
- production (process, assembly, cost)
- sales and distribution (packaging, transport, storage, company image)
- use (handling, ergonomics)
- disposal (recycling).

Seeger [7.251] underlines the close link between design for ergonomics and design for user-friendliness. Klöcker [7.152] focuses more on physiological and psychological aspects. In [7.252, 7.253] Seeger discusses the basic knowledge used for the development and embodiment of industrial products. Their appearance is developed from structure, form, colour and graphics. The impressions experienced by observers are of crucial importance. Information on this topic can be found in the literature from the partially overlapping areas of physiology, psychology and ergonomics. In his book entitled *Product Quality and Design* [7.111], Frick emphasises the importance of systematic collaboration between industrial and engineering designers in the context of an interdisciplinary development process. Using a series of examples, he proposes methods, procedures and tools to support such a collaboration.

2. Visual Information

In general, the technical function and the selected technical solution, together with its construction structure, determine the configuration and form and hence the appearance of assemblies and components. This results in a *functional embodiment* that is often difficult to change. An example of a simple functional embodiment is a spanner (lever arm and shape of bolt head), and a complex one is a dredger (kinematic requirements, shape of dredging buckets, power train, location of operator, etc.). Human beings not only see this functional embodiment but also other visual impressions, such as stability, compactness and a modern or striking appearance. They also expect information on operational procedures, safe areas, potential dangers, etc., which together form the *information presentation*.

In the embodiment design phase, the information presentation that is required or desired should be integrated with the functional embodiment. Based on Seeger [7.251], we list the essential information presentation areas and some related rules.

Market and User Information

When determining this type of information presentation, it is important to consider the type of user being addressed, such as technical expert, prestige seeker, nostalgia lover, and the avant-garde. In general, the overall appearance should be:

- simple, uniform and pure, and it should embody style
- structured and well-proportioned
- identifiable, definable and approachable.

Purpose Information

This information presentation should enable the purpose of the product to be easily recognised and understood. The outer shape, colouring and graphics should support identification of the functions and the actions involved, such as where a tool should be located and which parts exert forces.

Operation Information

The information presentation about the correct operation and intended use should:

- be centrally located and recognisable, for example control elements should have a function-related layout
- be ergonomically appropriate, in accordance with the action space of human limbs
- be labelled clearly, for example gripping and stepping areas
- identify the operational status
- use safety signs and colours [7.40, 7.42].

Manufacturer and Distributor Information

This information presentation expresses origin or house style. It contributes to continuity, confidence in known quality, involvement in the further development of successful products, and membership of a group. This can be achieved by easily recognisable and repeated elements, though the style and expression can be adapted to current fashions.

3. Guidelines for Aesthetics

Information presentation is achieved through specific and intended *expression*, such as lightness, compactness and stability, and by related *structure, form (shape), colour* and *graphics*. The following recommendations need to be considered (see Figures 7.101 to 7.103).

Select an Expression

- Provide a recognisable and uniform expression that creates an impression in the observer that is in accordance with the aim; for example an impression of being stable, light and compact.

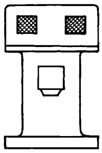
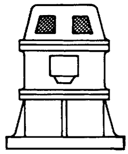
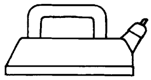
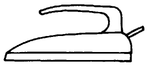
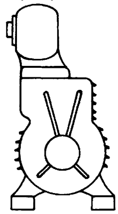
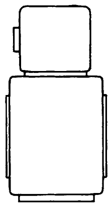
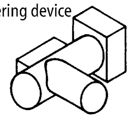
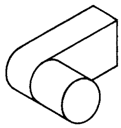
Embodiment Guidelines	Wrong	Right
Select an expression		
Provide a recognisable and uniform expression	Vertical three-phase AC motor  Unstable, top-heavy	 Stable, compact
	Iron:  Heavy, immobile	 Light, easy to handle
Structure the overall form		
Structure in a identifiable way	Vacuum pump  Unidentifiable	 Box shape
Divide into clearly distinguishable areas	Steering device  Unidentifiable	 Clear arrangement L-shape

Figure 7.101. Embodiment guidelines for aesthetics: expression and structure

Structure the Overall Form

- Structure in an identifiable way, such as in a block shape, a tower shape, an L-shape, a C-shape, etc.
- Divide into clearly distinguishable areas with identical, similar or adapted form elements.

Unify the Form

- Minimise variations in form and position; for example, use only circular shapes with horizontal orientation along the main axis, or only rectangular forms with vertical orientation.

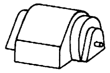
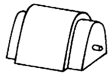
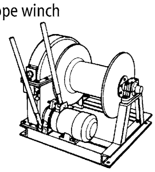
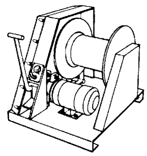
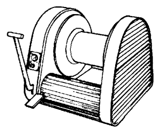
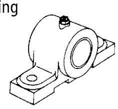
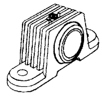
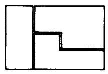
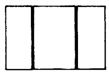
Embodiment Guidelines	**Wrong**	**Right**
Unify the form		
Minimise the number of different forms	Generator 	
	Rope winch 	 Open structure  Closed structure
Aim for similar forms and contours	Bearing 	
Adjust lines	Air conditioner  Confusing, inhomogeneous	 Block form  Layer form

Figure 7.102. Embodiment guidelines for aesthetics: form

- Introduce form elements and alignments appropriate to the basic form selected, for example, use the split lines of assemblies. Arrange the form by bringing several edges to one point or by running them parallel to one another. Support the intended expression with form elements and appropriate lines, such as horizontal lines to emphasise length. Keep an eye on the overall profile.

Support Using Colour

- Match colours to form.
- Reduce colours and material differences.

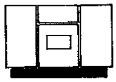
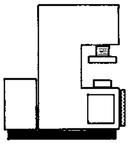
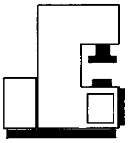
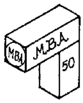
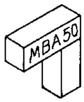
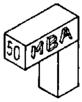
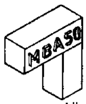
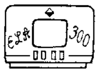
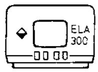
Embodiment Guidelines	**Wrong**	**Right**
Support using colour		
Match colour to form		 Functional surface
Reduce colours and material differences		
Choose one main colour supported by complementary colours		
Complement with graphics		
Use uniform styles for fonts and graphic symbols		 Focused, uniform
Unity expression		 All characters raised
Adjust size, form and colour of the graphics to the other forms and colours		

Figure 7.103. Embodiment guidelines for aesthetics: colour and graphics

- When using several colours, choose one main colour supported by complementary colours. For contrast use black and white, for example use black to contrast yellow, white to contrast red, green, blue, etc. (see also safety colours).

Complement with Graphics

- Use uniform styles for fonts and graphic symbols.
- Unify expression by using the same processes for the graphics, for example, etching, painting or embossing.
- Adjust size, form and colour of the graphics to the other forms and colours.

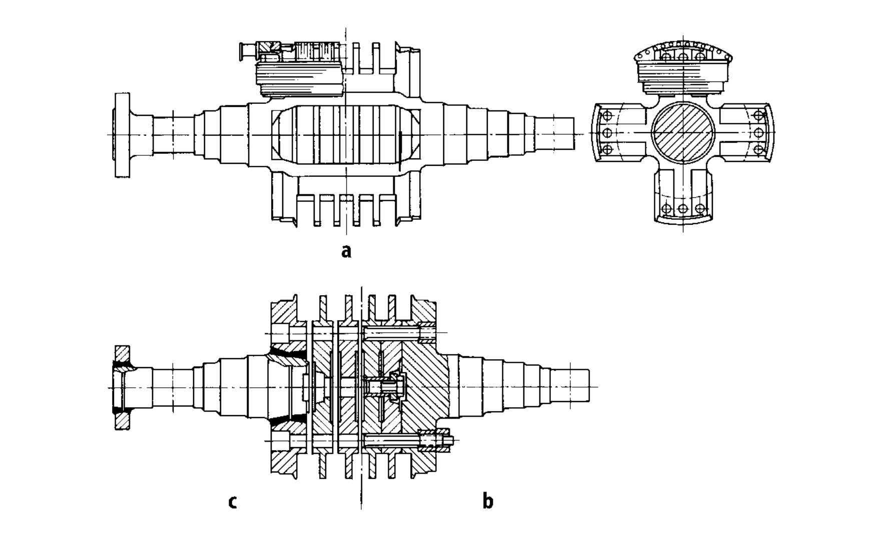


Figure 7.104. Rotor of a synchronous generator, after [7.8] (AEG-Telefunken): **a** as a forged part; **b** as a disc construction with forged flanges; **c** as for *b* but with welded flanges

7.5.8 Design for Production

1. Relationship Between Design and Production

The crucial influence of design decisions on *production costs*, *production times* and the *quality of the product* is described in [7.307,7.313]. *Design for production* means designing for the minimisation of production costs and times while maintaining the required quality of the product.

The term *production* usually refers to:

- the production of components in the narrow sense by accepted processes [7.49] (primary forming, secondary forming, material removal, joining, finishing, changing material properties)
- assembly, including transport of components
- quality control
- materials logistics
- operations planning.

Designers would therefore do well to consult the checklist (see Figure 7.3) under the headings *Production, Quality Control, Assembly* and *Transport*. In what follows we shall first concentrate on the design of components or assemblies in the narrower sense, while paying due regard to quality control and improvement of the overall production procedure. In Section 7.5.9 we shall then examine design features for improved assembly and transport.

Design for production is greatly facilitated if, from the earliest possible stage, decisions are backed up with data compiled by the standards department, the planning and estimating department, the purchasing department and the production manager. Figure 1.4 shows how the flow of information can be improved by systematic means, appropriate organisational measures and integrated data processing.

By observing the basic rules of simplicity and clarity (see Section 7.3), designers are already proceeding along the correct lines. The principles of embodiment design (see Section 7.4) can also lead them to a better and safer fulfilment of a given function and to the best solution from a production point of view. Another step in the same direction is the application of general and company standards (see Section 7.5.13).

2. Appropriate Overall Layout Design

The overall layout design, developed from the function structure, determines the division of a product into assemblies and components and:

- identifies the source of the components; that is, whether they are in-house, bought-out, standard or repeat parts
- determines the production procedure; for instance whether the parallel production of individual components or assemblies is possible
- establishes the dimensions and the approximate batch sizes of similar components, and also the means of joining and assembly
- defines suitable fits
- influences quality control procedures.

Conversely, production limitations such as the capacity of machines, assembly and transport facilities, etc., naturally have repercussions on the choice of the overall layout.

The appropriate subdivision of the overall layout can give rise to *differential*, *integral*, *composite* and/or *building-block* methods of construction.

Differential Construction Method

Differential construction refers to the breakdown of a component (a carrier of one or several functions) into several easily produced parts. This idea comes from lightweight engineering [7.135, 7.325], where this approach was introduced for the purpose of optimising load-carrying capacity. In both cases, we are entitled to speak of the "principle of subdivision for production".

To show an example of the differential method, let us consider the rotor of a synchronous generator (see Figure 7.104). The large forging shown at the top *a* is divided into several rotor discs consisting of simple forged parts and two considerably smaller flanged shafts *b*. Each of the latter can also be subdivided into shaft, disc support flange and coupling flange, in the form of a welded construction *c*.

The reason for this differential construction might be the market situation of large forgings (price, delivery date), and the easier adaptation of the generator to various output requirements (rotor sizes) and types of coupling. A further advantage is that the parts can be produced as stock and not necessarily to a specific order. However, the illustration also demonstrates the limitations of the differential approach—beyond a certain rotor length and diameter, the machining costs become too great and the stiffness of the joints too problematical.

Another example is shown in Figure 7.105. In the winding machine *a*, the winding head is integrated with the drive unit on a common shaft. The differential solution *b* was developed to facilitate the parallel production of drive units and winding heads to meet various customer requirements. In this way, a small number of standard drive units can be combined with a large number of winding heads.

The differential construction method also influences the production time. Figure 7.106 shows an example of the production procedure for a medium-powered electric motor. The times spent on acquiring the material and on producing the

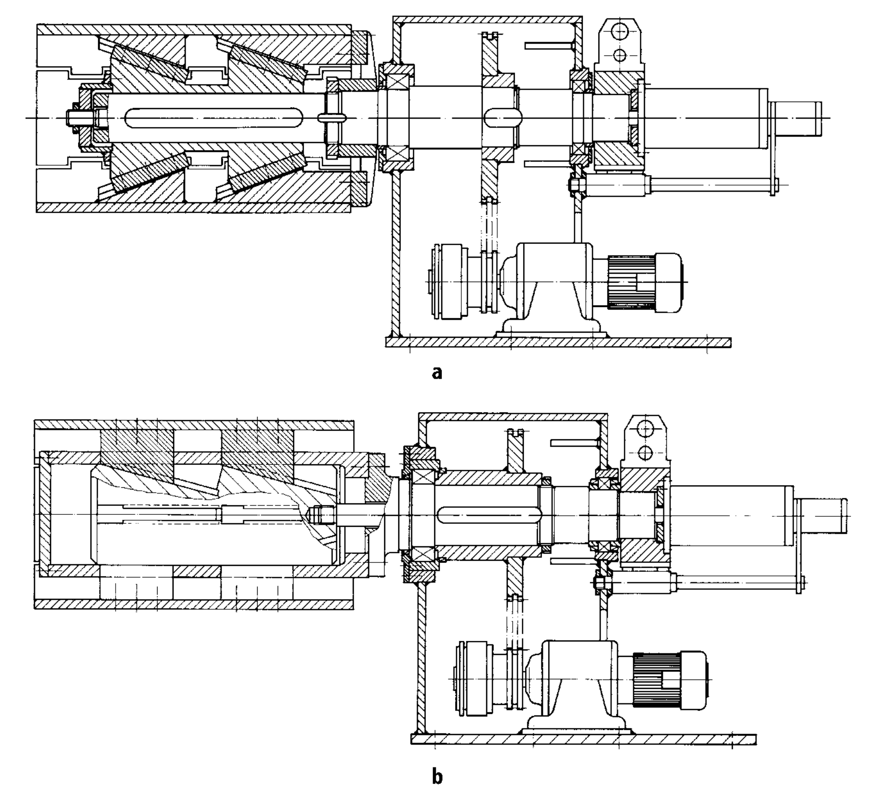


Figure 7.105. Winding machine (Ernst Julius KG): **a** winding head with integrated drive unit; **b** winding head with separate drive unit

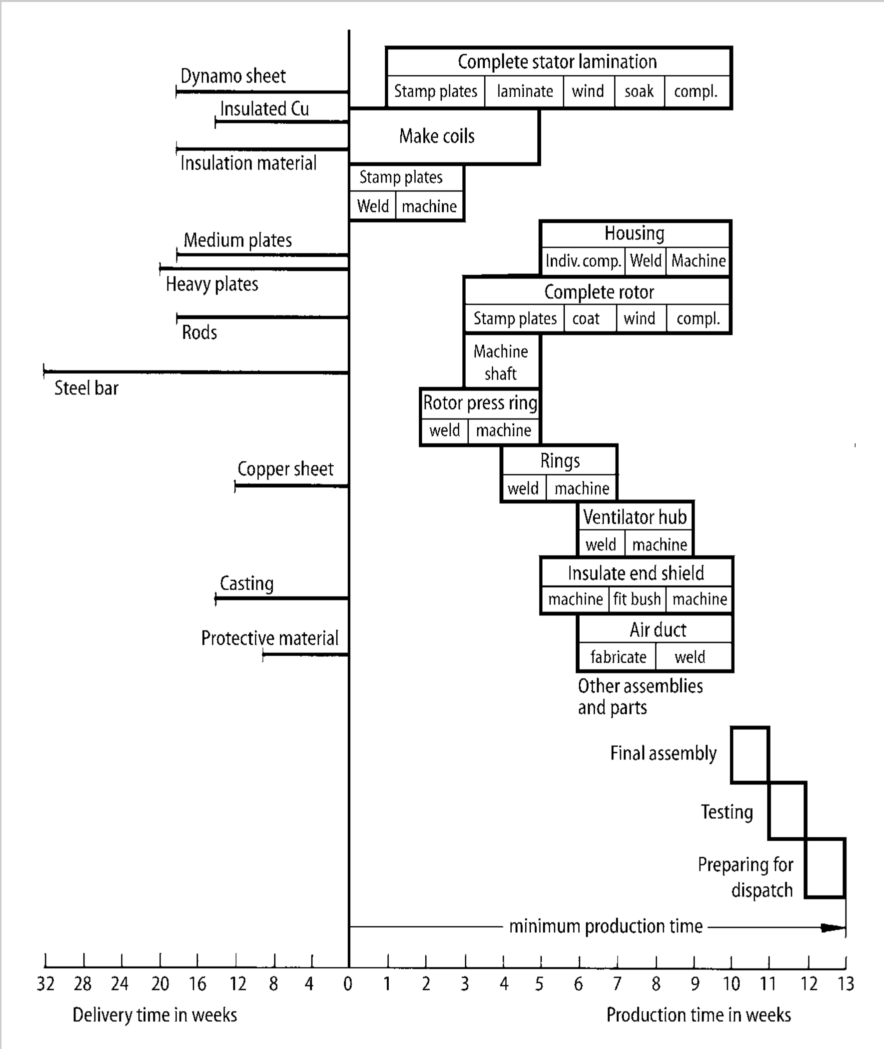


Figure 7.106. Production procedure for an electric motor from the series shown in Figure 9.17 (AEG-Telefunken)

components and assemblies are indicated by the lengths of the horizontal lines. The diagram not only makes clear where improvements can be made by choosing more quickly procurable raw and semi-finished materials or by keeping these materials in stock, but also where different production steps could be taken in parallel. Thus, by allowing the stator laminations to be built up in parallel with the construction of the housing (two time-consuming operations), a significant reduction in the overall production schedule is possible in comparison to older designs in which the stator laminations could only be inserted, followed by the windings, after the casing had been welded. All in all, differential designs have the advantages, disadvantages and limitations listed below:

Advantages:

- use of easily available and favourably priced semi-finished materials or standard parts
- easier acquisition of forged and cast parts
- easier adaptation to existing factory layout (dimensions, weight)
- increase in component batch sizes
- reduction in component dimensions allowing easier assembly and transport
- simpler quality assurance (more homogeneous materials)
- easier maintenance, for instance by simple replacement of worn parts
- easier adaptation to special requirements
- reduced risk of missing delivery dates
- reduced overall production time.

Disadvantages and limitations:

- greater machining outlay
- greater assembly costs
- greater need for quality control (smaller tolerances, necessary fits, etc.)
- limitations of function because of joints (stiffness, vibration, sealing).

Integral Construction Method

By the term *integral construction* we mean the combination of several parts into a single component. Typical examples are cast constructions instead of welded constructions, extrusions instead of connected sections, welded instead of bolted joints, etc. This method is often used for product optimisation because of the economic benefits of integrating several functions into one component. This method can indeed be an advantage for specific technical, production and procurement situations, particularly for labour-intensive production.

Figure 7.107 shows an example chosen from electrical engineering. Here, a cast and welded construction has been replaced with a single cast component. Though the casting is fairly complicated, it leads to a cost reduction of 36.5%. Naturally, this percentage will vary with the size of the batch and with market conditions.

Another example is the rotor of a hydroelectric generator (see Figure 7.108). Four different constructions with the same generator output and identical radial loads were investigated. Variant *a* has numerous individual support discs and may therefore be considered to be a differential construction. In variant *b*, the degree of division is reduced by the use of cast steel hollow shafts, two support rings and

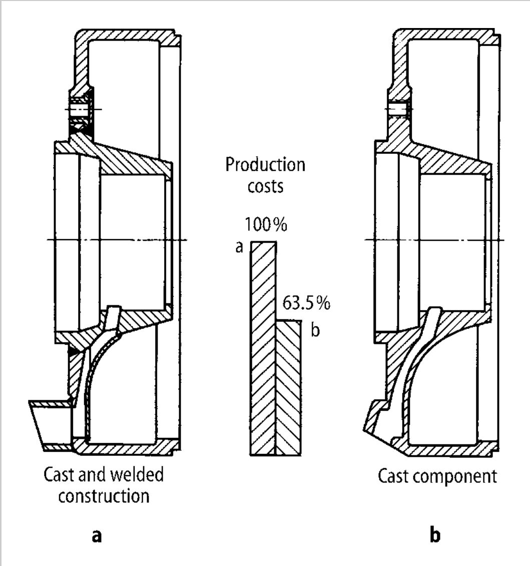


Figure 7.107. End cover of an electric motor, after [7.154] (Siemens): **a** composite construction; **b** integral construction

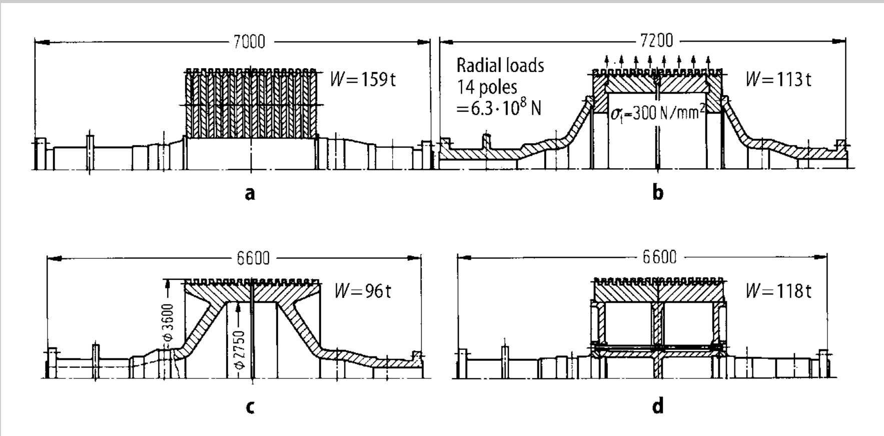


Figure 7.108. Rotor construction for a large-scale hydroelectric generator (Siemens)

end discs. Variant *c* is an integral construction in that two cast hollow bodies have been bolted together. In variant *d*, the cast construction is split up again (a cast central part, two forged shafts and two support rings). Weight comparisons show that the integral method saves material. In the end, however, variant *d* was chosen because of difficulties with procuring large castings.

The advantages and disadvantages of the integral construction method are easily determined through a reversal of the advantages and disadvantages of the differential method.

Composite Construction Method

By *composite construction* we mean:

- the inseparable connection of several, differently made, parts into a single component necessitating further work; for instance, the combination of cast and forged parts
- the simultaneous application of several joining methods for the combination of components [7.221]
- the combination of various materials for the optimal exploitation of their properties [7.290]

Figure 7.109 gives an example of the first method: the combination of cast steel components and rolled steel sheet into a welded construction.

Further examples are bogies with cast centres and welded arms, and also the welding of cast bar joints used in steel structures. Examples of the second method are combinations of adhesives and rivets or of adhesives and bolts. The combination of several materials into a single part is exemplified by synthetic components with cast-in thread inserts; by composite sound-absorption panels which have two plates separated by a plastic core; and also by rubber/metal components.

Another economical design of the composite type is the use of steel in prestressed concrete [7.120].

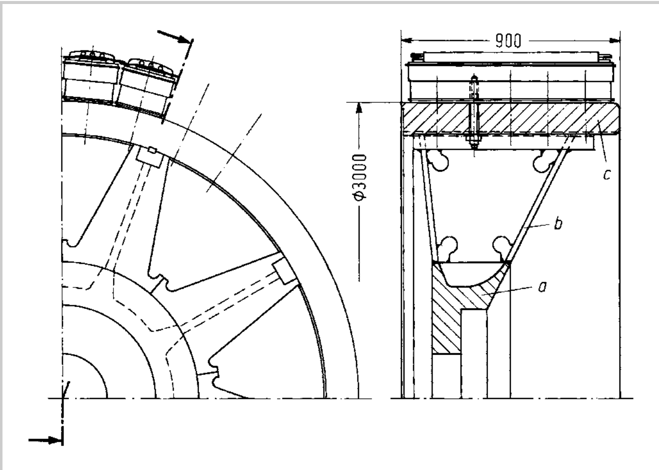


Figure 7.109. Magnet wheel of a hydroelectric generator of composite construction, after [7.15] (AEG-Telefunken): **a** Hub of cast steel; **b** Spoke of rolled steel sheet; **c** Support of cast steel

Building Block Construction Method

If the differential method is used to split a component in such a way that the resulting parts and/or assemblies can also be used in other products or product variants, then they can be considered to be building blocks. These are particularly useful if they are economical to produce. In a sense, the utilisation of repeat parts from stock can also be considered to be a building block construction method (see Section 9.2).

3. Appropriate Form Design of Components

During the form design of components, designers exert a great influence on production costs, production times and the quality of the product. Therefore, their choices of shapes, dimensions, surface finishes, tolerances and fits affect the selection of:

- production procedures
- types of machines, including tools and measuring instruments
- in-house components and bought-out components, preferably making use of repeat parts from within the company or suitable standard and off-the-shelf components
- materials and semi-finished materials
- quality control procedures.

Conversely, production facilities influence the design features. Thus, the available machine tools might limit the dimensions of components, necessitating that they be split up into several connected parts or that bought-out components be acquired. Many guidelines are available for the appropriate form design of components [7.19, 7.21, 7.123, 7.180, 7.198, 7.201, 7.262, 7.281, 7.283, 7.285, 7.287, 7.288, 7.291, 7.331–7.333]. Because of the importance of tolerances (geometry, dimension, position and surface) for the production and assembly of components, we specifically suggest the following literature: [7.36, 7.38, 7.39, 7.47, 7.143, 7.144].

It is important to use a *tolerancing basis* appropriate for the specific requirements [7.143]. A distinction is made between the *independent basis*, where dimensions are toleranced and checked individually, and the *envelope basis*, where geometrical features (such as a circle or pair of parallel surfaces) have an enveloping tolerance zone (maximum material condition) within which the dimension must lie. The latter cannot control deviations in position. For both tolerancing bases, deviations of position are independent of dimensional tolerances. The difference is whether deviations of geometry should be within the envelope. A fit has to remain within the envelope and, using the independent basis, this is indicated on the drawing with a fit specification, for example H7-j8. When the independent basis is used, *blanket tolerances* for geometry and position should be indicated. The envelope basis only requires a blanket tolerance for position [7.143, 7.144].

In keeping with the aims of this book, we shall present only essential design suggestions arranged systematically in the form of charts. Our classifying criteria will be production processes [7.48–7.50] with their individual *process steps*

(PS). In addition, we shall be assigning objectives—*reduction of costs* (C) and *improvement of quality* (Q)—to the various design guidelines. When designing components, designers should always bear these process steps and objectives in mind.

Form Design for Primary Shaping Processes

The form design of components to be shaped by primary processes, for example casting and sintering, must satisfy the demands and characteristics of the processes used.

In cast components (primary shapes obtained from the fluid state), designers must allow for the following process steps: *pattern* (Pa), *casting* (Ca) and *machining* (Ma). Figure 7.110 lists the most important design guidelines. The literature cited contains further information.

When designing *sintered* components (primary shapes obtained from the powder state), designers must allow for *tooling* (To) and *sintering* (Si). In particular, they must be guided by the latest findings in powder technology. The essential guidelines are shown in Figure 7.111.

Form Design for Secondary Shaping Processes

The form design of components to be shaped by secondary processes (hammer (free) forging, drop forging, cold extrusion, drawing and bending) must adhere to the guidelines listed below. Special considerations for the design of ferrous materials can be found in DIN 7521 to 7527 [7.46] and the design of nonferrous metals in DIN 9005 [7.51]. With *hammer forging*, designers need only allow for the actual forging process, since no complicated devices, for instance dies, are involved. The following design guidelines should be observed:

- Aim at simple shapes, if possible with parallel surfaces (conical transitions are difficult) and with large curvatures (avoid sharp edges). *Objectives*: reduction of costs, improvement of quality.
- Aim at light forgings, perhaps by separation and subsequent combination. *Objective*: reduction of costs.
- Avoid excessive deformations or excessive differences in cross-sections due, for instance, to the presence of excessively high and fine ribs or of excessively narrow indentations. *Objective*: improvement of quality.
- Try to place bosses and indentations on just one side. *Objective*: reduction of costs.

Design guidelines for *drop forging* have been collated in Figure 7.112. They allow for the process steps of: *tooling* (To), *forging* (Fo) and *machining* (Ma).

Figure 7.113 lists design guidelines for the cold extrusion of simple rotationally symmetrical solid and hollow bodies. They allow for the process steps of *tooling* (To) and *extrusion* (Ex). It must be stressed that only certain types of steel can

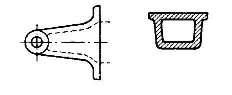
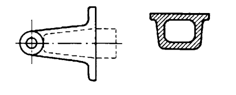
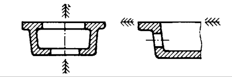
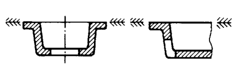
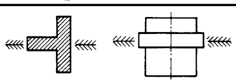
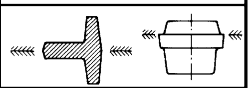
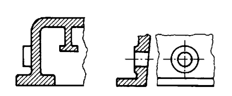
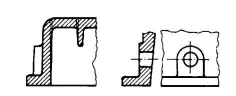
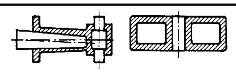
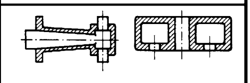
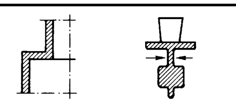
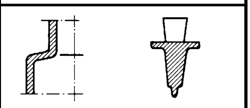
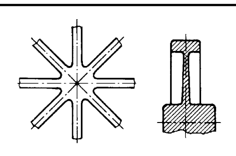
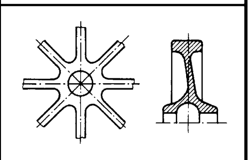
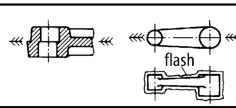
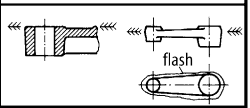
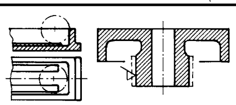
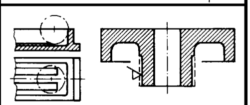
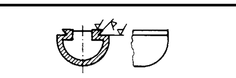
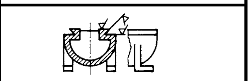
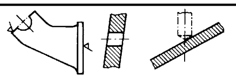
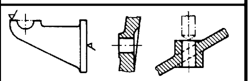
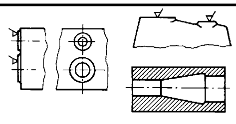
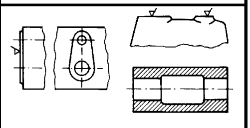
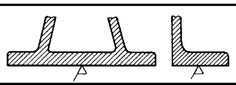
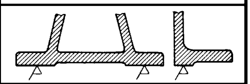
PS	Guidelines	Objec-tives	Wrong	Right
Pa	Choose simple shapes for patterns and cores (straight lines, rectangles).	C		
Pa	Aim at undivided patterns, if possible without cores (e.g. by means of open cross sections).	C		
Pa	Provide tapers from the split-line.	Q		
Pa	Arrange ribs so that pattern can be removed; avoid undercuts.	Q		
Pa	Ensure accurate location of cores.	Q		
Ca	Avoid vertical sections (bubbles, blowholes) and reduced cross-sections to the risers.	Q		
Ca	Aim at uniform wall thicknesses and cross-sections and gradual changes of cross-section; select material allowing adequate wall thicknesses and component sizes.	Q		
Ma	Set split-lines to avoid misalignment and to permit easy removal of the flash.	C Q		
Ma	Arrange castings to ease machining.	C Q		
Ma	Provide adequate support surfaces.	Q C		
Ma	Avoid sloping machining and boring surfaces.	C Q		
Ma	Combine machining processes by appropriate arrangement of machining and boring surfaces.	C		
Ma	Avoid unnecessary machining by breaking up large surfaces.	C		

Figure 7.110. Design guidelines with examples for cast components, after [7.123, 7.180, 7.198, 7.230, 7.331, 7.332]

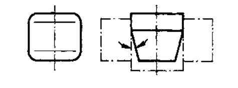
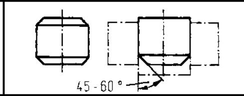
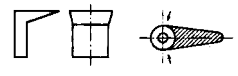
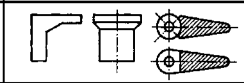
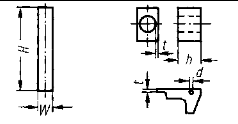
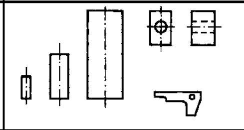
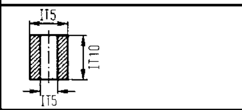
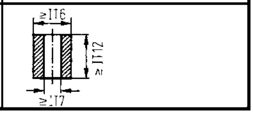
PS	Guidelines	Objectives	Wrong	Right
To	Avoid rounded edges and sharp angles.	C Q		
Si	Avoid sharp edges, sharp angles and tangential transitions.	Q		
Si	Observe dimensional limits and relations: Height H/Width $W < 2.5$ Wall thicknesses $t > 2$ mm Holes $d > 2$mm.	Q		
Si	Avoid small-toothed profiles	Q		
Si	Avoid excessively small tolerances.	Q		

Figure 7.111. Design guidelines with examples for sintered components, after [7.106]

be used economically. Like all other cold forming methods, cold extrusion gives rise to work hardening, in which the yield strength is raised while the toughness of the material drops significantly. Designers must take this factor into consideration. The best materials for cold extrusion are case-hardening and heat-treatable steels.

For *drawing*, the following design guidelines are recommended in [7.230]:

- Allow for tooling (To): choose the dimensions in such a way that the smallest number of drawing steps possible are needed. Objective: reduction of costs.
- Allow for tooling and drawing (To/Dr): aim at rotationally symmetrical hollow bodies; producing the corners of rectangular hollow bodies leads to high loading of the materials and tools. Objectives: improvement of quality, reduction of costs.
- Allow for drawing (Dr): choose tough materials. Objective: improvement of quality.
- Allow for drawing (Dr): for the design of flanges see [7.201]. Objective: improvement of quality.

Bending (cold bending), as used for the production of sheet metal components in precision and electrical engineering as well as for casings, claddings and air ducts in general mechanical engineering, involves two separate steps: *cutting* (Cu) and *bending* (Be). Designers must therefore allow for both. The design guidelines shown in Figure 7.114 apply to the bending process alone; cutting is covered under the next heading.

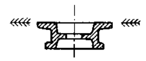
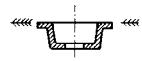
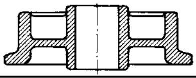
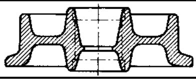
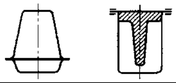
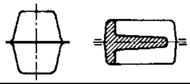
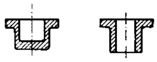
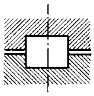
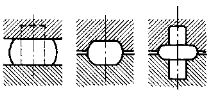
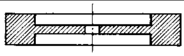
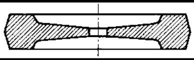
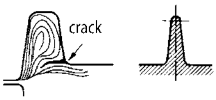
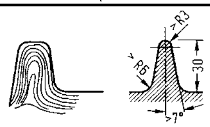
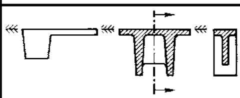
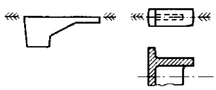
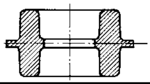
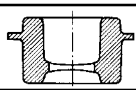
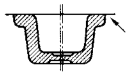
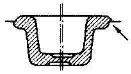
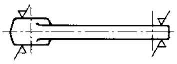
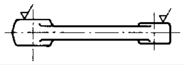
PS	Guidelines	Objec-tives	Wrong	Right
To	Avoid undercuts.	C		
To	Provide tapers.	C		
To	Aim for split lines at about half height perpendicular to smallest height.	C		
To	Avoid bent split lines.	C Q		
To Fo	Aim at simple, if possible rotationally symmetrical, parts. Avoid great protusions.	C		
Fo	Aim at shapes that occur during unrestrained pressing. For large numbers adapt to finishing shape.	C Q		
Fo	Avoid excessively thin sections.	Q		
Fo	Avoid large curvatures, excessively narrow ribs, fillets and excessively small holes.	Q		
Fo	Avoid sharp changes in cross-section and cross-sections that project excessively into the die.	Q		
Fo	Stagger split lines in the case of cup-shaped parts or large depth.	Q		
Ma	Select the split line so that misalignment is easily detected and removal of flash is simple.	C		
Ma	Arrange for surfaces to be machined to stand proud.	Q		

Figure 7.112. Design guidelines with examples for drop-forged parts, after [7.19, 7.145, 7.230, 7.238, 7.336]

Form Design for Separation

Of the separating procedures mentioned in DIN 8577 and 8580 [7.48, 7.49], we shall only consider "machining with geometrically defined cuts" (turning, boring, milling), "machining with geometrically undefined cuts" (grinding), and "separating" (cutting). In all separating processes, designers must allow for *tooling* (To), including clamping, as well as *machining* (Ma).

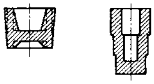
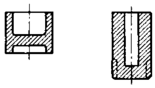
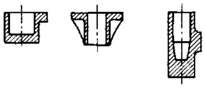
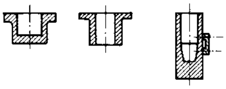
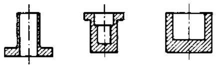
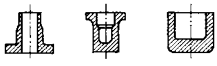
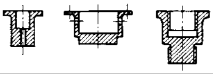
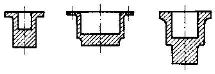
PS	Guidelines	Objectives	Wrong	Right
To Ex	Avoid undercuts.	Q C		
Ex	Avoid tapers and excessively small diameter diffrences.	Q		
Ex	Provide rotationally symmetrical parts without material protusions, otherwise split and join.	Q		
Ex	Avoid sharp changes in cross-section, sharp edges and fillets.	Q		
Ex	Avoid small, long or lateral holes and threads.	Q		

Figure 7.113. Design guidelines with examples for cold extrusions, after [7.108]

Design for tooling involves:

- The provision of adequate clamping facilities. *Objective*: improvement of quality.
- A preferential sequence of operations that does not necessitate the reclamping of components. *Objectives*: reduction of costs, improvement of quality.
- The provision of adequate tool clearances. *Objective*: improvement of quality.

Design for machining in all separating processes involves:

- The avoidance of unnecessary machining; that is, the reduction of machined areas, fine surface finishes and close tolerances to the absolute minimum (protruding bosses and cut-outs placed at the same height or depth are advantageous). *Objective*: reduction of costs.
- The location of machined surfaces parallel or perpendicular to the clamping surfaces. *Objectives*: reduction of costs, improvement of quality.
- The choice of turning and boring in preference to milling and shaping. *Objective*: reduction of costs.

Figure 7.115 represents the design guidelines for components machined by turning; Figure 7.116 shows them for components machined by boring; Figure 7.117 for components machined by milling; and Figure 7.118 for components machined by grinding.

In the design of *cut-out components*, the characteristics of the *tools* (To) and the *cutting method* (Cu) [7.19, 7.230] must be taken into consideration (see Figure 7.119).

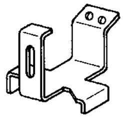
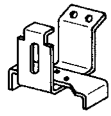
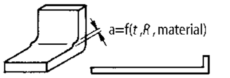
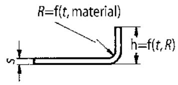
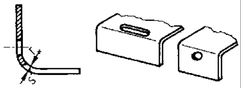
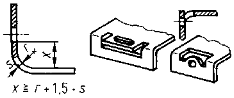
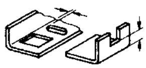
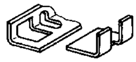
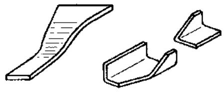
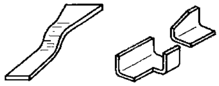
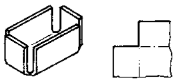
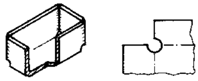
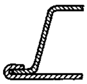
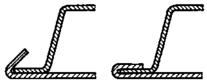
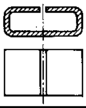
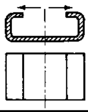
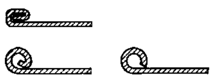
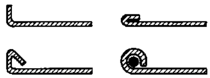
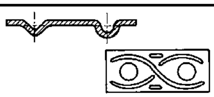
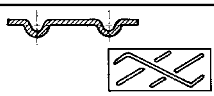
PS	Guidelines	Objec-tives	Wrong	Right
Be	Avoid complex bent parts (material waste); rather split and join.	C		
Be	Allow for minimum values of bending radii (bulging in the compression area and overstretching in tension area) flange height and tolerances.	Q		
Be	Provide sufficient distance between pre-pierced holes and bend.	Q		
Be	Aim at holes and notches to cross the bend when it is not possible to provide the minimum gap.	Q		
Be	Avoid sloping edges and tapers in the region of the bend.	Q		
Be	Provide clearances at the corners when all sides are to be bent up.	Q		
Be	Provide folded seam of sufficient width.	Q		
Be	Aim at large access openings for hollow shapes and undercut bends.	Q C		
Be	Provide stiffening at sheet edges.	A		
Be	Aim at identation forms.	A		

Figure 7.114. Design guidelines with examples for bent parts, after [7.1, 7.19]

Form Design for Joining

Of the joining methods discussed in DIN 8593 [7.50], we shall only consider welding under the above heading. For separable joints, the reader is referred to Section 7.5.9, “Design for Ease of Assembly”.

Welding involves three process steps, namely *preparation* (Pr), *welding* (We) and *finishing* (Fi). The following design guidelines apply:

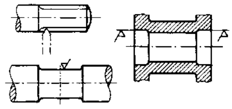
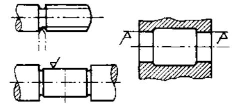
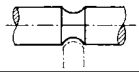
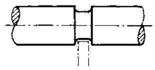
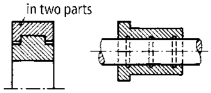
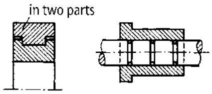
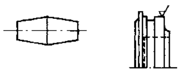
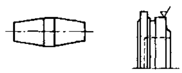
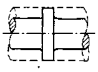
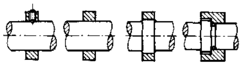
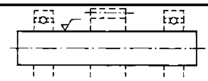
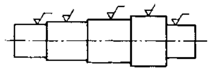
PS	Guidelines	Objectives	Wrong	Right
To	Provide adequate tool runout.	Q		
To	Aim for simple tool shapes.	C		
To	Avoid grooves and tight tolerances on inner surfaces.	C Q		
To	Provide for adequate clamping.	Q		
Ma	Avoid excessive machining, e.g. replace high collars by separate parts.	C		
Ma	Adapt working length and surface finish to the required function.	C		

Figure 7.115. Design guidelines with examples for components machined by turning, after [7.180, 7.230]

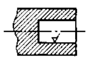
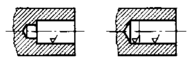
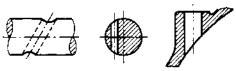
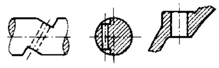
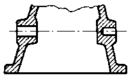
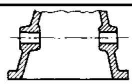
PS	Guidelines	Objectives	Wrong	Right
To Ma	Where possible, use boring tools on blind holes.	C Q		
To Ma	Provide starting and finishing flats for holes breaking through angled surfaces.	Q		
To	Aim for continuous holes, avoiding blind holes.	C		

Figure 7.116. Design guidelines with examples for components machined by boring, after [7.180, 7.198, 7.230]

- Pr, We, Fi: avoid the imitation of cast designs; preferably select standard, easily obtainable or prefabricated plates, sections or other semi-finished materials; make use of composite constructions (cast/forged components). *Objective*: reduction of costs.
- We: adapt the material, welding quality and welding sequence to the required strength, sealing and shape. *Objectives*: reduction of costs, improvement of quality.
- We: aim for short weld seams and small weld cross-sections to reduce damage through heating and to simplify handling. *Objectives*: improvement of quality, reduction of costs.

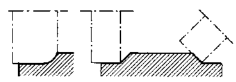
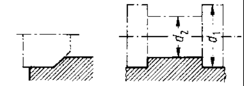
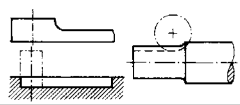
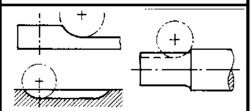
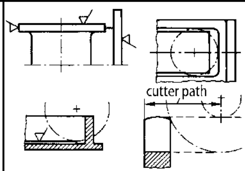
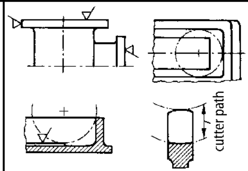
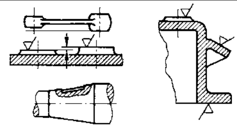
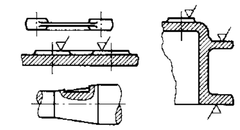
PS	Guidelines	Objec-tives	Wrong	Right
To	Aim for straight milling surfaces (form tools are expensive); select dimension for gang milling.	C		
To	Provide runouts for edge mills (edge milling is cheaper than end milling).	C Q		
To	Adapt runout to milling tool diameter. Avoid long milling cuts by selecting curved surfaces (e.g. slots).	C		
Ma	Arrange surfaces on one level and parallel to the clamping.	C Q		

Figure 7.117. Design guidelines with examples for components machined by milling, after [7.180, 7.230]

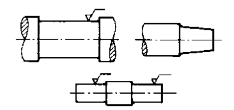
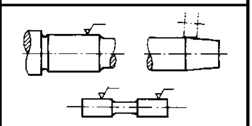
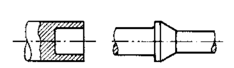
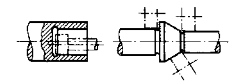
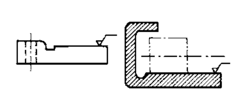
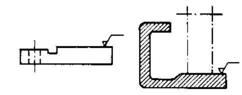
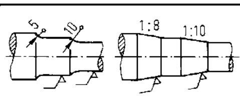
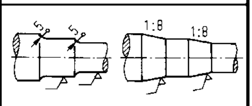
PS	Guidelines	Objec-tives	Wrong	Right
To	Avoid edge limitations.	Q C		
To	Provide runouts for grinding wheels.	Q		
To	Aim for unimpeded grinding by appropriate selection of surfaces.	C Q		
To Ma	Give preference to equal blend radii (if no runout possible) and to equal tapers.	C Q		

Figure 7.118. Design guidelines with examples for components machined by grinding, after [7.230]

- We,Fi: minimise the amount of welding (heat input) to avoid or reduce distortion and corrective work. *Objectives*: improvement of quality, reduction of costs.

Further guidelines are given in Figure 7.120.

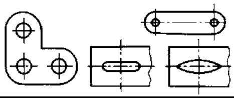
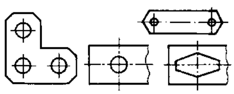
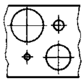
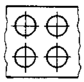
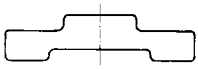
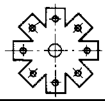
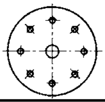
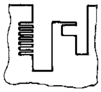
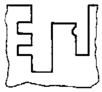
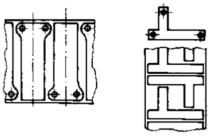
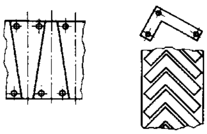
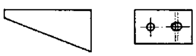
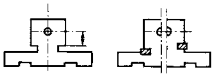
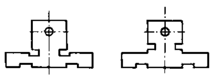
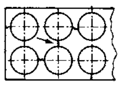
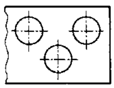
PS	Guidelines	Objec-tives	Wrong	Right
To	Aim for simple cuts, prefer angular corners, avoid curves.	C		
To	Aim for identical cut-out parts.	C		
To	Aim for sharp-edged transitions to facilitate the cutting of the template and to ensure easy grinding.	C Q		
To	Avoid complex contours.	C Q		
To	Avoid very narrow die cuts.	C Q		
Cu	Avoid waste by careful layout of cut-out parts on standard plate widths.	C		
Cu	Avoid sharp-angled shapes and excessively tight tolerances.	Q		
Cu	Prefer shapes permitting subsequent cuts without danger of damage.	Q		
Cu	Avoid very narrow spacing between holes.	Q		

Figure 7.119. Design guidelines for cut-out components, after [7.19, 7.230]

4. Appropriate Selection of Materials and of Semi-Finished Materials

An optimum choice of materials and semi-finished materials is difficult to make because of interactions between the characteristics of the function, working principle, layout and form design, safety, ergonomics, production, quality control, assembly, transport, operation, maintenance, costs, schedules and recycling. When the material costs of a proposed solution are particularly high, careful material selection becomes of the utmost economic importance (see Chapter 11). In general, designers are advised to consult the checklist (see Figure 7.3) and to evaluate the materials accordingly. The chosen materials and the resulting processing and

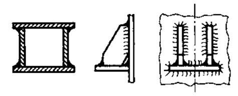
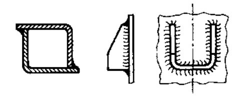
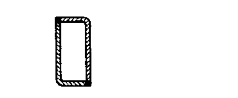
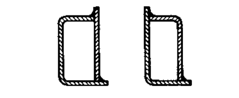
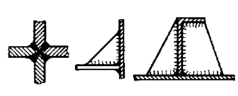
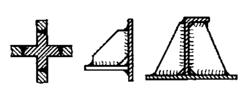
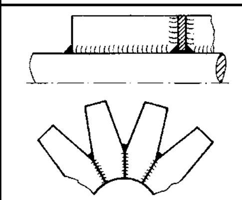
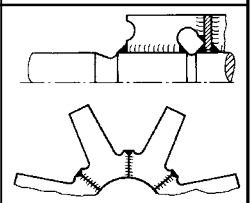
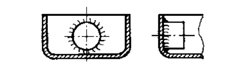
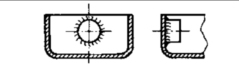
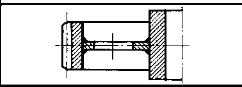
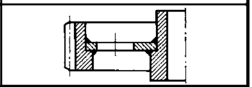
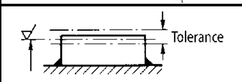
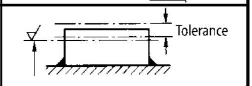
PS	Guidelines	Objec-tives	Wrong	Right
Pr	Prefer solutions with few parts and weld seams.	C		
Pr We Fi	Aim for easily weldable seams if loads permit.	C		
Pr We	Avoid build-up of weld material and intersecting weld seams.	C Q		
Pr We	Reduce residual stresses due to shrinkage by appropriate choice of weld seams and welding sequence, and of connecting sections of low stiffness (flexible tongues and corners).	Q		
We	Aim for good accessibility.	C Q		
We Fi	Ensure positive location of the components prior to welding.	Q		
Fi	Allow sufficient material for machining after welding.	Q		

Figure 7.120. Design guidelines for welded components, after [7.19, 7.198, 7.220, 7.281]

machining of the components, their quality and the market conditions influence the selection of:

- production procedures
- types of machine, including tools and measuring instruments
- materials handling, for example, purchasing and storage
- quality control procedures
- in-house and subcontract production.

The close relationship between design, production procedures and materials technology calls for cooperation between designers, production engineers, materials experts and buyers.

The most important recommendations for the selection of materials for primary shaping processes (for example casting and sintering) and secondary shaping processes (for example forging, extrusion, etc.) have been set out by Illgner [7.137]. For production processes such as ultrasonic welding, electron-beam welding, laser technology, plasma cutting, spark erosion and electrochemical processes, see the following literature [7.27, 7.95, 7.133, 7.182, 7.240, 7.250, 7.262].

Closely connected with the selection of materials is the choice of *semi-finished materials* (for example tubes, standard extrusions, etc.). Because of the common method of costing by weight, designers tend to think that cost reduction invariably goes hand-in-hand with weight reduction. However, as Figure 7.121 makes clear, this belief is often mistaken.

The following example throws further light on this problem. Figure 7.122 shows a welded electric motor housing. The old layout required eight different plate thicknesses to achieve the required stiffness with minimum weight. In the mod-

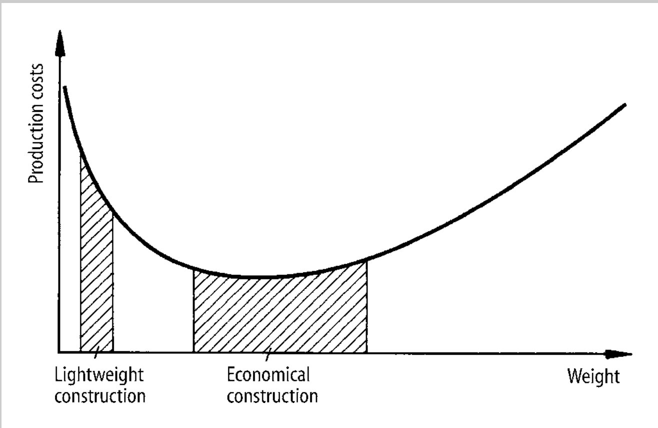


Figure 7.121. Cost areas for lightweight and economical constructions, after [7.297]

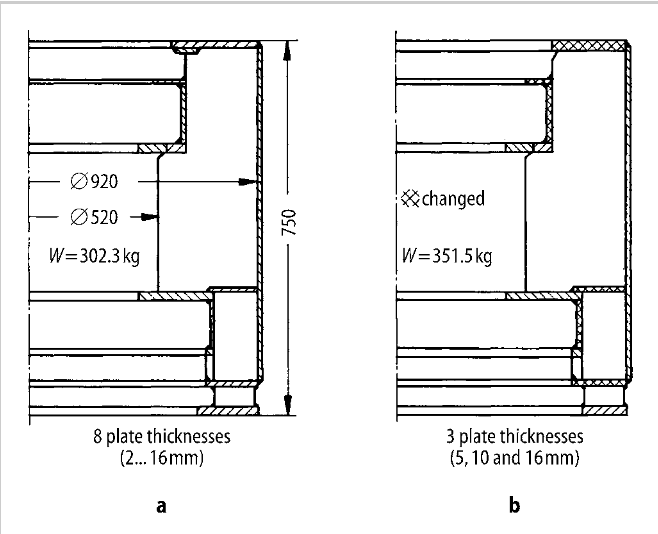


Figure 7.122. Electric motor housing of welded construction (Siemens): **a** current design; **b** proposed design

ified design, however, the number of plate thicknesses was deliberately reduced, although this increased the weight. This change in the design involved the replacement of standard flame cutting by numerically controlled machines. The extra outlay was to be justified by keeping the programming and re-equipping costs low, and through maximum utilisation of the plate material by stacking before cutting [7.5]. A cost analysis showed that, despite an increase in weight due to oversizing of some of the housing parts, the new design was cheaper than the old thanks to lower labour costs and lower production overheads. Admittedly, the actual saving was not very great, but this example serves to show that the minimisation of weight, which often involves a great deal of design and production effort, does not necessarily lead to minimum costs. Moreover, even when the calculated cost reductions resulting from the incorporation of semi-finished materials and simplification in production processes are not great, the actual savings may be much greater because of the consequent reduction in idle time and time spent on operations scheduling (see Chapter 11).

A further example of the economic use of semi-finished materials is given in Figure 7.123, which shows the plate-cutting plan for a welded motor housing. To allow the use of circular blanks for the end-wall bearing shields *d*, the end-walls are made from four parts *b* which are then welded together. The resulting aperture, even after machining, is smaller than the bearing shield made from the blank. In addition, this arrangement provides the support feet *c*.

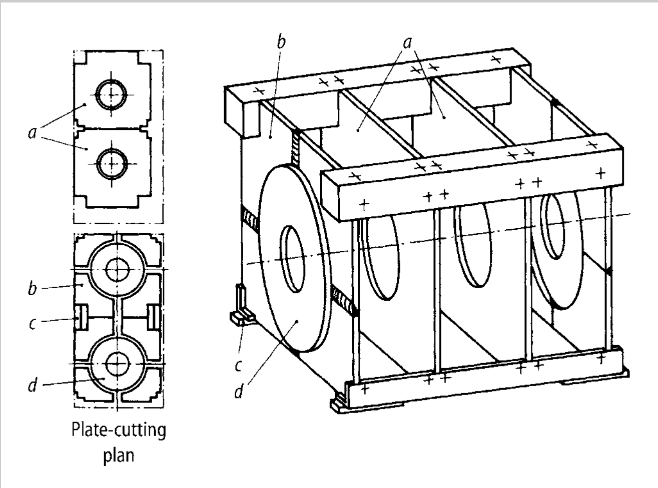


Figure 7.123. Electric motor housing. Welded construction with plate-cutting plan, after [7.162] (Siemens)

5. Appropriate Use of Standard and Bought-Out Components

Designers should always try to use components that do not have to be specially produced but that are readily available as *repeat*, *standard*, or *bought-out* parts. In this way, they can help to create favourable supply and storage conditions.

Easily available bought-out parts are often cheaper than parts made in-house. The importance of standard parts has already been stressed on several occasions.

The decision on whether components should be made in-house or bought-out depends on the following considerations:

- number (one-off, batch or mass production)
- whether production is for a specific order or for the general market
- market situation (costs, delivery dates of materials and bought-out parts)
- available production facilities
- utilisation of existing production facilities
- available or desired degree of automation.

These factors influence not only the decision on whether in-house production is to be preferred to subcontract production, but also the design approach. Unfortunately, most of the factors vary with time. This means that a particular decision may be justified at the time that it was made, but it may no longer be correct if the market situation and the production capacity change. Particularly in the case of one-off or batch products in the heavy engineering industry, the market and production situation needs to be re-examined at regular intervals.

6. Appropriate Documentation

The effect of production documents (in the form of CAD models, drawings, parts lists and assembly instructions) on costs, delivery dates, product quality, etc., is often underestimated. The layout, clarity and comprehensiveness of such documents have a particularly marked influence. They determine the execution of the order, production planning, production control and quality control.

7.5.9 Design for Assembly

1. Types of Assembly

Designers not only have a major influence on the costs (see Chapter 11) and the quality of the production of components, but also on the costs and quality of assembly [7.329].

By *assembly* we refer to the combination of components into a product and to the auxiliary work needed during and after production. The cost and quality of an assembly depend on the type and number of operations and on their execution. The type and number, in their turn, depend on the layout design of the product, on the form design of the components and on the type of production (one-off or batch production).

The following guidelines for design for assembly can therefore be no more than general hints [7.2, 7.32, 7.101, 7.102, 7.316, 7.318, 7.329]. The aims of the guidelines are to simplify, standardise, automate and ensure quality. In individual cases, they may be influenced or overridden by referring to the following headings in the checklist (see Figure 7.3): Function, Working Principle, Layout, Safety, Ergonomics, Production, Quality Control, Transport, Operation, Maintenance and Recycling. The particularities of specific cases must be checked [7.132, 7.170, 7.171, 7.223, 7.289].

According to Guideline VDI 3239 [7.309] and [7.3, 7.268], the following essential operations are involved:

- *Storing* (St) of parts to be assembled, if possible in a systematic manner. Automatic assembly further necessitates the programmed supply of parts and connecting elements.
- *Handling* (Ha) of components, including:
  - identifying the part by fitter or robot, e.g. by checking its orientation
  - picking up the part, if necessary in conjunction with individual selection and dispensing
  - moving the part to the assembly point, if necessary in conjunction with separation (removal, rejection, etc.), manipulation (rotation, inversion, etc.) and combining components.
- *Positioning* (Po) (placing the part correctly for assembly), and aligning (final adjustment of the position of the part before and possibly after joining).
- *Joining* (Jo) parts by the provision of appropriate connections. According to DIN 8593 [7.50], the following operations must also be included here:
  - bringing together, for example by inserting, superposing, suspending or folding
  - filling, for example by soaking
  - pressing together, for example by bolting, clamping or shrink-fitting
  - joining by primary processes, for example by fusing, casting and vulcanising
  - joining by secondary processes, for example by bending or via auxiliary components
  - joining by the combination of materials, for instance by welding, soldering or gluing.
- *Adjusting* (Ad) to equalise tolerances, to restore the required play, etc. [7.269].
- *Securing* (Se) the assembled parts against unwanted movements under operational loads.
- *Inspecting* (In). Depending on the degree of automation, various testing and measuring operations must be performed, possibly between individual assembly operations.

These operations are involved in every assembly process, their importance, sequence and frequency depending on the number of units (one-off assembly, batch assembly) and the degree of automation (manual, part automatic or fully automatic assembly).

According to [7.112], the linking of assembly operations or assembly cells can be divided into the following types: unbranched, branched, single level and multilevel assembly. The assembly process can be stationary or flowing.

It is also important to distinguish whether assembly takes place within the company or on site, by experts or by less well trained customer personnel. In general, the improvements one can make to automate assembly will also simplify manual assembly and vice versa. The selected type of assembly and the embodiment are closely related, that is, they influence one another.

2. General Guidelines for Assembly

In accordance with the steps of the embodiment design phase (see Section 7.1), it seems useful to start considering assembly even while working on the working structure and the layout. An easy-to-assemble layout can be achieved if the assembly operations are:

- structured
- reduced
- standardised
- simplified.

This will lead to a reduction in expenditure because the assembly process is improved and to increase in product quality because assembly is clearer and easier to control [7.94,7.105,7.257]. A layout that has been selected for these reasons could also lead a reduction in the number of components or at least the standardisation of components.

The embodiment guidelines that focus on ease of assembly are classified in Figure 7.124. The column *operation* contains the assembly operations that are primarily affected by the specific embodiment guidelines. The third column indicates whether the guideline leads to an improvement of *manual assembly* (MA) or *automated assembly* (AA), or both. This classification should ease the use and selection of embodiment guidelines for specific assembly situations.

3. Designing Assembly Interfaces

Another important aspect of improving assembly is the design of interfaces that are influenced by the layout. Improvements to the interfaces are achieved if they are:

- reduced
- standardised
- simplified.

These actions reduce the number of connecting elements and assembly operations, and minimise the quality requirements of the interfacing elements [7.2, 7.112, 7.273].

In Figure 7.125, the embodiment guidelines are again classified according to the aims and the affected assembly operations.

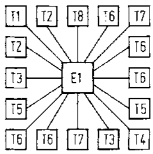
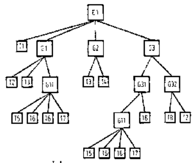
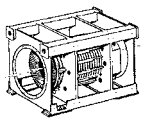
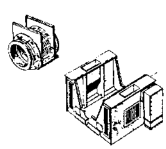
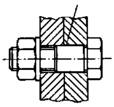
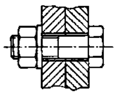
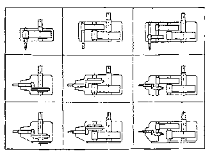
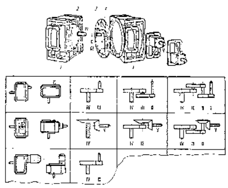
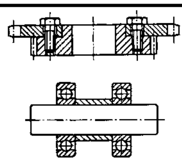
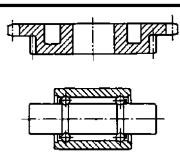
Oper.	Guidelines	Type	Wrong	Right
Arrange assembly operations				
St Ha Po Jo Ad Se In	Divide into assemblies to enable stepwise assembly with preassembly and final assembly.	MA AA		
Ha In	Arrange in independent assembly groups, e.g. to allow parallel assembly.	MA AA		
Jo	Avoid production operations during assembly.	MA AA		
Jo Ad In	Structure a variant product programme such that variants are created towards the end and at the same place in the assembly sequence.	AA		
In	Enable assembly groups to be inspected separately, especially for variant design.	MA AA	Balancing with a fully assembled machine.	Balancing the rotor on its own.
In	Aim at function testing of assembly groups or the whole product without testing individual parts.	MA AA	Measuring gear profiles on individual gears. Testing air-thigthness of components.	Measuring noise level of gearbox. Testing air-tightness of pipe system.
Reduce assembly operations				
St Ha Po Jo Ad Se In	Connect parts using integral and composite structures.	MA AA		

Figure 7.124. Embodiment guidelines for designing the layout for assembly

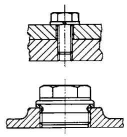
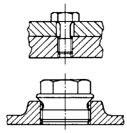
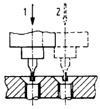
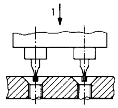
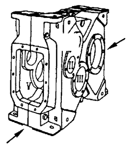
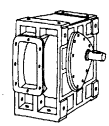
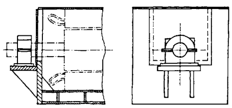
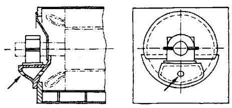
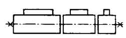
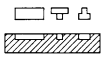
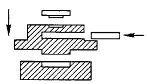
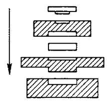
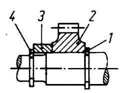
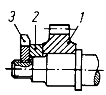
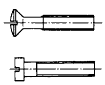
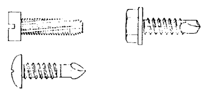
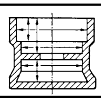
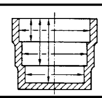
Oper.	Guidelines	Type	Wrong	Right
Reduce assembly operations				
St Ha Po Jo Ad Se In	Use function integration to reduce number of parts.	MA AA		
Jo	Execute assembly operations simultaneously.	AA		
Jo Ad Se	Reduce number of interfaces to be joined.	MA AA		
Ad Se In	Avoid disassembly to test functions of assembled groups and products.	MA AA	 Measuring of air gap not possible	 Measuring of air gap directly possible
Standardise assembly operations				
Po Jo In	Provide a basic component in every assembly group, e.g. to allow interlocking constructions.	AA		
Jo	Aim for uniform joining directions and procedures within an assembly group.	AA		
Simplify assembly operations				
Po Jo Ad Se In	Constrain assembly operations (clear assembly sequence).	MA	 or: *4 3 2 1*	
Jo	Combine production and assembly operations.	MA AA		
Ad In	Provide access for tests; enable visual inspection.	MA AA		

Figure 7.124. (continued)

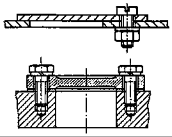
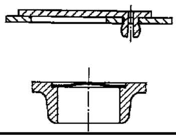
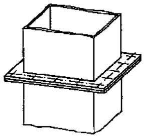
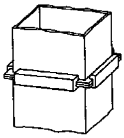
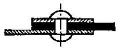
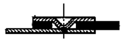
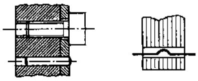
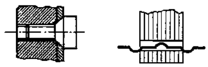
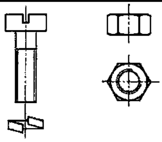
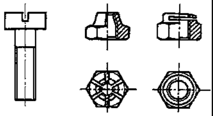
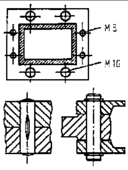
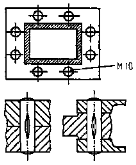
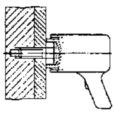
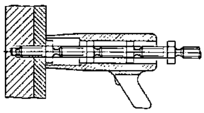
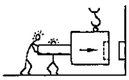
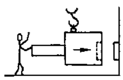
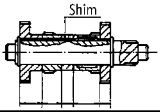
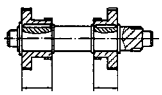
Oper.	Guidelines	Type	Wrong	Right
Reduce interfaces				
St Ha Jo Ad Se	Reduce connecting elements, e.g. by using clamp and snap connections.	MA AA		
St Ha Jo	Reduce connecting elements by using special connecting elements.	MA AA		
St Jo Se	Aim for direct connections without connecting elements.	MA AA		
Po	Aim for self-adjustment and positioning.	AA		
Se	Prefer self-locking connecting elements, e.g. through elastic-plastic deformation.	AA		
Standardise interfaces				
St Ha Jo	Use identical connecting elements, if possible even for different functions.	MA AA		
Simplify interfaces				
St Ha	Prefer connecting elements that can be delivered by belt or in a continuous flow.	AA		
Ha Jo		MA AA		
Po Jo	Avoid dimension chains with tight tolerances by splitting the dimension chain.	MA AA		

Figure 7.125. Embodiment guidelines for designing the interfaces for assembly

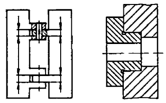
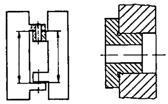
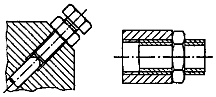
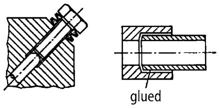
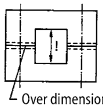
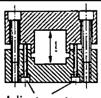
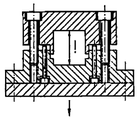
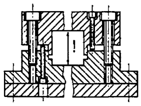
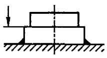
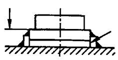
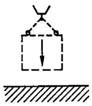
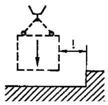
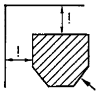
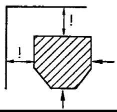
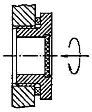
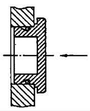
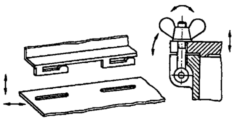
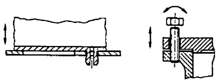
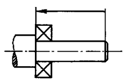
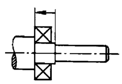
Oper.	Guidelines	Type	Wrong	Right
Simplify interfaces				
Po Jo	Avoid double fits to enable unambiguous positioning and to reduce tolerances on dimensions.	MA AA		
Po Ad	Prefer simple adjustments or provide positioning guides.	MA AA		
Po Ad	Enable continuous adjustment.	MA AA		
Po Ad	Aim for accessibility to allow adjustment without disassembling other parts.	MA AA		
Po Ad	Compensate tolerances by using compensation components.	MA		
Po Ad In	Provide reference surfaces, edges and points.	MA AA		
Po Ad In	Aim for unambiguous and independent adjustment operations.	MA AA		
Jo	Prefer translational joining motions.	AA		
Jo	Avoid joining motions involving multiple axes, in particular curves.	AA		
Jo	Avoid long joining paths.	MA AA		

Figure 7.125. (continued)

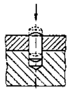
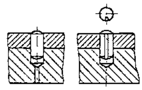
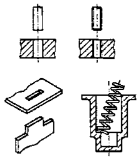
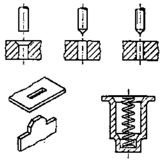
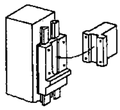
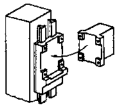
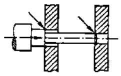
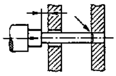
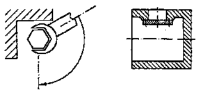
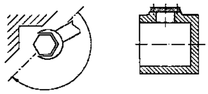
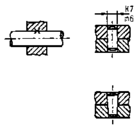
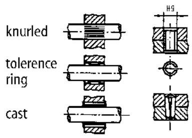
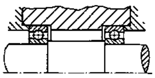
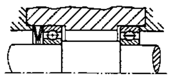
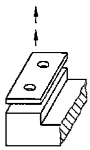
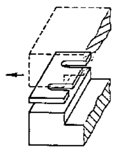
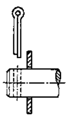
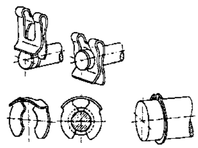
Oper.	Guidelines	Type	Wrong	Right
Simplify interfaces				
Jo	Avoid hindering caused by air pockets.	MA AA		
Jo	Provide tapering to ease joining.	MA AA		
Jo	Divide large interfaces into several smaller ones.	MA AA		
Jo Ad	Avoid simultaneous operations that influence each other.	MA AA		
Jo Ad	Provide access for assembly tools.	MA AA		
Jo Ad Se	Prefer connecting elements with elastic, elastic-plastic or material tolerance compensation.	MA AA		
Jo Se	Allow for large tolerances through assemply parts that are flexible.	MA AA		
Ad	Adapt using standardised matching parts without disassembling.	MA AA		
Se	Apply locking elements that are easy to assemble.	AA		

Figure 7.125. (continued)

4. Designing Interface Elements

Closely linked to the design of interfaces is the design of the interfacing elements. To improve automatic storage and handling, including the identification, ordering, picking-up and moving of the interfacing elements, these operations should be:

- enabled
- simplified.

This is particularly important for the application of automatic assembly machines (AA) [7.2, 7.103, 7.273, 7.289]. Figure 7.126 shows the design guidelines.

In summary, the essential guidelines can be derived from the basic guidelines of *simplicity* (simplify, standardise, reduce) and *clarity* (avoiding over constraining and under constraining) (see Sections 7.3.1 and 7.3.2). Further examples are given in [7.2, 7.104, 7.112, 7.114, 7.248, 7.249, 7.308].

5. Guidelines for Application and Selection

Design for assembly should, in line with the overall approach (see Section 7.1), involve the following five steps [7.112, 7.249] at appropriate stages of the design process.

Step 1: Draw-up demands and wishes for the requirements list that determine or influence assembly. This list will specify requirements such as:

- individually designed product or variant range
- number of variants
- safety and legal requirements
- production and assembly constraints
- test and quality requirements
- transport and packaging requirements
- assembly and disassembly requirements for maintenance and recycling
- requirements related to assembly operations undertaken by the user.

Step 2: Check for ways of easing assembly by using technical opportunities in the principle solution (working structure) and especially in the overall layout (construction structure), that is:

- Reduce the number of variants in a product range by using series and modular construction (see Chapter 9) or by concentrating on a few different types.
- Apply the embodiment guidelines shown in Figure 7.124 and use these to select layouts.

Step 3: Embody the assemblies, interfaces and interfacing elements that determine the assembly process, that is:

- Apply the embodiment guidelines shown in Figures 7.125 and 7.126 and use these to select embodiment variants.

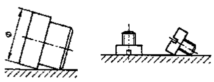
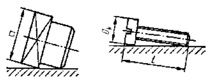
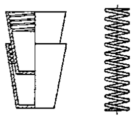
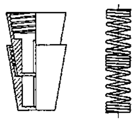
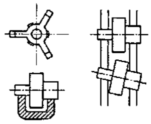
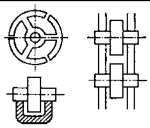
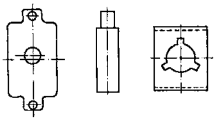
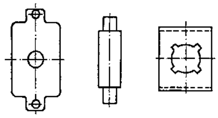
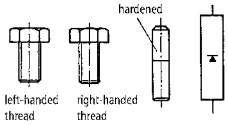
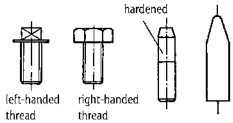
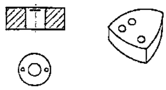
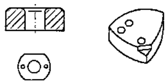
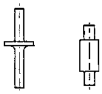
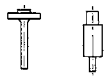
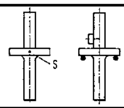
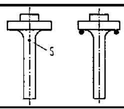
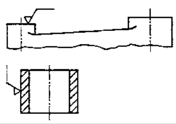
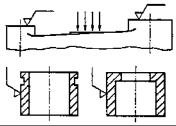
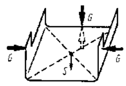
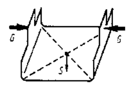
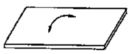
Oper.	Guidelines	Type	Wrong	Right
Enable and simplify automatic storage and handling				
St	Prefer interface elements that have a stable position.	AA		
St	Avoid identical interface elements that can interlock.	MA AA		
St Ha	Aim for interface elements that can roll.	AA		
Ha	Aim for symmetric contours when a specific position is not required.	AA		
Ha	Aim for geometric identifiers.	AA		
Ha	Prefer identifiers on the outer contour.	AA		
Ha	Avoid near symmetry when a specific position is required.	AA		
Ha	Ease handling by using interface elements that can be suspended and prefer a position based on the centre of gravity.	AA		
Ha	Provide features and surfaces outside functional surfaces to aid handling.	MA AA		
Ha	Position handling surfaces based on the centre of gravity.	MA AA		
Ha	Aim for interface elements with stable geometry.	MA AA		

Figure 7.126. Embodiment guidelines for designing interface elements for assembly

- Take into account special production and assembly restrictions (batch size; available machine tools; manual, semi-automatic or automatic assembly).
- Select connecting elements and processes not only based on functional requirements (strength, sealing, and corrosion resistance) but also based on requirements of assembly and disassembly (ease of loosening during disassembly, reuse, potential for automation).
- Consider production and assembly costs together.

Step 4: Evaluate embodiment variants technically and economically, paying particular attention to the required interfacing procedures, that is:

- Evaluate the ease of assembly of a design, preferably as soon as the principle solution is established. Designers should work together with the production planning department, because the assembly plan (assembly sequence and structure [7.112]) and the assembly processes and tools, including quality control, cannot be determined by designers alone. One way to aid the development of an assembly plan is to mentally divide the overall layout drawing into its individual elements; that is, to start by drawing up a disassembly plan. The inverse of this can then provide the basis for the assembly plan of the product. It can also be useful to simulate the assembly process using computer-supported production and assembly planning (CAP) and the production of prototypes.
- Assess the assembly process in terms of the supply of subcontract, bought-out and standard parts.
- Derive evaluation criteria from the goals and embodiment guidelines listed in Figures 7.124 to 7.126, adapting them where necessary to the particular situation.

Step 5: Prepare detailed assembly instructions together with the production documents. This includes overall layout drawings for subassemblies and the product (preassembly and final assembly), the assembly parts list and other assembly information.

7.5.10 Design for Maintenance

1. Goals and Terminology

Technical systems and products are subject to wear and tear, reduction of useful life, corrosion, contamination and changes in time-dependent material properties, such as embrittlement. After a certain period of time, whether in use or not, the actual condition of a system will no longer be the intended one. Deviations from the intended condition cannot always be recognised directly and can cause changes in performance, failures and dangerous situations. This can substantially reduce the functionality, economy and safety of a technical system. Sudden breakdowns disrupt normal operation, and because they are unexpected they require considerable cost to rectify. Not checking the condition of a system until damage has occurred, possibly involving injury, is unacceptable from both human and economic points of view.

Because systems and products have become more complex, the application of maintenance as a *preventative* measure has become increasingly important. Designers have a significant influence on maintenance costs and procedures through their selection of the principle solution and embodiment features, which according to [7.62, 7.304] strongly determine maintainability. We have already emphasised the importance of maintenance in our systematic approach; for example in the guidelines (see Sections 2.1.7 and 5.2.3, Figure 5.3, Section 6.5.2, and Figure 6.22) and their application in connection with the basic rules (see Section 7.3). More recent publications [7.139,7.151] emphasise the importance of an early consideration of maintainability and a systematic approach.

Maintenance is related to safety (see Section 7.3.3), ergonomics (see Section 7.5.6) and assembly (see Section 7.5.9). As the sections in this book addressing these topics already include suggestions and rules relevant to maintenance, this section focuses on what is necessary for a general understanding of maintenance and on design for ease of maintenance.

According to DIN 31051 [7.62], *maintenance* involves monitoring and assessing the actual condition of a system and maintaining or recovering the intended condition.

Possible measures are:

- *Service*, to maintain the intended condition
- *Inspection*, to monitor and assess the actual condition
- *Repair*, to recover the intended condition.

The type, extent and duration of service and inspection measures obviously depend on the type of system, its intended function, its required availability, its desired reliability, and on any potential dangers. The selected measures determine whether inspection and service has to take place after a fixed period of time, after a specific number of operating hours, or after a particular intensity of load.

The *maintenance strategy* is also influenced by the rate of deterioration of components, for example through wear that reduces operating life. The measures applied to recover the intended condition must be taken before components are predicted to fail. Accordingly, two types of repair are distinguished:

- *Failure repair* that takes place after a component has failed. This strategy is applied, and is often the only possibility, when failures cannot be predicted accurately. It is important that such failures do not cause danger. The disadvantage of this approach is the effect it has on planning. An example is the shattering of a car windscreen. This strategy is not suitable for production plant, and in situations where a function must be fulfilled or where danger is involved.
- *Preventive repair* that takes place before a component has failed. This can be determined by either *interval* or *condition*. Interval repair takes place after a fixed period of time, a specific distance or a set number of operations. An example is when the oil in an vehicle engine is changed after 10 000 km. Condition repair is based on actual performance measures, such as the loads or temperatures experienced in operation. When an unwanted condition is observed, the service

or repair measures must be carried out. An example of this is when the oil in a vehicle engine is changed after a certain number of cold starts, or the integrated average temperature of the oil reaches a certain value. Another example is when brake linings are replaced after a measured amount of wear. Whether the interval or condition strategy is applied depends on the operating conditions. A combination of the two strategies is also possible. A power station, for example, will use the time interval repair strategy to safeguard the base load. For components that can last several intervals, the condition repair strategy will be adopted.

More detailed discussions of maintenance strategies can be found in [7.282, 7.304]. Predictions of both the probability of failure and component reliability are discussed in [7.232].

2. Design for Maintenance

Maintenance requirements should have been included in the requirements list, see Figure 5.3 and VDI 2246, Part 2 [7.304]. When solutions have to be selected, easily maintained variants should be preferred. Examples are variants that require minimal servicing, include components that can be exchanged easily, and use components with similar life expectancies. During the embodiment phase, it is important to consider accessibility and ease of assembly and disassembly. However, design for maintenance should never compromise safety.

According to [7.282], a technical solution should, in principle, require as few preventative measures as possible. The aim is complete freedom from the need for service by using components with identical lives, reliability and safety. The chosen solution should thus incorporate features that make maintenance unnecessary or reduce it substantially.

Only when such features cannot be realised or are too costly should service and inspection measures be introduced. In principle, the following aims are important:

- Prevent damage and increase reliability.
- Avoid the possibility of errors during disassembly, reassembly and start-up.
- Simplify service procedures.
- Make the results of servicing checkable.
- Simplify inspection procedures.

Service measures usually concentrate on refilling, lubricating, conserving and cleaning. These activities should be supported by embodiment features and appropriate labelling based on ergonomic, physiological and psychological principles. Examples are easy access, nontiring procedures and clear instructions.

Inspection measures can be reduced to a minimum when the technical solution itself embodies direct safety techniques, see Section 7.3.3, and thus promises high reliability. Overloading, for example, can be avoided by using appropriate principles such as self-help that provide protection against failures and disturbing influences, see Section 7.4.3. When service and inspection measures cannot be avoided, embodiment guidelines, discussed earlier, should be applied [7.282]. In what follows, we limit ourselves to lists and short explanations.

Technical measures that can reduce the service and inspection effort, and should have been considered already in the conceptual phase, include:

- Prefer self-balancing and self-adjusting solutions.
- Aim at simplicity and few parts.
- Use standard components.
- Allow easy access.
- Provide for easy disassembly.
- Apply modular principles.
- Use few and similar service and inspection tools.

Service, inspection and repair instruction documents have to be prepared, and service and inspection points have to be labelled clearly. Guidance on developing maintenance manuals can be found in DIN 31052 [7.63], and guidance on determining maintenance intervals in DIN 31054 [7.64].

To facilitate the execution of service, inspection and repair measures, the following ergonomic rules, supported by appropriate technical embodiments, should be applied:

- Service, inspection and repair locations should be easily accessible.
- The working environment should follow safety and ergonomic requirements.
- Visibility should be ensured.
- Functional processes and supporting measures should be clear.
- Damage localisation should be possible.
- Exchange of components should be easy.

Instructive examples for each of these requirements can be found in [7.282].

Finally, maintenance should be part of the total concept. Maintenance procedures must be compatible with functional and operational constraints of the technical system, and must be included in the overall cost along with the purchase and operating costs.

7.5.11 Design for Recycling

1. Aims and Terminology

To save and reuse raw materials in order to move towards more sustainable development, the following possibilities can be considered [7.141, 7.142, 7.169, 7.186, 7.197, 7.218, 7.302, 7.305, 7.321]:

- *reducing material use* through better utilisation (see Section 7.4.1) and by reducing waste during production (see Section 7.5.8)
- *substituting materials* for those becoming rare and expensive [7.9]
- *recycling materials* by reusing or reprocessing production waste, products and parts of products.

In what follows, possible types of recycling and recycling processes are explained based on VDI Guideline 2243 [7.302]. They help us to understand the embodiment guidelines that support recycling (see Figure 7.127).

Production waste recycling involves reusing production waste in a new production process, for example offcuts (after they have been preprocessed).

Product recycling involves reusing a product or part of it, for example reusing a vehicle's engine (after it has been reconditioned).

Used material recycling is the reuse of old products and materials in a new production process, for example the reprocessing of materials from scrapped vehicles (after they have been preprocessed). These secondary materials or parts do not necessarily have a lower quality than new materials or parts, in which case they can be reused. When the quality is significantly reduced, they can only be used for other purposes.

Preprocessing and reconditioning make significant contributions to effective recycling.

The materials left over from the recycling system end up in waste dumps or in the environment. It is possible that in the future these materials will also be used as resources.

Various methods of recycling are possible within the recycling loops shown in Figure 7.127. Basically one can distinguish between *reusing* products and *reprocessing* products.

Reuse involves retaining the product shape whenever possible. This type of recycling represents a high level of utilisation and should therefore be aimed for. Two types of reuse can be distinguished. In the first, the product fulfils the same function, e.g. refillable gas cylinders, and in the second a different function, e.g. reusing car tyres as boat fenders.

Reprocessing destroys the product shape, and so this process leads to a lower utilisation value. Two types of reprocessing can be distinguished. In the first, reprocessing takes place for application in the same product production process, e.g. reprocessing the materials from scrapped vehicles; in the second, reprocessing takes place for a different application, e.g. converting old plastic into oil by pyrolysis.

2. Recycling Processes

Preprocessing

The reprocessing of production waste and scrap materials is influenced strongly by the necessary preprocessing methods [7.186, 7.197, 7.277, 7.302].

Compacting of loose scrap by *pressing* eases the process of charging in metal making, but does not allow the separation of materials in mixed scrap. It is therefore only suitable for the recycling of unmixed production waste and scrap metals, e.g. food cans.

Cutting heavy or large products can be done with *shears* or *flame cutting*. These methods are particularly suitable when the materials have to be separated afterwards.

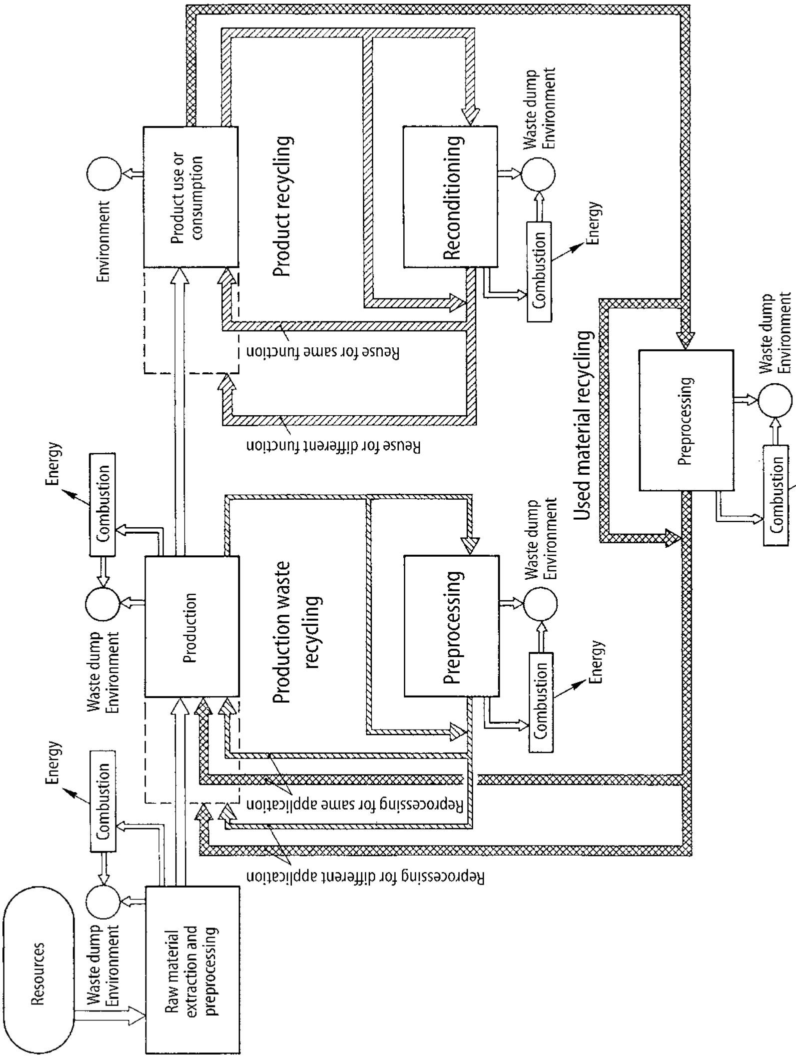


Figure 7.127. Possibilities for recycling, after [7.186, 7.302]

Separating can take place in a *shredding plant* based on the principle of a hammer pulveriser, in which a rotating hammer tears the product apart. In series with this pulveriser are other processes, such as dust removal, magnetic separation, size separation, and manual sorting of materials. Shredded scrap has high quality because of its high density, purity and uniform piece size. These technically complex and labour-intensive preprocessing methods are used for about 80% of scrapped vehicles and about 20% of scrapped domestic products, e.g. refrigerators. *Grinders* provide the same waste quality. They are just as technically complex, differing only in the method of pulverising used prior to material separation.

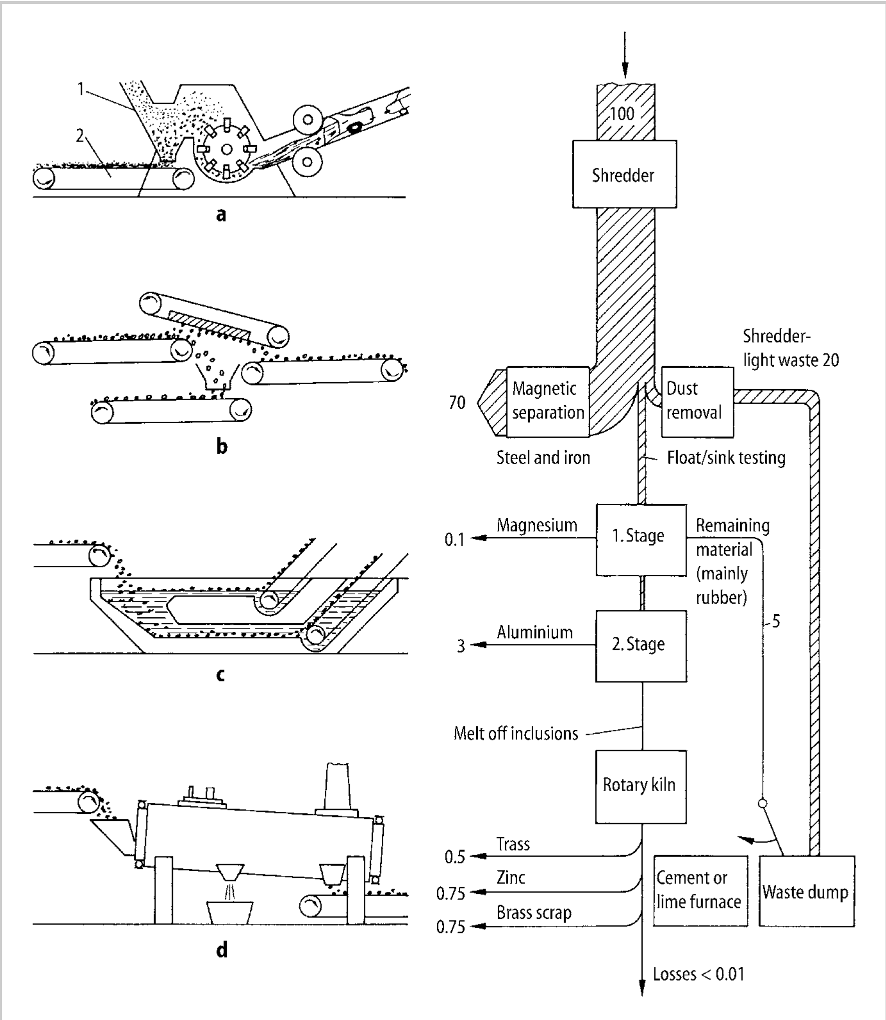


Figure 7.128. Operating principles and material flow in a shredding pant: **a** shredder, *1* dust removal, *2* sorting conveyors; **b** magnetic separation; **c** float/sink testing; **d** rotary kiln

Float/sink testing can be linked to shredders and grinders for improved separation of nonferrous and nonmetallic parts. *Dropping weights* can be used to reduce large grey iron castings with large wall thicknesses. *Chemical preprocessing* can be used to separate harmful materials and alloys before they are used again in metal making.

Figure 7.128 illustrates the material flow in a modern shredding plant [7.302].

Because *plastics* now make up a large proportion of scrap, it is becoming increasingly important to recycle these materials [7.18, 7.109]. The preprocessing of thermoplastics can be achieved through shredding, washing, drying and granulating, provided this waste has been presorted. This is difficult for household waste. The preprocessing of mixed plastic waste can be performed by mechanical separation, such as sorting, sizing and sieving, after it has been broken down into smaller parts. Other methods of separating include the use of electrostatics and floatation for density testing. Such preprocessing methods are still under development, so the sorting of plastics prior to collection would provide an economically viable alternative. Chemical preprocessing can be used for thermosetting plastics and elastomers [7.184].

The best waste and scrap quality—that is, the highest material reutilisation rate—is achieved by *disassembling* the product prior to preprocessing. Such disassembly into appropriate material groups can be undertaken by either specialist companies or by the product manufacturers themselves on dedicated disassembly lines.

The prerequisites for economic disassembly should be established by designers through the selected *embodiment features* and *assembly methods* (see Section 7.5.9). Economic preprocessing of scrap products and materials involves an appropriate combination of disassembly and preprocessing methods [7.186, 7.302].

Reconditioning

In order to be able to reuse products after they have been used for the first time, a reconditioning process that comprises the following steps is required [7.197, 7.266, 7.267, 7.302, 7.319]:

- complete disassembly
- cleaning
- testing
- reuse of worthwhile parts, repair of worn areas, reworking of parts to be adapted, replacement of unusable parts with new ones
- reassembly
- testing.

Two methods are used to recondition products, whether this is undertaken in special companies or by the product manufacturers [7.10]. The first method retains the identity of the original product; that is, while changing and reworking parts the configuration of the parts is retained and the tolerances are matched to each other.

For example, an engine reconditioned using this method will retain its original engine number. The second method breaks up the original product in such a way that all parts are treated as new ones along with their individual tolerances. The result is that the reconditioned original parts and the new parts are combined at the reassembly stage as if they were all new. This method has a promising future because the same production and assembly facilities can be used for both the reconditioned and original products.

3. Design for Recycling

To support preprocessing and reconditioning procedures, designers can introduce specific measures during product development [7.12–7.14, 7.22, 7.141, 7.142, 7.186, 7.187, 7.196, 7.302, 7.320, 7.321, 7.323]. These measures, however, must not conflict with the other goals and requirements of the task (see Figure 2.15). In particular, the cost effectiveness of production and operation must be guaranteed.

Recycling Considerations During the Design Process

Recycling possibilities should be considered during all stages of the design process (see Figures 1.9, 6.1, 7.1, 8.1). Figure 7.129 shows which recycling related design tasks should be undertaken in each of the design phases set out in VDI Guideline 2221 [7.270, 7.323].

Embodiment Guidelines for Preprocessing

The following guidelines relate to the overall product and the individual assemblies. They can be applied singly or in combination, with the aim of improving preprocessing or direct reprocessing.

Material compatibility. It is very difficult to design products made from a single material that can be reprocessed easily. For indivisible units, therefore, the aim should be to use materials that are compatible with regard to reprocessing. This results in an output from the process that is more economical and has higher quality.

To fulfil this aim, the production requirements for reprocessing need to be known. Here it is useful to define so-called scrap material groups or base materials to which compatible materials are assigned. Until such generally applicable groups are identified by materials scientists and the materials processing industry, designers should check the material compatibility in each case with experts. This is particularly important for large batch production with high recycling potential. Figure 7.130 shows a sample compatibility table for plastics.

Material separation. When material compatibility cannot be realised for inseparable parts or assemblies, additional interfaces should be introduced to break products down in such a way that the incompatible materials can be separated during preprocessing, for example through disassembly.

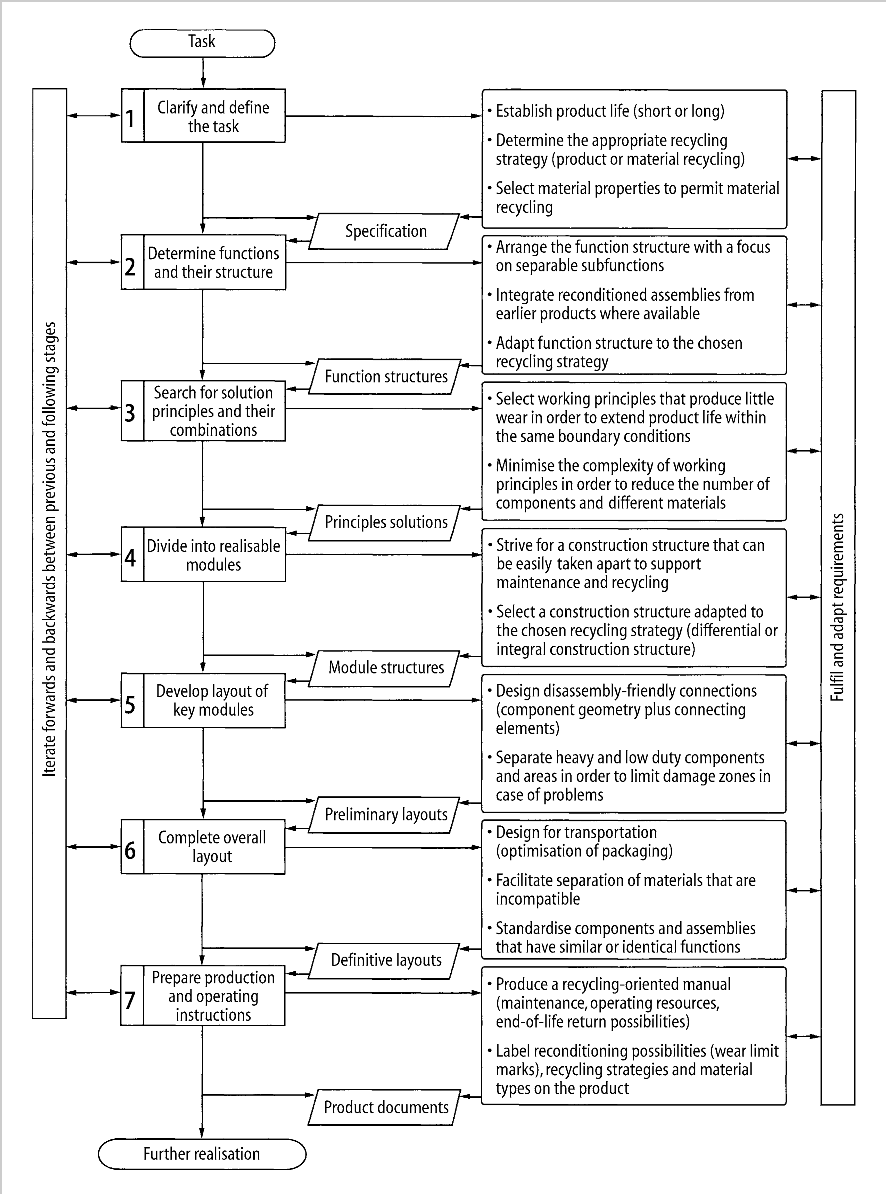


Figure 7.129. Recycling-related tasks allocated to the phases of the design process in VDI 2221 [7.270, 7.293, 7.323]

Interfaces suitable for preprocessing. Interfaces that support high-quality and economic preprocessing should be easily accessed and disassembled, and located near the outer edges of the product. Figure 7.131 shows types of connections that can be easily disassembled. Composite constructions usually require a higher recycling effort [7.119] and should, where possible, be avoided.

Basic material	Important synthetic design materials	Additive: PE	PVC	PS	PC	PP	PA	POM	SAN	ABS	PBTP	PETP	PMMA
	PE	●	○	○	○	●	○	○	○	○	○	○	○
	PVC	○	●	○	○	○	○	○	●	◐	○	○	●
	PS	○	○	●	○	○	○	○	○	○	○	○	○
	PC	○	◔	○	●	○	○	○	●	●	●	●	●
	PP	◔	○	○	○	●	○	○	○	○	○	○	○
	PA	○	○	◔	○	○	●	○	○	○	◔	◔	○
	POM	○	○	○	○	○	○	●	○	○	◔	○	○
	SAN	○	●	○	●	○	○	○	●	●	○	○	●
	ABS	○	◐	○	●	○	○	◔	○	●	◔	◔	●
	PBTP	○	○	○	●	○	◔	○	○	◔	●	○	○
	PETP	○	○	◔	●	○	◔	○	○	◔	○	●	○
	PMMA	○	●	◔	●	○	○	◔	●	●	○	○	●

● Compatible
◐ Limited compatibility
◔ Compatible in small quantities
○ Not compatible

Figure 7.130. Compatibility table for plastics [7.146, 7.302]

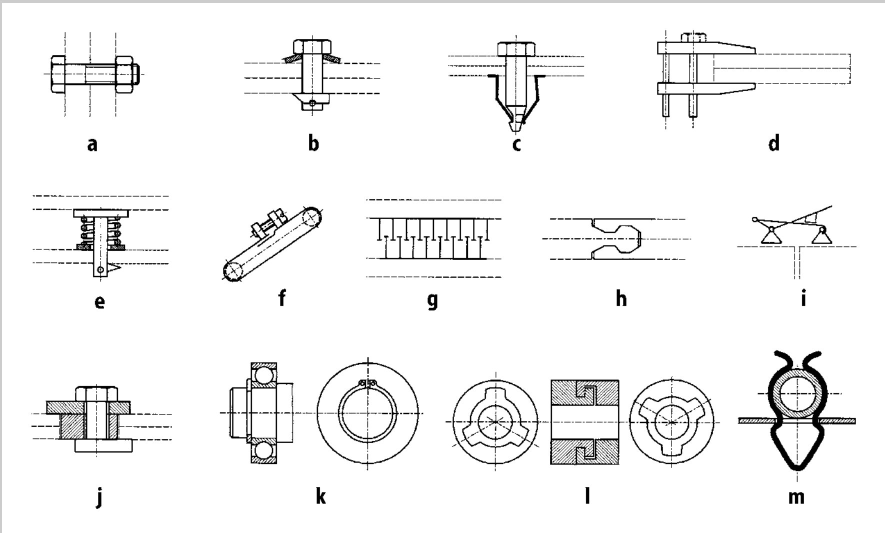


Figure 7.131. Disassembly-friendly connections [7.197, 7.244]. **a** Bolt, **b** quarter-turn fastener, **c** push-turn fastener, **d** clamp, **e** push-push fastener, **f** jubilee clip, **g** velcro, **h** form-fit fastener, **i** lever clamp, **j** eccentric fastener, **k** circlip, **l** bayonet, **m** spring clip

Economical disassembly. Simple tools, automatic processes and untrained personnel are preferred, in particular for disassembly at scrap yards.

High value materials. Valuable and rare materials should be positioned favourably and labelled to facilitate separation.

Dangerous materials. Materials, liquids and gases that can be dangerous to humans and the environment during preprocessing or direct reprocessing should always be easy to separate or remove.

Embodiment Guidelines for Reconditioning

The following guidelines should be applied:

- Ensure easy and damage-free disassembly (see [7.134,7.160,7.194,7.270] for further disassembly guidelines and Figure 7.132 for concepts that ease disassembly—also compare with Section 7.5.9).
- Ensure that all reusable parts can be cleaned easily and without damage.
- Facilitate testing and sorting through appropriate embodiment.
- Ease the reworking of parts or the deposition of material by providing additional material and facilities for locating, clamping and measuring.
- Ease reassembly by using existing tools from one-off and small batch production.

To reduce the number of new parts that are needed, the following measures are useful:

- Limit wear to special-purpose, easily adjustable or exchangeable parts (see Sections 7.4.2 and 7.5.5).
- Make it easy to identify the state of wear of a part and to decide whether it can be reused.
- Ease material deposition on areas of wear by selecting appropriate base materials.
- Minimise corrosion through embodiment and protective measures to increase the reusability of parts (see Section 7.5.4).
- Select connections that function throughout the product life yet can be easily undone, do not slacken after repeated disconnecting, and are not subject to corrosion bonding [7.245, 7.286].

Labelling of Recycling Possibilities

The recycling possibilities and the required recycling procedures for assemblies and modules should be labelled in line with the proposed recycling strategy and the embodiment developed to fulfil that strategy. This allows easy and safe adoption of the required recycling processes and measures. Figure 7.133 provides an example of the labelling of plastic parts.

4. Examples of Design for Recycling

Recycling of Plain Pedestal Bearings (Used Material Recycling)

Plain pedestal bearings (see Figure 9.25) are so common in machines that it is economic to consider recycling. The first possibility is to recycle by reconditioning

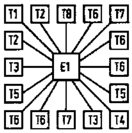
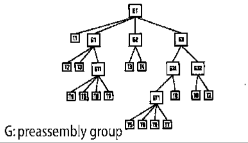
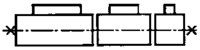
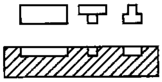
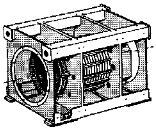
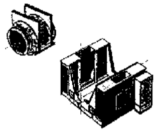
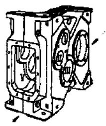
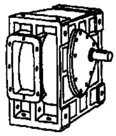
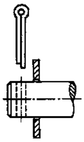
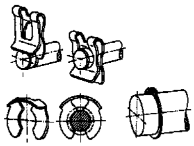
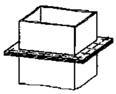
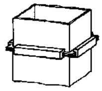
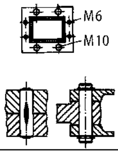
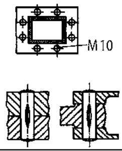
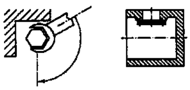
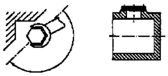
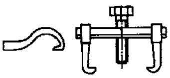
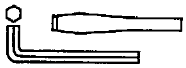
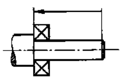
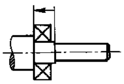
Guidelines	Wrong	Right
Disassembly-friendly construction structures		
Arrange in assemblies consisting of components and materials that are compatible regarding reprocessing.		
Assign the base component of an assembly to a scrap material group suitable for reprocessing.		
Avoid composite construction structures with materials that are incompatible regarding reprocessing where they cannot be separated.		
Reduce the number of interfaces.		
Disassembly-friendly interfaces		
Use connecting and locking elements that can easily be disassembled or destroyed, even after a long operating life.		
Reduce the number of connecting elements.		
Use identical connecting elements.		
Ensure good accessibility for disassembly tools.		
Use simple standard tools.		
Avoid long disassembly paths.		

Figure 7.132. Embodiment guidelines for ease of disassembly [7.197, 7.244]

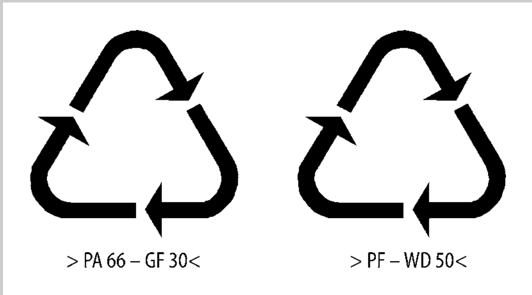


Figure 7.133. Example of labels used for plastic components according to DIN ISO 11469, DIN 7728 T.1 and DIN ISO 1043

the worn-out parts; that is, to provide new or renewed cast bearing shells, lubrication rings and seals. The second is to exchange the bearing completely. Up until now about 99% of used pedestal bearings have been reprocessed as whole bearings (used material recycling, see Figure 7.127), resulting in low reprocessing quality. The reprocessing quality is determined by the purity of the material after the product has been preprocessed. This quality depends on the material combination in the product and the preprocessing technology used. Commonly available plain pedestal bearings, for example, consist of about 74% cast iron, 22.3% unalloyed steel, 3.5% nonferrous metals and 0.2% nonmetals. The weight percentage of the elements in a bearing, similar to the one in Figure 9.25, are compared to the percentages allowed for the scrap material group "unalloyed steel" in Figure 7.134 [7.186]. This figure shows that the percentages of lead (Pb), which can produce a poisonous gas, and both copper (Cu) and antimony (Sb), which cannot be removed, are too high. Thus the recycling of the bearing as a whole has a negative effect on the reprocessing effort and resulting steel quality. Removal of the copper-containing "lubrication ring" and "cast bearing shells" is not economic prior to preprocessing, for example, by shredding. A redesign of the bearing that takes into account recycling consists of choosing materials for these parts that are compatible with the other alloys in the main scrap material group. The lubrication rings, for example,

% of admissible weight / Scrap material group	Evaporating elements			Slag making elements									Addition to slag				Non separable elements								Evaporating elements			
	Li	C	Zn	Ca	Mg	Al	B	V	Ti	Si	Nb	Zr	Mn	Cr	P	S	As	Sb	Co	W	Mo	Ni	Sn	Cu	Toxic Cl	Cd	Be	Pb
Unalloyed steel	Any	2,0 (3,0)	4,0	Any	2,0 (3,0)	2,0 (3,0)	0,2 (0,5)	2,0 (3,0)	2,0 (3,0)	1,5 (2,5)	2,0 (3,0)	1,0 (1,5)	3,0 (4,0)	0,6	0,1 (0,3)	0,1 (0,2)	≪ 0,1	≪ 0,1	0,1	≪ 0,05	≪ 0,05	≪ 0,1	≪ 0,03	≪ 0,3	•	≪ 0,1	≪ 0,1	≪ 0,1
Plain pedestal bearing ERNLB 18-180	% of weight (more than 1%)																											
% of weight	-	2.12	0.012	-	-	0.08	-	-	-	1.16	-	-	0.17	-	0.16	0.16	0.015	0.4	-	-	-	0.01	0.15	0.8	-	0.02	-	2.07

Figure 7.134. Comparison of the weight percentages of the elements in a plain pedestal bearing with the percentages allowed for the scrap material group "unalloyed steel" (Renk-Wülfel)

could be made out of an aluminium alloy with a low copper content (for example $AlMg_3$), and the bearing shell from grey cast iron, with or without a plastic coating.

Recycling of White Goods (Used Material and Product Recycling)

White goods such as washing machines, dishwashers, refrigerators, etc., are valuable for recycling because they are produced in large numbers and contain valuable materials. Figure 7.135 shows the weight percentages of the main materials in a dishwasher. There are numerous nonferrous metals and nonmetals, and a particularly high percentage of high alloy steels. Preprocessing the product as a whole by, for example, shredding is not economic because the high alloy steels cannot be reprocessed separately. In addition, the nonferrous metals complicate the reprocessing process, or at least increase the reprocessing effort. A product structure more suitable for reprocessing would comprise main assemblies that are easy to

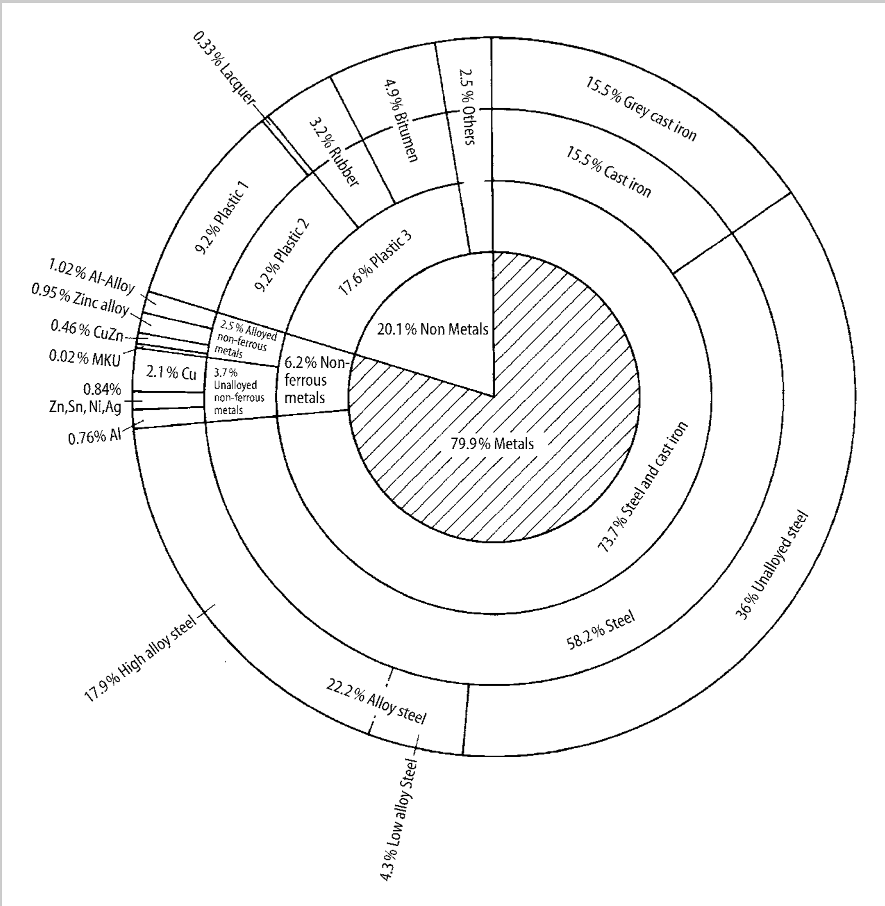


Figure 7.135. Material weight percentages of an AEG dishwasher from 1979/80, after [7.186]

separate or disassemble so that they can be preprocessed separately by, for example, shredding, cutting or compacting. This might also enable the reuse of individual components or even the whole product (product recycling).

Figure 7.136 shows an embodiment variant for the dishwasher. In this embodiment, the base *1* contains all of the accessories including a circulating pump *2*, a water distribution pump *3*, a washing detergent pump *4*, and the electronics *5*. This base assembly has been designed so that no connecting elements are required for the components. They are simply kept in place by the lower part of the casing *6*. The casing and the base can be opened and closed by means of the hinge *7*. The maximum angle achieved after tilting the casing is large enough to assemble all the components and to remove them for recycling (preprocessing or reconditioning).

Another example of white goods is shown in Figure 7.137. Different variants of a washing machine were produced by varying the construction structure of the housing and the location of the functional components. A Use-Value Analysis showed that variant B is the best because it has a lower number of parts and a lower number of reassembly interfaces, which is not only beneficial for recycling but also for maintenance.

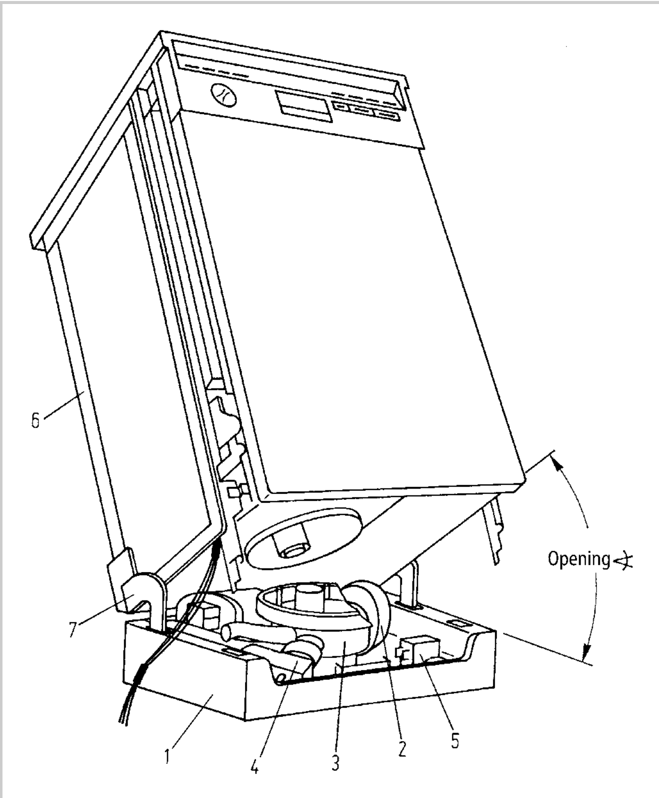


Figure 7.136. Dishwasher designed for recycling (Bosch-Siemens)

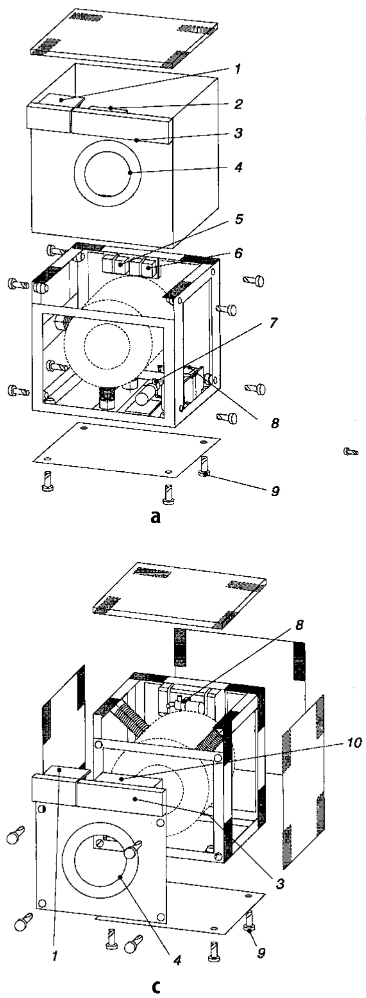


Figure 7.137. Construction structure variants of a washing machine (after Löser, TU Berlin). *1* Dispenser; *2* programme control; *3* display; *4* door; *5* socket and fuses; *6* power electronics; *7* detergent pump; *8* heater; *9* ¼-turn fastener; *10* central electrical unit

Disassembly-Friendly Drive Assembly

Figure 7.138 shows the drive assembly of a hammer drill in which the locating bearing of the motor shaft is not retained axially by the usual circlip, which in principle is easy to disassemble, but by a U-shaped clip that can be pulled out to separate the drive assembly from the motor. The reason for this solution is that a circlip would not be accessible in this assembly.

When developing products that are easier to recycle, particular care must be taken to ensure that they are not more expensive than traditional solutions as far as production and assembly are concerned.

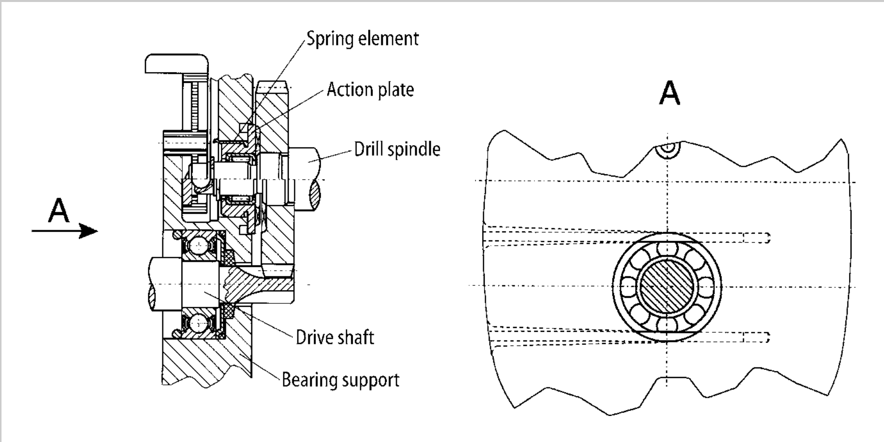


Figure 7.138. Disassembly-friendly gearbox of a hammer drill (Bosch) [7.118]

5. Evaluating Recycling Potential

When developing new products, it is necessary to evaluate solution variants against their potential for recycling [7.160,7.222]. Recycling criteria can simply be included in the evaluation procedure discussed in Section 3.3.2.

Figure 7.139 lists evaluation criteria, which are divided into those related to product recycling and those related to material recycling. To determine the overall rating, the recycling rating can be combined with the technical/economic rating of a product. S-diagrams and value profiles can be used, in particular those that show the distance of a solution variant from an imaginary ideal solution (see Section 3.2.2) [7.11,7.118], to illustrate the individual rating and the overall rating.

Such evaluation procedures can be extended into a product impact assessment [7.118, 7.263, 7.264, 7.324].

7.5.12 Design for Minimum Risk

Despite provisions against faults and disturbing factors (see Chapter 10), designers will still be left with gaps in their store of information and with evaluation uncertainties: for technical and economic reasons, it is not always possible to cover everything with theoretical or experimental analyses. Sometimes all designers can hope to do is to set limits. Thus, despite the most careful approach, some doubt may remain as to whether the chosen solution invariably fulfils the functions laid down in the requirements list or whether the economic assumptions are still justified in a rapidly changing market situation. In short, a certain risk remains.

One might be tempted to always design in such a way that the permitted limits are not exceeded, and to obviate any impairment of the function or early damage by designing a technical system to operate below its potential capacity. Experienced designers know that with this approach they rapidly encounter another risk: the cho-

Product recycling criteria	Material recycling criteria
Function-oriented product structure	**Ease of disassembly:**
Modular structure	Number of disassembly operations
Low complexity	Number of different disassembly operations
Parallel disassembly (flat disassembly tree)	Number of disassembly directions
Easy disassembly (cf. material recycling)	Number of connecting elements
Damage-free disassembly	Number of different connecting elements
Cleaning possibilities	Accessibility
Testing possibilities	Disassembly automation possibilities
Identification possibilities	Low energy for unlocking and separating
Sorting possibilities	Equipment expenditure
Reworking possibilities	Number of required disassembly tools
Reassembly possibilities	
Upgrading possibilities	**Ease of separation:**
Wear detection	Number of required separation process steps and expenditure
Use of standard components	Number of required special treatments and expenditure
Process automation possibilities	Material identification possibilities
	Number of materials to be separated
	Number of materials that cannot be recycled
	Reprocessing opportunities (Degree of utilisation):
	Reuse possibilities for identical functions
	Reuse possibilities for different functions
	Required reprocessing processes
	Degree of recycling
	Degree of quality reduction
	Material upgrading possibilities
	Degree of contamination

Figure 7.139. Evaluation criteria for product and material recycling, after [7.118, 7.197]

sen solution becomes too large, too heavy or too expensive and can no longer compete in the market. The lower technical risk is offset by the greater economic risk.

1. Coping with Risks

Faced with this situation, designers must ask themselves what countermeasures they can take; provided, of course, that the solution was carefully chosen in the first place and that the appropriate guidelines were scrupulously followed. The essential approach is that designers must, on the basis of the analysis of faults, disturbing factors and weak spots, provide a substitute solution to counter the possibility that the original solution might not cover all uncertainties.

In the systematic search for solutions, several solution variants should have been elaborated and analysed. In that case, the advantages and disadvantages of individual solutions will have been discussed and compared, which may have led to a new and improved solution. As a result, designers will be familiar with the range of possible solutions; they will have been able to rank them and also to take stock of the economic constraints.

In principle, the cheapest solution will have been selected, provided that it has sufficient technical merit. Although it may be more risky, it will afford the greatest economic leeway. The chances of marketing the resulting product, and hence of judging the validity of the solution, are greater than those of marketing a costlier product, which might jeopardise the entire development or, because of its "riskless" design, be unable to provide information about performance limits. While they are well advised to adopt this strategy, designers should assiduously avoid risky developments that might lead to damage, breakdowns and a great deal of unnecessary irritation.

If risks cannot be eliminated by theoretical analyses or experiments in good time or with justifiable outlay, designers may be forced to opt for a cheaper and riskier solution, but they should always keep a more costly, less risky alternative in reserve.

To that end, the less cost-effective solution proposals elaborated in the conceptual and embodiment phases should be developed into a second or third solution reserved for critical design areas, and ready for immediate use if needed. Provision for such development should be built into the chosen solution. If the latter does not meet all expectations, it can then be modified, if necessary step-by-step, without any great outlay of money and time.

This systematic approach not only helps to reduce economic risks for a tolerable outlay, but also to introduce innovations one-at-a-time, and to provide a detailed analysis of their performance, so that further developments can be made with minimum risk and at minimum cost. This approach must, of course, be coupled with a systematic follow-up of the practical experiences gained through it.

Through *design for minimum risk*, designers thus try to balance the technical against the economic hazards and so provide the manufacturer with valuable experience and the user with a reliable product.

2. Examples of Design for Minimum Risk

Example 1

A study of possible improvements in the performance of a stuffing box showed that, to increase the sealing pressure and the surface speed, the resulting frictional heat on the shaft had to be removed rapidly in order to keep the temperature in the sealing areas below the limit for the material used in the seals. To that end, it was suggested that the packing rings be mounted on the shaft so as to rotate with it and rub against the housing rather than the shaft. The heat generated by friction could then be extracted through the thin wall (see Figure 7.140a). Theoretical and experimental studies showed that a marked improvement could be obtained if forced convection cooling replaced natural convection cooling (see Figures 7.140b and 7.141).

This raised the difficult question of whether natural convection cooling would nevertheless meet the required operational conditions and, if not, whether the more elaborate and more costly alternative with its additional cooling circuit would be accepted by the customers.

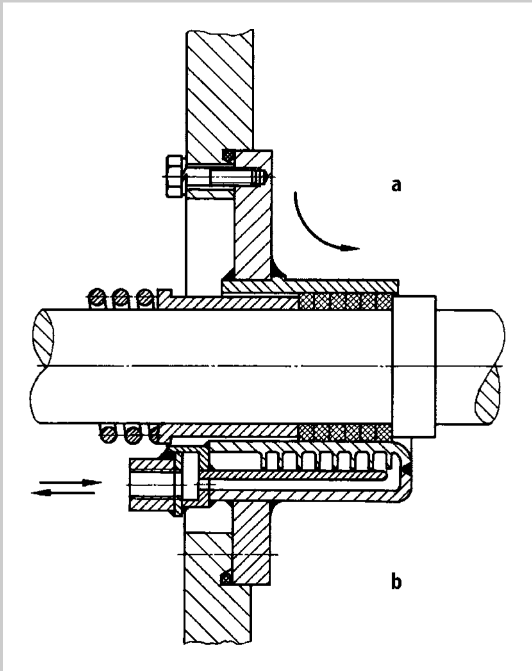


Figure 7.140. Cooled stuffing box in which the packing revolves with the shaft. Appropriate design of the shaft and press ring ensures the internal connection of the packing rings; a very short heat path facilitates good heat extraction. **a** Heat extraction by natural convection currents in the surrounding medium, dependent on the prevailing air flow; **b** heat extraction by forced convection due to separate cooling air flow, ensuring higher flow velocities and increased heat extraction

The minimum risk decision—that is, to construct the housing in such a way that either cooling system could easily be used—helped the designers gain experience for only a small increase in cost.

Example 2

In the development of a series of high-pressure steam valves operating at temperatures of more than 500°C, the question arose as to whether the customary method of nitriding the valve spindles and bushes should be retained despite the fact that the nitrided surface expands with temperature (thereby reducing the radial clearance), or whether very much more expensive stellite hard facing would have to be substituted. When the problem first arose, there was a lack of adequate information about the long-term behaviour of such layers at high temperatures. The minimum risk solution adopted was to select wall thicknesses and dimensions of valve spindles and bushes such that, if necessary and without changing the other components, stellite-treated parts could be substituted for the others. As it turned out, the operating temperature range was considerably lower than had been anticipated, so that nitriding provided a satisfactory solution and also helped to

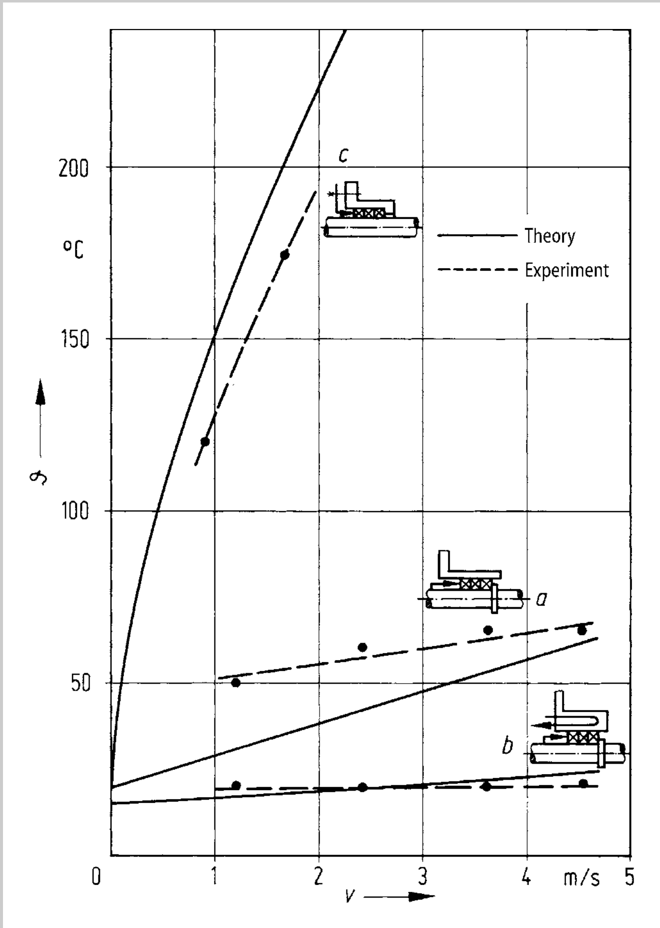


Figure 7.141. Theoretical and experimental temperatures at the seal, plotted against the peripheral speed on the shaft: **a** layout as in Figure 7.140a; **b** layout as in Figure 7.140b; **c** conventional stuffing box with packing attached to the housing

identify the operational limits. Once these limits were known, the more expensive solution could be reserved for more demanding conditions.

Example 3

Reliable design calculations for large machine parts, particularly in one-off production, depend on the analytical methods and the postulated constraints. It is not always possible to predict all characteristics with the necessary degree of accuracy. This applies, for instance, to the determination of the critical whirling speeds of shafts. Often it is impossible to predict the precise flexibility of the bearings and foundations. However, the difference between higher critical whirling speeds in high-speed installations is small within the range of flexibilities normally encountered. In the situation depicted in Figure 7.142, minimum risk design can once again be applied advantageously because the spacing of the bearings, which has a major influence on the critical speed, can be adjusted (see Figure 7.143). Interposed spring laminations (see Figure 7.144), moreover, allow alteration of the effective flexibilities. Both measures, taken together or separately, will produce the

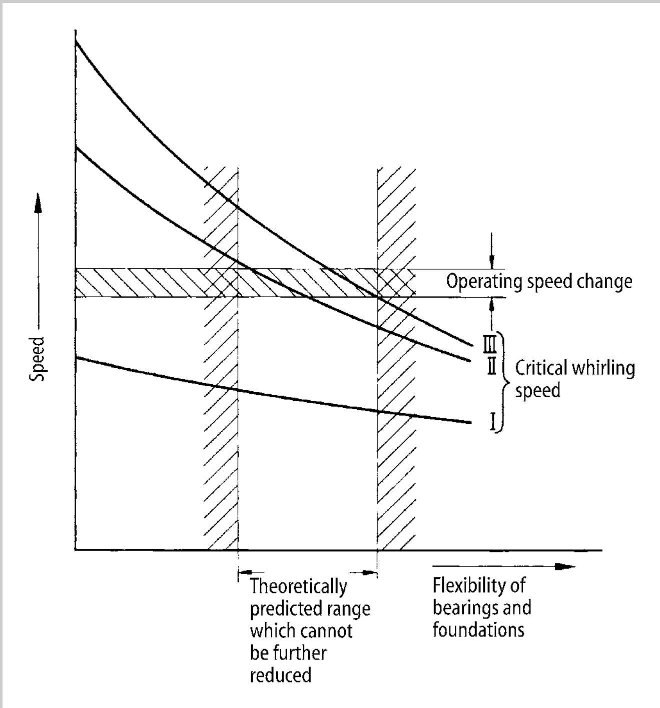


Figure 7.142. Critical whirling speeds (qualitative) for a shaft plotted against the flexibility of bearings and foundations

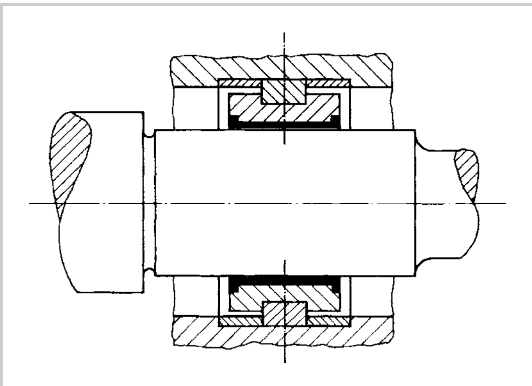


Figure 7.143. Support that allows the distances between the bearings to be varied through the selection of different spacers

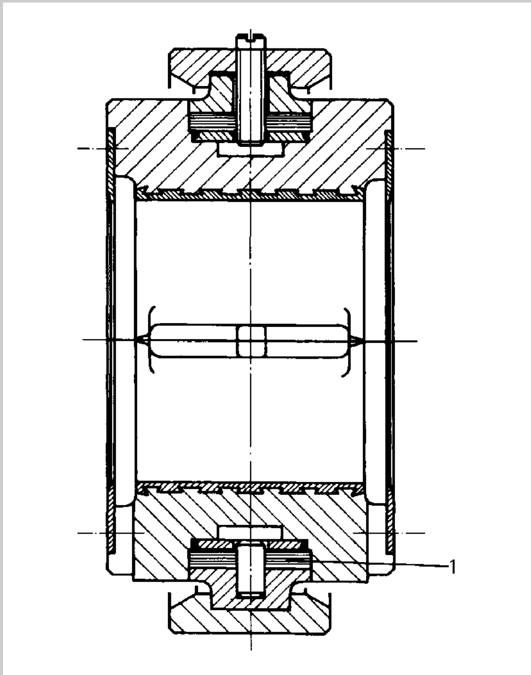


Figure 7.144. Plain bearings with laminated springs 1 that allow the flexibility to be adjusted (laminated springs also have good clamping properties, thus narrowing the critical range)

required effect so that the second or third critical whirling speeds can be eliminated from the operating speed range of the machine.

Example 4

Among the many suggestions put forward for a device to wind a strip into a double-layered ring, two seemed particularly promising (see Figures 7.145a and b).

The solution shown in Figure 7.145a is the simpler and cheaper but also the riskier of the two, because it is not certain whether the inner rotating mandrel *1* alone is invariably able—despite the increased friction produced by the knurling and the pressure of the springs *2*—to move the strip *3* forward.

The solution shown in Figure 7.145b is less risky, because the pressure rollers attached to the ends of the springs and the feed roller *5*, which moreover can be power-driven, make the advance of the strip more certain. This solution, however, is the more costly of the two, and also more susceptible to wear because of the greater number of small moving parts.

The minimum risk solution is to adopt the one shown in Figure 7.145a, but with a feed-in roller as in Figure 7.145b, and arranged in such a way that, if necessary, it can be driven without alteration of the other parts, see Figure 7.145c. This additional feed-in roller proved essential when the machine was tested, and was readily available.

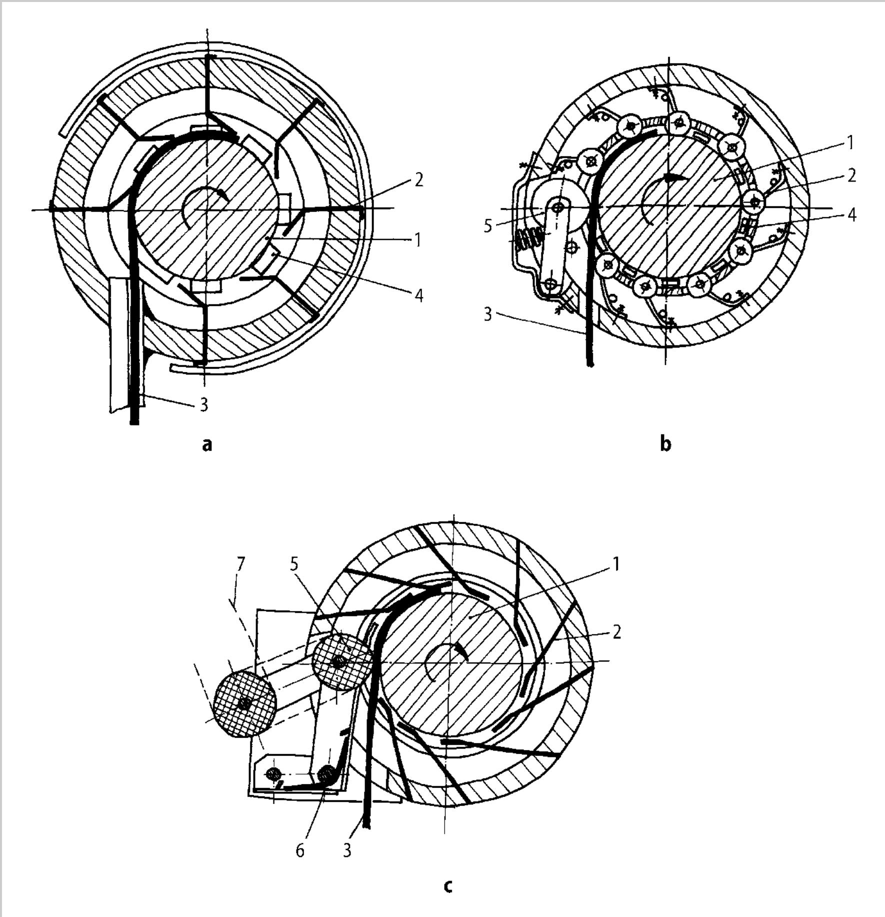


Figure 7.145. a Proposed winding device: *1* rotating mandrel, *2* pressure springs, *3* strip to be wound, *4* parts of the ejection mechanism; **b** proposed winding device: *1* rotating mandrel, *2* springs with pressure rollers, *3* strip to be wound, *4* parts of the ejection mechanism, *5* feed-in roller loaded by spring and possibly driven; **c** Chosen solution: *1* rotating mandrel, *2* pressure springs, *3* strip to be wound, *5* feed-in roller tensioned by spring *6* and driven by belt *7*

Example 5

In complex ventilation systems it is often very difficult to precalculate the airflow and pressure losses precisely. An embodiment with minimum risk for ventilators might have blades that can be adjusted before they are welded to the disc. When enough experience has been gained, it is possible to substitute a nonadjustable and cheaper cast construction.

All of these examples are intended to show that designers should meet risks not by simply considering the first potential problem but by also considering the second and third, which can often be done at relatively minor cost. Experience has shown that the application of emergency measures to correct unforeseen faults is many times more costly and time consuming.

7.5.13 Design to Standards

1. Objectives of Standardisation

If we examine the systematic approach outlined in this book in the light of the minimisation of effort, we are bound to ask to what extent can generally applicable function carriers be determined and documented so that designers can have ready access to tested solutions; that is, to known elements and assemblies. This has also been raised in connection with standardisation which, according to Kienzle [7.149], can be defined as follows: "Standardisation lays down the definitive solution of a repetitive technical or organisational problem with the best technical means available at the time. It is therefore a form of technical and economic optimisation limited by the time factor." Further definitions can be found in [7.34, 7.85].

Standardisation considered as the unification and determination of solutions, for instance in the form of national and international standards (BSI, DIN, ISO), of company standards, or of generally applicable design catalogues, and also of data sheets, is becoming of increasing importance in systematic design. Here, the fact that the objectives of standardisation are to limit the range of possible solutions in no way conflicts with the systematic search for a multiplicity of solutions, because standardisation is largely confined to the determination of individual elements, subsolutions, materials, computation and testing procedures, etc., while the search for a multiplicity of solutions and their optimisation is based on the combination or synthesis of known elements and data. Standardisation is therefore not simply an important complement to but a prerequisite of the systematic approach, in which various elements are combined as so many building blocks.

Traditionally, the speed of research and development allowed standards to be formulated only after the relevant knowledge had been verified and proven in practice. Today, the pace of change, for example in information technology, means that regulations and standards regarding new technologies increasingly have to depend on less well-tested knowledge. This situation is has arisen due to the need to remain competitive in a global market and to influence the direction of further developments. Development and standardisation therefore go hand-in-hand [7.98, 7.128, 7.226], resulting in the increasing publication of pre-standards.

In what follows, we shall be examining the possibilities of, the need for, and the limits of standards in the design process. In addition, the reader is referred to the literature [7.34, 7.85, 7.89–7.93, 7.129, 7.150, 7.216, 7.220, 7.227].

2. Types of Standard

The following discussion of *types of standard* is meant to:

- encourage designers to make wide use of standards
- invite them to suggest new standards or, at the very least, to influence the development of standardisation

- remind them of the crux of standardisation, namely, the systematic arrangement of facts with a view to their unification and optimisation in the light of functional considerations.

In terms of their *origin*, we distinguish between:

- national standards of the BSI (British Standards Institution) or the DIN (Deutsche Institut für Normung: the German Standards Institution)
- European (EN) standards of the CEN (Comité Européen de Normalisation) and CENELEC (Comité Européen de Normalisation Electrotechnique)
- recommendations and standards of the IEC (International Electrotechnical Commission)
- recommendations and standards of the ISO (International Organisation for Standardisation).

In terms of their *content*, we distinguish, for instance, between communication standards, classification standards, type standards, planning standards, dimensional standards, material standards, quality standards, procedural standards, operational standards, service standards, test standards, delivery standards and safety standards.

In terms of their *scope*, we distinguish between basic standards (general and interdisciplinary standards) and special standards (standards used in specialist fields).

Besides the national and international standards we have mentioned, designers can also refer to the rules and regulations published by professional engineering institutions, e.g. VDI, ASME, IMechE. These are important as they pave the way for further standardisation after initial trials.

Designers can also refer to a variety of *internal company standards* and regulations [7.86–7.88]. These can be classified as follows:

- compilations of representative standards; that is, a *selection* of general standards that are applicable to the special requirements of a particular company, such as stock lists and comparisons of old with new standards (synoptic standards)
- catalogues, lists and data sheets on *bought-out parts*, including their storage and also data on the acquisition (ordering/supplying) of raw materials, semi-finished materials, fuels, etc.
- catalogues or lists of *in-house parts*, for instance machine elements, repeat parts, standard solutions, assemblies, etc.
- information sheets used for *technical and economic optimisation*, for instance those on production capacity, production methods, cost comparisons (see Section 11.3.2).
- rules and regulations for the *calculation and embodiment design* of machine elements, assemblies, machines and plant, if necessary with a selection of sizes and/or types

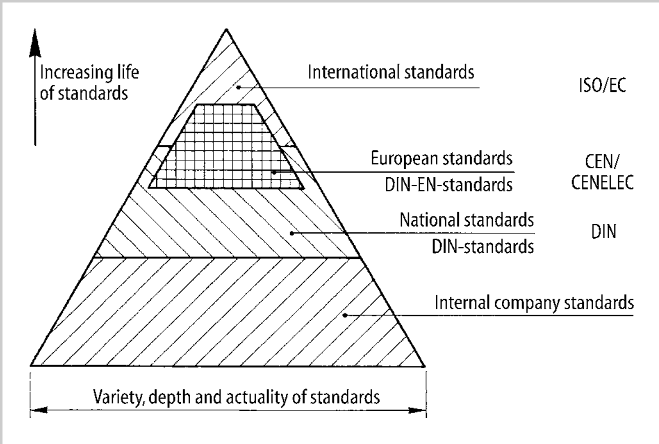


Figure 7.146. Relation between company, national, European and international standards based on DIN

- information sheets on *storage and transport* resources
- regulations concerning *quality control*, for example inspection and testing procedures
- rules and guidelines for the *preparation and processing of information*, for instance of drawings, parts lists, numbering systems and electronic data processing
- rules laying down *organisational and working procedures*, for instance the updating of parts lists and drawings.

The relation between company, national, European and international standards is shown in Figure 7.146. Company standards are developed or selected for specific products or processes and adapted to the actual situation. This implies that their depth and actuality is high. National and international standards require a longer period of development, but are more generally applicable. The variety and depth of these standards is generally lower. It is more difficult to adapt them to changes and therefore their dissemination and effects are more important.

3. Preparing Standards

Searching for and using standards, regulations and other information during the design process requires considerable effort. There are various ways in which information is made available: folders with standards, BSI or DIN handbooks and guides, microfiche and increasingly computer databases. These databases are now being integrated into CAD systems, providing designers not only with the textual information contained in standards, but also with the geometry of the components [7.6, 7.124, 7.238, 7.239].

4. Using Standards

Although there are no absolutely binding standards in the legal sense at the time of writing, national and international standards are widely treated as regulations, adherence to which is of great advantage in the case of legal disputes. This is particularly true of safety standards [7.23, 7.57, 7.115, 7.254, 7.303].

In addition, all company standards should be considered binding within their sphere of application, not least for economic reasons.

The *sphere of application* of a given standard is largely set by Kienzle's definition (see above). A standard can only be valid and binding if it does not conflict with technical, economic, safety or even aesthetic demands. Even in the case of such conflicts, however, designers should guard against rejecting or replacing the relevant standards out of hand, without assessing the possible consequences. Moreover, they should never make such assessments by themselves, but should always consult the standards organisation and the head of department.

In what follows, a number of recommendations and hints for the correct use of standards are listed.

First of all, we recommend adherence to national basic standards since other standards are based on these and the preferred sizes laid down in them help to determine the dimensions of all components. If these basic standards are ignored, then unpredictable long-term consequences (for instance, in the provision of spare parts) and grave technical and economic risks may ensue.

The use of standards should be examined against the checklist provided in Section 7.2, as illustrated by the following examples.

Layout

The basic and special standards—especially constructional, dimensional, material and safety—must be fully taken into account. Testing and inspection procedures also influence the embodiment.

Safety

Established component, work and environmental safety standards and regulations must be rigorously observed. Safety standards must always be given precedence over rationalisation procedures and economics.

Production

Here, the observance of production standards is particularly important and that of factory regulations is binding. This necessitates the continual updating of the relevant standards. Designers should only deviate from production standards after a broad assessment of all the industrial and relevant market (purchase and sales) aspects.

Quality Control

Test standards and inspection rules are essential features of quality control.

Maintenance

Standard symbols (for instance, circuit diagrams) should be used and service standards should be provided.

Recycling

For reuse and reprocessing, test, material, quality, dimensional, production and communication standards are particularly important.

The above recommendations on the use of standards are by no means exhaustive—the work of designers is much too varied and complex for that, and the range of general and company standards much wider than we have been able to cover in our summary. By working their way down the checklist, designers can tell how much a particular standard fits the various headings quickly and accurately.

5. Developing Standards

Since designers bear much of the responsibility for the development, production and utilisation of products, they should play a leading role in the revision of existing standards, and the development of new ones.

To make a useful contribution to the development of standards, they must first determine whether the revision of an existing standard or the development of a new standard is technically and economically justified. There is rarely a clear-cut answer to this question. In particular, completely reliable assessments of the economic consequences are seldom possible because of the complex effects of in-house costs and market influences, and, in any case, they would involve considerable research.

The following principles of developing general standards, and particularly company standards, can be set down [7.7, 7.30, 7.33, 7.271]. Whether something should be standardised depends on several prerequisites, that is, the envisaged standard must:

- document the state of the art of the technology
- be accepted by the majority of experts in the field
- ensure the complete interchangeability of parts, for example if a standardised product is modified in such a way that it can no longer be freely interchanged even with respect to a single feature, its designation (identification number) must be altered
- only be used if it is economical and useful, that is, there must be a need
- only be altered for technical, not purely formal, reasons
- always support a simple, clear and safe solution
- not contain any provisions that conflict with the law, e.g. with monopoly restrictions or safety regulations

- not include solutions that are protected, e.g. by patents or copyright
- not formulate design and production details
- not concern topics that are developing rapidly
- not hinder technical progress
- not allow subjectiveness or interpretation
- not standardise fashion and taste
- not endanger the safety of humans and the environment
- not serve a single individual; that is, the people affected must be consulted during the development and no standardisation should take place when important groups are opposed.

Moreover, the following aspects should be considered:

- Standards must be unambiguous, framed in clear terms and easily understood [7.35].
- Standard dimensions must, as far as possible, agree with preferred number series.
- All standards must be based on SI units [7.93].
- The layout of a standard should support its use and application. In particular, the use of computer-based information systems should be facilitated [7.124, 7.238, 7.239].

The development of a standard should generally include the following steps:

- A standard is proposed.
- The proposal is discussed in a working committee which develops a draft standard.
- This draft is circulated to all interested and affected parties and modified.
- After the draft has been accepted, a pre-standard can be issued for evaluation purposes.
- The final standard is issued.

Because a standard can be regarded as an artificial system, its preparation should also follow the steps of systematic design (see Chapters 4, 6 and 7). This ensures the optimisation of a standard's content and layout, and facilitates its careful development, which can be subsequently verified.

The evaluation criteria set out in Figure 7.147, once again arranged in accordance with the checklist, can be of great help in the assessment of existing or newly proposed standards if they are used in conjunction with the usual evaluation procedure. Not all the evaluation criteria we have mentioned apply to the assessment of individual standards. Thus, the evaluation of a drawing standard is influenced by its clarity; by the improvement in communication; by the simplification of the design activity and the overall execution of the order it provides; by the degree to which it is generally accepted; and also by the costs its development entails. Before

Headings	Examples
Function	Lack of ambiguity ensured.
Working principle	Market position of the product favourably influenced.
Layout	Material and energy expenditure reduced. Complexity of the product reduced. Design work improved and simplified. Use of replacement parts facilitated.
Safety	Safety increased.
Ergonomics	Clarity of instructions improved. Psychological and aesthetic conditions improved.
Production	Materials handling, storekeeping, production and quality control facilitated. Precision and reproducibility ensured. Execution of the orders simplified. Planning improved. Production capacity increased.
Quality control	Inspection and testing simplified. Quality improved.
Assembly	Assembly facilitated.
Transport	Transport and packing simplified.
Operation	Operation clarified.
Maintenance	Replacement of parts improved. Spare parts service and maitenance facilitated.
Recycling	Recycling facilitated.
Costs	Costs of, and/or time spent on, design, work preparation, materials handling, production, assembly and quality control reduced. Test costs reduced. Calculations simplified. Electronic data processing introduced.

Figure 7.147. Evaluation criteria for the assessment of standards

they make an evaluation, standards engineers or designers should therefore grade the importance of the various evaluation criteria and discard those that may not apply. In much the same way as with the recommendations in Section 3.3.2, there must be an adequate value rating to justify the development of a standard.

7.6 Evaluating Embodiment Designs

In Section 3.3.2 we discussed the subject of design evaluation. The basic procedures outlined there apply equally well to the conceptual and to the subsequent phases. As embodiment progresses, the evaluation will, of course, rest on more and more concrete objectives and properties.

In the embodiment phase, the technical properties must be evaluated in terms of the *technical rating* R_t and the economic properties separately with the help of the calculated production costs in terms of the *economic rating* R_e. The two ratings can then be compared in a diagram (see Figure 3.35).

The *prerequisites* for this approach are the following:

- All the embodiment designs have the same degree of concreteness; that is, the same information content (for instance, rough designs must only be compared with rough designs). In many cases it suffices, while keeping the overall perspective in mind, to evaluate only those aspects that show marked differences from one another. Once that has been done, their relationship to the whole, of course, must be examined; for example the relationship between part costs and total costs.

- The manufacturing costs (materials, labour and overheads) can be determined (see Chapter 11). If a particular solution introduces subsidiary costs, such as operating costs, and demands special investment, then—depending on the point of view (the producer's or the user's)—these factors must be allowed for, if necessary by amortisation. In addition, optimisation can help to achieve a minimisation of production and operating costs.

If the calculation of manufacturing costs is omitted, then the economic rating can only be evaluated qualitatively, as it was in the conceptual phase. In the embodiment phase, however, costs should, in principle, be determined more concretely (see Chapter 11).

As we mentioned in Section 3.3.2, the first step is to establish the *evaluation criteria*. They are derived from:

- the requirements list:
  - desirable improvement on minimum demands (how far exceeded)
  - wishes (fulfilled, not fulfilled, how well fulfilled)
- the technical properties (to what extent present and fulfilled).

The comprehensiveness of the evaluation criteria can be tested against the headings of the checklist (see Figure 7.148), which is specially adapted to the level of embodiment attained.

At least one significant evaluation criterion must be considered for each heading, although sometimes more will be needed. A heading may only be ignored if the corresponding properties are absent from, or identical in, all the variants. This approach avoids subjective over-valuation of individual properties. It must be followed by the procedural steps outlined in Section 3.3.2. The economic feasibility should be established by this stage at the latest.

In the embodiment phase, the search for weak spots, errors and disturbing influences, along with their elimination, is essential, in particular when evaluating the final layout.

7.7 Example of Embodiment Design

The *conceptual design phase* involves a process that focuses mainly on functions and working structures and results in principle solutions (concepts).

In the *embodiment design phase*, the emphasis is on determining the construction structures of the individual assemblies and components. In VDI 2223 and in Chapter 4 (Figure 4.3) and Chapter 7 (Figure 7.1) of this book, a systematic approach is proposed that has been tested in practice. The variations in approach

Headings	Examples
Function, Working principle	Fulfilment in accordance with the selected working principle: efficiency, risk, susceptibility to disturbances
Layout design	Space requirements, weight, arrangement, fits, scope for modifications
Form design	Material utilisation, durability, deformation, strength, operating life, wear, shock resistance, stability, resonance
Safety	Direct safety methods, industrial safety, protection of the environment
Ergonomics	Human–machine relationship, workload, handling, aesthetics
Production	Risk-free methods, setting-up time, heat treatment, surface treatment, tolerances
Quality control	Quality standards, testing possibilities
Assembly	Unambiguous, easy, comfortable, adjustable, upgradable
Transport	Internal and external transportation, means of despatch, packing
Operation	Handling, operational behaviour, corrosion properties, consumption of resources
Maintenance	Servicing, checking, repair and exchange
Recycling	Disassembly, reuse potential, reprocessing potential
Costs	Evaluated separately (economic rating)
Schedules	Production schedule and completion date

Figure 7.148. Checklist for evaluating embodiment designs

and methods needed to deal with different tasks and problems are greater in embodiment design than in conceptual design. Embodiment design, characterised by a further elaboration of the selected principle solution, requires a more flexible approach, extensive knowledge of the relevant domain and greater experience.

Explaining embodiment design using examples for different tasks would require too much space. It would also be misleading because such examples might suggest that the specific approach described is the only correct one. The example used in the rest of this chapter is based on the principle solution discussed in Chapter 6. Its only purpose is to show how the main embodiment steps of Figure 7.1 are executed and linked together.

The embodiment task is the concretisation of the principle solution for the impulse-loading test rig for shaft–hub connections (see Section 6.6.2). That section described the clarification of the task and the setting up of the requirements list (see Figure 6.43); the identification of the essential problems through abstraction (see Table 6.2); the establishment of function structures (see Figures 6.44 and 6.45); the search for working principles (see Figure 6.46); the combination of working principles into working structures (see Figure 6.47); the selection of suitable working structures (see Figure 6.48); their concretisation into principle solution variants (see Figures 6.49 to 6.52); and the evaluation of these solution variants (see Figures 6.55 and 6.56). We now continue with the embodiment design of this example following the steps shown in Figure 7.1.

Steps 1 and 2: Identifying Embodiment-Determining Requirements and Clarifying Spatial Constraints

The following items from the requirements list were identified as determining the embodiment features:

- Determining layout:
  test connection held in position
  loading applied to stationary shaft in one direction only
  hubside load take-off variable
  torque input variable
  no special foundation.
- Determining dimensions:
  diameter of shaft to be tested ≤ 100 mm
  adjustable torque $T \leq 15\,000$ Nm (maintained for at least 3 s)
  adjustable torque increase $\mathrm{d}T/\mathrm{d}t = 1.25 \times 10^3$ Nm/s
  power consumption ≤ 5 kW.
- Determining material:
  shaft and hub: 45C.
- Other requirements:
  production of the test rig in own workshops
  bought-out and standard parts wherever possible
  easy to disassemble.

The requirements list did not contain specific spatial constraints.

Step 3: Identifying Embodiment-Determining Main Function Carriers

The basis for this step was function structure variant No 4 (see Figure 6.45) and the principle solution variant V_2 (see Figure 6.47). Table 7.6 lists the *main function carriers* used in the selected solution variant to fulfil the various subfunctions, along with their main characteristics. The function carriers that determined the embodiment are:

- the test specimen
- the lever between the cylindrical cam and the shaft of the test specimen
- the cylindrical cam.

The other main function carriers are:

- the electric motor
- the flywheel

Table 7.6. Main function carriers

Functions	Function carriers	Characteristics
Transform energy; increase energy component	Electric motor	Power P_M Speed n_M Run-up time t_M
Store energy	Flywheel	Moment of inertia J_F Speed n_F Torque transmitted T_{CL}
Release energy	Clutch	Torque transmitted T_{CL} Maximum speed n_{CL} Response time t_{CL}
Increase energy component	Gearbox	Power P_G Maximum output torque T_G at output speed n_G Gear ratio R_G
Control magnitude and time	Cylindrical cam	Power P_{CAM} Torque T_{CAM} Speed n_{CAM} Diameter D_{CAM} Cam angle α_{CAM} Rise h_{CAM}
Transform energy into torque	Lever	Length l_L Stiffness s_L
Load test specimen	Test specimen	Torque T Rate of torque increase $\mathrm{d}T/\mathrm{d}t$
Take up forces and torque	Frame	

- the clutch
- the gearbox
- the frame.

Step 4: Developing Preliminary Layouts and Form Designs for the Main Function Carriers

Figure 7.149 shows a preliminary layout drawing for the three embodiment-determining function carriers.

The embodiment of the test specimen in line with DIN 6885 and of the transmission lever, modelled and analysed as a cantilever, were relatively straightforward. The development and embodiment of the cylindrical cam, however, required a more detailed kinematic and dynamic analysis based on specific items in the requirements list.

A more precise analysis showed that the initial estimates undertaken in the conceptual phase of the cylindrical cam's performance were insufficient to proceed directly to embodiment. The following analysis therefore had to be carried out before determining the main dimensions.

Figure 7.150 shows that:

Torque on the shaft: $T = s_L \cdot h_{CAM} \cdot l_L$

Torque increase: $\mathrm{d}T/\mathrm{d}t = \pi \cdot D_{CAM} \cdot n_{CAM} \cdot \tan \alpha_{CAM} \cdot s_L \cdot l_L$

Hold time: $t_L = \dfrac{U_{CAM}}{2\pi \cdot D_{CAM} \cdot n_{CAM}} = \dfrac{1}{2 \cdot n_{CAM}}$

The equation for the torque increase is only valid if the lever movement is parallel to the cam track. In order to minimise friction, a roller follower was required (see Figure 7.151), so the actual torque increase was lower than calculated and also varies. We therefore used the average increase in our calculations (see Figure 7.152).

If, in line with the requirements list, the average torque increase $\mathrm{d}T/\mathrm{d}t$ is used, then the calculation of $\mathrm{d}T/\mathrm{d}t$ should not involve the full circumferential speed v_X, but instead the effective circumferential speed v_X^*, thus:

$$v_X^* = K \cdot v_X$$

The correction K depends on:

- the cam angle α_{CAM}
- the diameter of the roller follower d
- the rise of the cylindrical cam h_{CAM}.

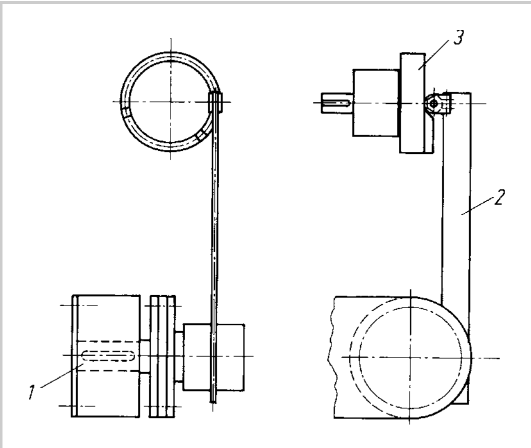


Figure 7.149. Main function carriers that determine the layout: *1* test connection; *2* transmission lever; *3* cylindrical cam

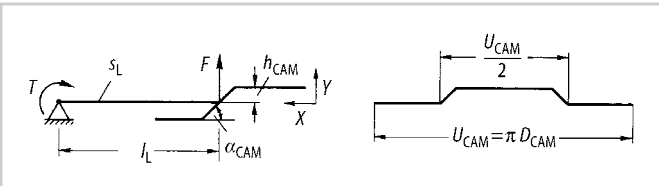


Figure 7.150. Geometric constraints for the cylindrical cam and lever. s_L is the stiffness of the lever

The correction K was derived from Figure 7.153:

$$x = \frac{h_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}}$$

$$x = d/2 \cdot \left(\sin \alpha_{\mathrm{CAM}} - \frac{1 - \cos \alpha_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}} \right)$$

$$K = \frac{v_{\mathrm{X}}^{*}}{v_{\mathrm{X}}} = \frac{x}{x + \Delta x}$$

The formula is only valid when $d/2 \cdot (1 - \cos \alpha_{\mathrm{CAM}}) \leq h_{\mathrm{CAM}}$, for example:

$$K = \frac{\frac{h_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}}}{\frac{h_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}} + d/2 \cdot \left(\sin \alpha_{\mathrm{CAM}} - \frac{1-\cos \alpha_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}} \right)}$$

To obtain a value for K, the following estimates were made:

- cam angle $\alpha_{\mathrm{CAM}} = 10 \ldots 45°$

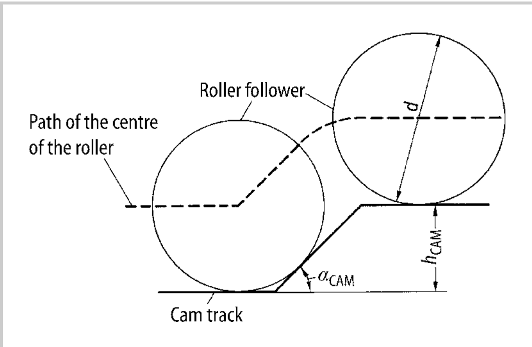


Figure 7.151. Cam path and lever movement

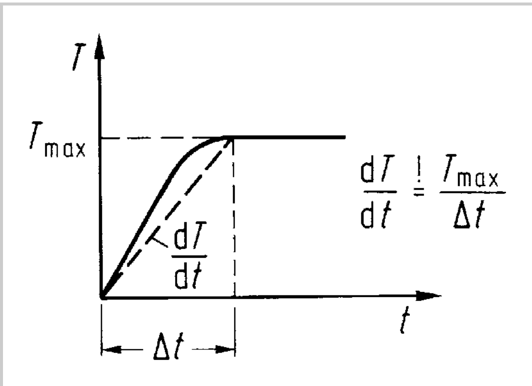


Figure 7.152. Torque increase

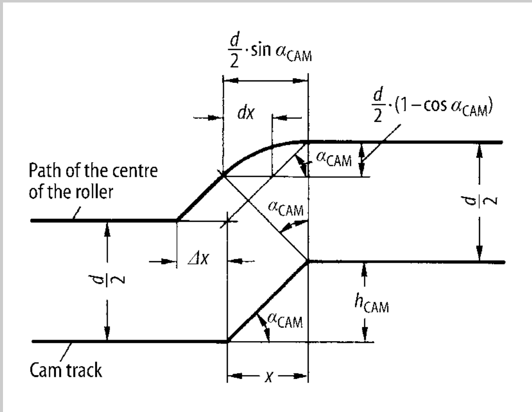


Figure 7.153. Derivation of correction K

- the diameter of the roller follower $d = 60$ mm
- the rise of the cylindrical cam $h_{CAM} = 7.5$ mm and 30 mm, respectively.

Table 7.7 contains the values of K obtained from the above formula.

After converting the cylindrical cam speed n_{CAM} and using the calculated correction value K, the formula including torque increase $\mathrm{d}T/\mathrm{d}t$ became:

$$n_{CAM} = \frac{\frac{\mathrm{d}T}{\mathrm{d}t}}{K \cdot \pi \cdot D_{CAM} \cdot \tan \alpha_{CAM} \cdot s_L \cdot l_L}$$

The speed controller range C

$$C = \frac{n_{CAM\max}}{n_{CAM\min}}$$

was determined as follows.

If the diameter of the cylindrical cam D_{CAM}, the stiffness s_L and the length l_L of the lever are considered constant for this solution concept, the above formula can be used to calculate the extremes of the speed n_{CAM} in relation to the other parameters $\mathrm{d}T/\mathrm{d}t$, K and α_{CAM} (see Table 7.8).

B is a constant that includes units and the other constants (π, D_{CAM}, s_L, l_L).

Table 7.7. Reference values for K corrections

h_{CAM} mm	α_{CAM}	45°	40°	30°	20°	10°
7.5	K	0.41	0.45	0.62	0.79	0.94
30.0	K	0.71	0.76	0.87	0.94	0.98

Table 7.8. Determination of $n_{\mathrm{CAM}_{\min}}$ and $n_{\mathrm{CAM}_{\max}}$

	$\mathrm{d}T/\mathrm{d}t$	α_{CAM}	K	n_{CAM}
Minimum	20	10	0.98	$116 \cdot B$
Maximum	125	45	0.41	$305 \cdot B$

The speed control range C therefore became:

$$C = \frac{305 \cdot B}{116 \cdot B} = 2.6$$

This meant that:

- The function "control magnitude and time" could not be fulfilled by the cylindrical cam alone.
- The function structure had to change if we wished to maintain the principles underpinning the concept.
- The cylindrical cam had to have an adjustable drive with a speed control range of approximately $C = 2.6$.

Figure 7.154 shows the adapted function structure variants (see Figure 6.45). The subfunction "adjust speed" was added. This could, for example, be realised by a continuously adjustable drive motor. Several variants were possible (4/1 to 4/3).

The quantitative developments of the cylindrical cam based on these formulae resulted in the following values for the main characteristics: spring stiffness of the lever $s_{\mathrm{L}} = 700$ N/mm; lever length $l_{\mathrm{L}} = 850$ mm; cylinder diameter $D_{\mathrm{CAM}} = 300$ mm; cam angle $\alpha_{\mathrm{CAM}} = 10 \ldots 45°$; constant $B = 0.107\ \mathrm{min}^{-1}$ (see Table 7.8); speed range for the required rate of torque increase ($\mathrm{d}T/\mathrm{d}t_{\min} = 20 \times 10^3$ Nm/s, $\mathrm{d}T/\mathrm{d}t_{\max} = 125 \times 10^3$ Nm/s), $n_{\mathrm{CAM}} = 12.4 \ldots 32.6\ \mathrm{min}^{-1}$ for a control range $C = 2.6$.

The requirements for the adjustable torque increase $\mathrm{d}T/\mathrm{d}t$ could therefore be realised with the selected values.

This was not the case for the required hold time for the maximum torque. This value was $t_{\mathrm{L}} = 0.5 \cdot n_{\mathrm{CAM}} = 2.4 \ldots 0.92$ s, which was lower than the required value of 3 s. After a discussion with the client, the requirement was reduced to $t_{\mathrm{L}} \geq 1$ s, which could be realised by using slightly more than half of the circumference of the cylindrical cam.

Before a scale layout for the main function carriers that determine the embodiment could be drawn, the following issues had to be resolved:

- What spatial layout of the test specimen and the cylindrical cam should be used?
- To what extent should auxiliary function carriers be considered?

It was decided that the test specimen should be positioned horizontally, and as a consequence the cylindrical cam should rotate about a vertical axis for the following reasons:

- Easy exchange of test specimen and cylindrical cam (design for assembly).

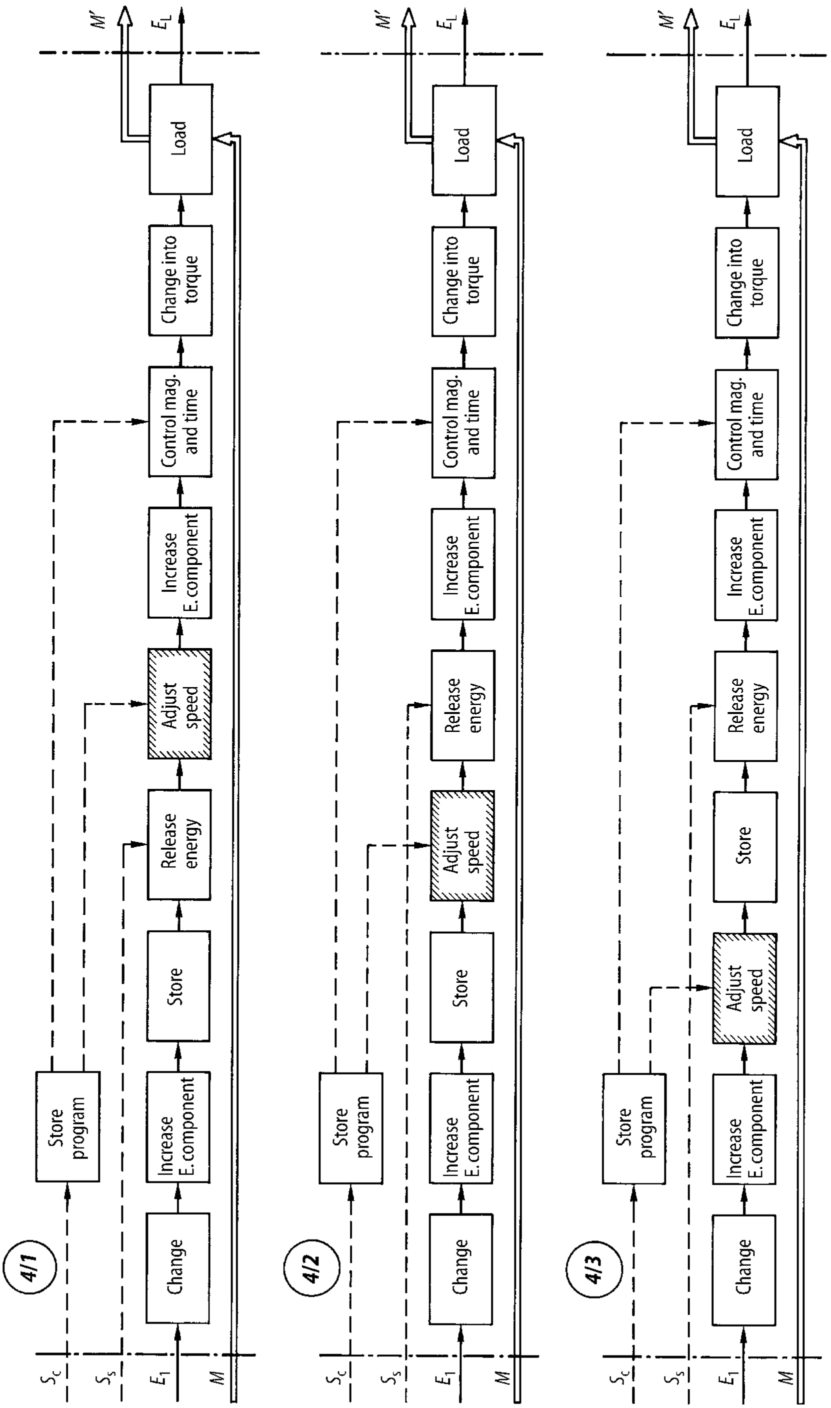


Figure 7.154. Function structure variants for function structure 4, after Figure 6.45

- Easy access to the test specimen for measurements (design for ergonomics).
- Smooth transmission of the clamping forces of the test specimen into the foundation (short and direct force transmission paths).
- Easy resetting of the test rig for different types of specimen, in particular larger specimens (design for minimum risk).

The need for auxiliary function carriers was then assessed and the space requirements determined on the basis of experience. It was found that:

- A separate bearing was needed for the cylindrical cam because of the axial force F_A and the tangential force F_T:

$$F_A = F_T = \frac{T_{max}}{l_L} = 17.6\ \text{kN}$$

- The outer diameter of the bolted joint between test specimen and lever had to be about 400 mm to provide a torsionally stiff connection.

The analysis showed that the auxiliary function carriers had only a marginal influence on the dimensions of the embodiment.

Figure 7.155a shows a preliminary layout based on function structure variant *4/1*, where the speed control is achieved by means of an adjustable mechanism that is located behind the clutch in terms of the energy flow. Figure 7.155b shows

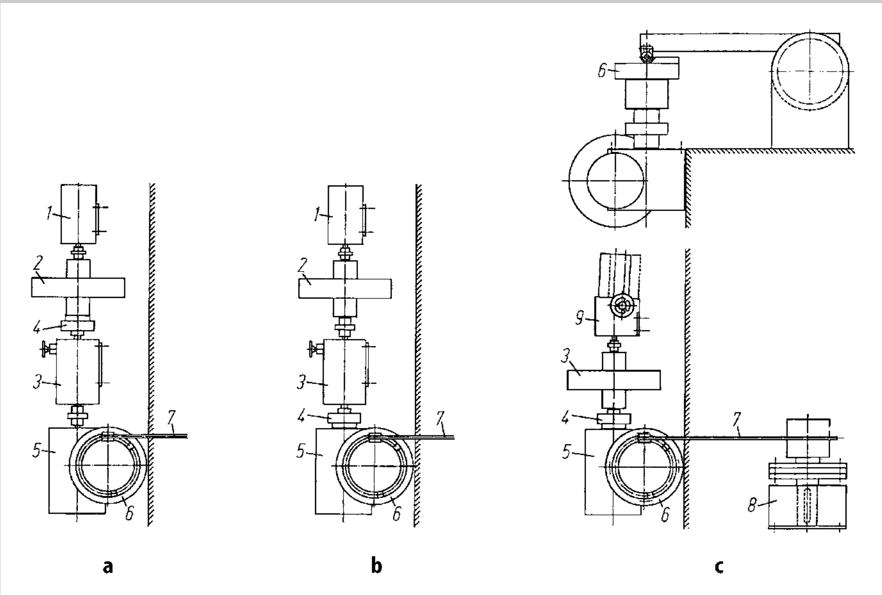


Figure 7.155. Layout of main function carriers: **a** for function structure variant *4/1*; **b** for function structure variant *4/2*; **c** for function structure variant *4/3*; *1* motor, *2* flywheel, 3 adjustable gear, *4* clutch, *5* worm gear (angular), 6 cylindrical cam, *7* transmission lever, *8* test connection, *9* adjustable geared motor

a preliminary layout based on function structure variant *4/2*, where the adjustable mechanism is located before the clutch. Variant *4/3* (see Figure 7.155c) employs an adjustable geared motor.

Step 5: Selecting Suitable Preliminary Layouts

Variant *4/3* was selected for further detailing because it took up less space due to the adjustable geared motor (function integration).

Step 6: Developing Preliminary Layouts and Form Designs for the Remaining Main Function Carriers

The preliminary layouts and form designs for the remaining main function carriers were based on the following requirements identified in step 4:

- motor drive speed for cylindrical cam

$$n_{\mathrm{CAM}} = 12.4 \ldots 32.6\ \mathrm{min}^{-1}$$

- speed control range

$$C = 2.6$$

- driving torque of cylindrical cam

$$T_{\mathrm{CAM}} = F_{\mathrm{T}} \cdot D_{\mathrm{CAM}}/2 \text{ and } F_{\mathrm{T}} = F_{\mathrm{A}} = T/l_{\mathrm{L}} \text{ gives } T_{\mathrm{CAM}} = 2650\ \mathrm{Nm}$$

- driving power of cylindrical cam

$$P_{\mathrm{CAM}} = T_{\mathrm{CAM}} \cdot \omega_{\mathrm{CAM}}, \text{ thus } P_{\mathrm{CAM}} = 9\ \mathrm{kW}$$

For reasons of safety, the maximum flywheel speed n_{F} (and therefore also that of the motor n_{M}) was chosen to be:

$$n_{\mathrm{F}} = 1000\ \mathrm{min}^{-1}$$

This required a transmission ratio of:

$$i = 80.7 \ldots 30.7$$

For the other main function carriers, the characteristics were estimated as follows:

- Transferred torque of the coupling based on the driving torque of the cylindrical cam $T_{\mathrm{CAM}} = 2\,650$ Nm and the actual transmission ratio i between the cylindrical cam and clutch

$$T_{\mathrm{CL}} = T_{\mathrm{CAM}}/i$$

- Moment of inertia of the flywheel from the actual torque T_F taken up by the flywheel, the impact time Δt, the flywheel speed n_F and the allowable drop in speed $\Delta n = 5\%$

$$J_F = \frac{T_F \cdot \Delta t}{2 \cdot \pi \cdot n_{CAM} \cdot \Delta n}$$

- The power of the electric motor P_M after calculating the required acceleration torque T_A from the moment of inertia J_F of the flywheel, the motor speed n_M, the run-up time $t_M = 10$ s and the maximum acceleration torque of the motor $T_{A_{max}}$ (from manufacturer's data)

$$T_A = \frac{J_F \cdot 2 \cdot \pi \cdot n_M}{t_M} < T_{A_{max}}$$

Table 7.9 lists the calculated values for the main characteristics. Apart from the flywheel, the main function carriers could all be selected from catalogues and bought directly from suppliers.

The following characteristics were chosen for the flywheel:

- speed $n_F = 1010\ \text{min}^{-1}$
- moment of inertia $J_F = 1.9\ \text{kg m}^2$.

Because losses such as those from friction had not been taken into account, the final value of J_F was chosen to be substantially larger than this.

To save weight, the flywheel was made from a hollow cylinder:

- Outer diameter $D_o = 480$ mm
- Inner diameter $D_i = 410$ mm
- Width $W = 100$ mm
- Mass $m = 38$ kg.

The final preliminary layout drawing was then produced on the basis of the main function carriers shown in Figure 7.155c and by adding the frame.

Table 7.9. Calculated values for the characteristics of the main function carriers of variant *4/3*

Functions	Function carriers	Calculated values
Change energy Increase E-component Adjust speed	Electric motor with mechanical adjustment-variant 4/3	Power $P_M = 1.1$ kW Speed $n_M = 380 \dots 1000\ \text{min}^{-1}$ Speed control range $C = 2.6$
Store energy	Flywheel	Moment of inertia $J_F = 1.4\ \text{kg m}^2$ Speed $n_F = 380 \dots 1000\ \text{min}^{-1}$
Release energy	Electromagnetic clutch	Transferred torque $T_{CL} = 86$ Nm
Increase E-component	Gear	Power $P_G = 9$ kW Nominal torque $T_G = 2650$ Nm at speed $n_G = 32\ \text{min}^{-1}$ Transmission ratio $i_G = 40.7$

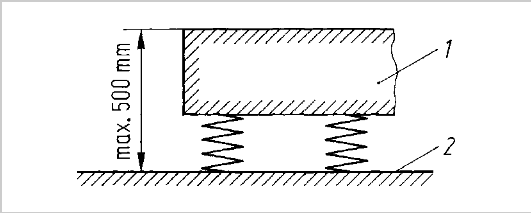


Figure 7.156. Final spatial constraints: *1*, base plate for fixing the test machine; *2*, foundation

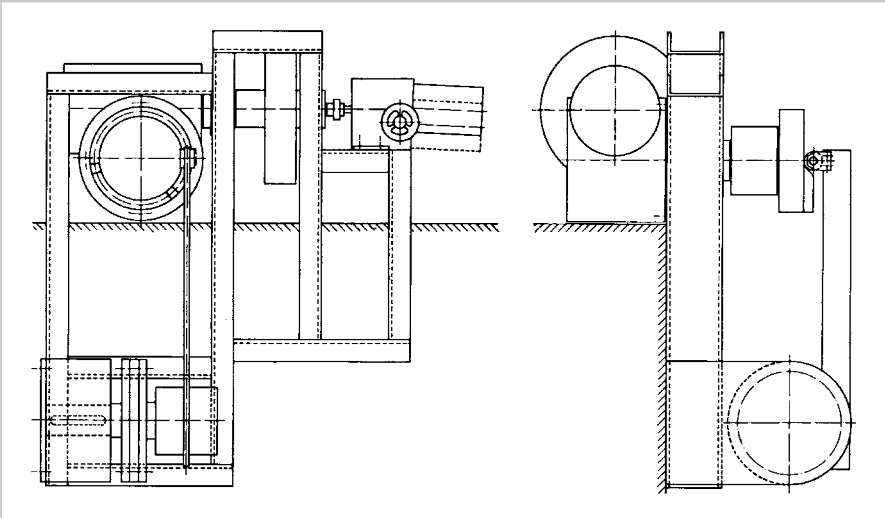


Figure 7.157. Preliminary layout drawing for the main function carriers

Because the combined height of the lever bearing and the test specimen was much smaller than the combined height of the cylindrical cam and the entire drive system, the spatial constraints for the test rig shown in Figure 7.156 were selected after a discussion with the client.

Steel channel sections were used for the frame for the following reasons:

- large second moment of area for a small cross-sectional area
- no round corners
- three flat reference surfaces available
- cheap.

Figure 7.157 shows the completed preliminary layout drawing for the main function carriers.

Step 7: Searching for Solutions for Auxiliary Functions

The production of a detailed layout drawing involved the following steps:

- Searching for and selecting auxiliary function carriers.

- Detailing the embodiment of the main function carriers based on the auxiliary function carriers.
- Detailing the embodiment of the auxiliary function carriers.

These steps were much more interrelated than those for the preliminary layout drawing. They influenced each other because they dealt with more concrete aspects which often required a repetition of previous steps on a higher information level.

The auxiliary function carriers were divided into three groups:

- Carriers that connect the main function carriers together.
- Carriers that support those main function carriers that move relative to the frame.
- Carriers that permanently connect main function carriers to the frame.

The auxiliary function carriers that connected the main function carriers together were:

- A bolted joint between the lever and test specimens; a form-fit membrane to avoid additional bending moments and to ensure easy assembly.
- A torsionally stiff connection between the worm gear pair and the cylindrical cam. This connection can be of two types (see Figure 7.158):
  - a worm gear pair with hollow shaft—cylindrical cam.
  - a worm gear pair—torsionally stiff connection—cylindrical cam.

  The following arguments favour the torsionally stiff connection:
  - separate assembly of worm gear pair and cylindrical cam possible (design for assembly).
  - no interruption of the frame caused by a high shaft position (simple embodiment).
  - easy centering of worm gear pair and cylindrical cam (design for production).
- Torsionally flexible connection between the flywheel and the electric motor.

The auxiliary function carriers used to support those main function carriers that move relative to the frame were:

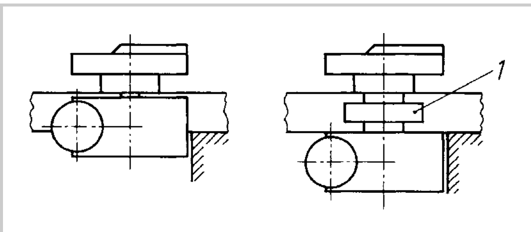


Figure 7.158. Connections between the worm gear pair and the cylindrical cam: *1*, coupling

- *Flywheel support*. The requirements were: simple production (i.e. no accurate balancing needed); direct safety techniques to withstand the dynamic forces (safe-life principle); and suspend from the frame. The use of bought-out parts (bearing housing with roller bearings) was not possible because these bearing housings are usually cast and are more suitable for standing rather than suspended applications. Because the flywheel was to be produced in-house, the magnitudes of the dynamic forces were relatively uncertain and so its support needed to be specially designed.
- *Support for the cylindrical cam and lever*. Commercially available rolling element bearings were selected.

The auxiliary function carriers used to permanently connect main function carriers to the frame were:

- Simple half-finished products (welded sheet steel), to which the main function carriers were bolted.
- A special solution for connecting the test specimen to the lever (i.e. the frame). The requirements were: easy to assemble but separable connection; movable in the axial direction; free of play; and no tight tolerances. A Ringfeder connection was chosen.

Step 8: Detailing the Main Function Carriers Taking into Account the Auxiliary Function Carriers

The main function carriers had to be adapted so as to match the solutions selected for the auxiliary function carriers. This resulted in the following:

- electric motor: bought-out part
- flywheel: see Figure 7.159
- clutch: bought-out part
- gearbox: bought-out part
- cylindrical cam: see Figure 7.160
- lever: see preliminary layout drawing in Figure 7.161
- test specimen: see preliminary layout drawing in Figure 7.161
- frame: modified to suit the geometry of the selected motor.

Step 9: Detailing the Auxiliary Function Carriers and Completing the Preliminary Layout

The flywheel support bearing is taken as an example, using the guidelines for embodiment design shown in Figure 7.3.

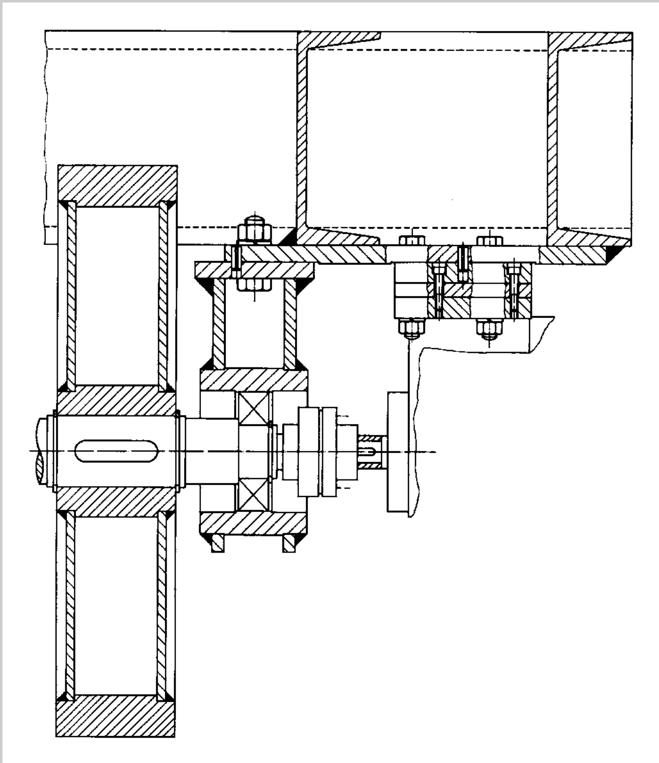


Figure 7.159. Detailed layout of the flywheel and the flywheel shaft bearing

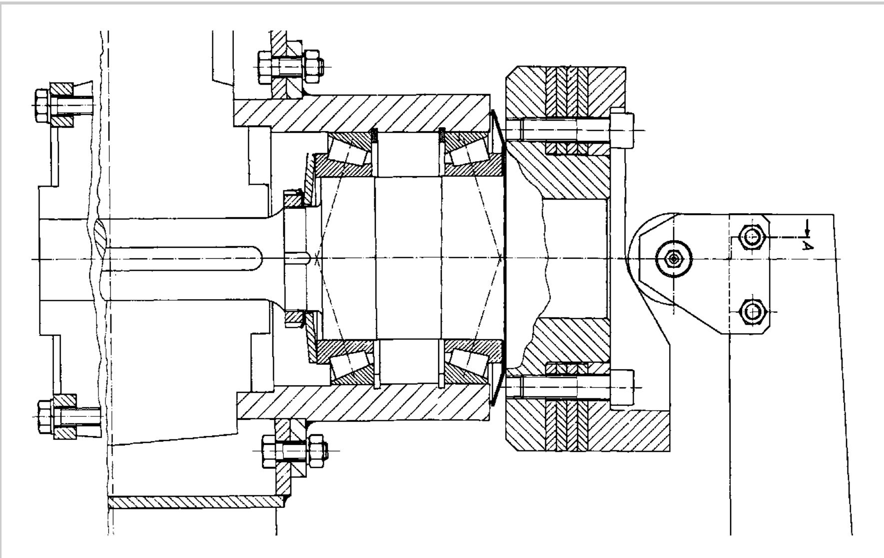


Figure 7.160. Detailed layout of the bearing arrangement for the cylindrical cam

Layout

The bearing forces were estimated as follows:

$$F_B = F_{dyn} + F_{stat}$$

with the weight being:

$$F_{stat} = m \cdot g = 400 \text{ N}$$

and the dynamic force being:

$$F_{dyn} = m \cdot e \cdot 4 \cdot \pi^2 \cdot n_F^2$$

With a mass $m = 40$ kg; speed $n_F = 1\,750 \text{ min}^{-1}$ (= max motor speed); eccentricity of flywheel $e = 0.6$ mm (based on: dimensional and shape accuracy of flywheel = 0.3 mm; play in flywheel shaft and bearings = 0.2 mm; and unbalanced mass distribution = 0.1 mm), the bearing force is:

$$F_B = 1130 \text{ N}$$

This implies that even when additional gyroscopic forces occur, the bearing (dynamic capacity 65 000 N) and all the other parts that are in the force transmission path have adequate dimensions.

Resonance

The embodiment of the bearing and frame was made very rigid so that resonance excited by the flywheel (maximum 30 Hz) was unlikely.

Production

The embodiment allowed easy production because the flywheel support bearing did not require tight tolerances for the frame.

Assembly

The support for the flywheel could be assembled easily due to:

- the application of a simple bottom-up approach
- the easy accessibility to the connecting screws
- the simple adjustment of the clutch using a spacer after accurate location of the flywheel bearing support using dowel pins (possible without the flywheel).

Maintenance

Maintenance-free bearings were used.

Figure 7.161 shows the preliminary layout drawing of the test rig resulting from the embodiment steps discussed above.

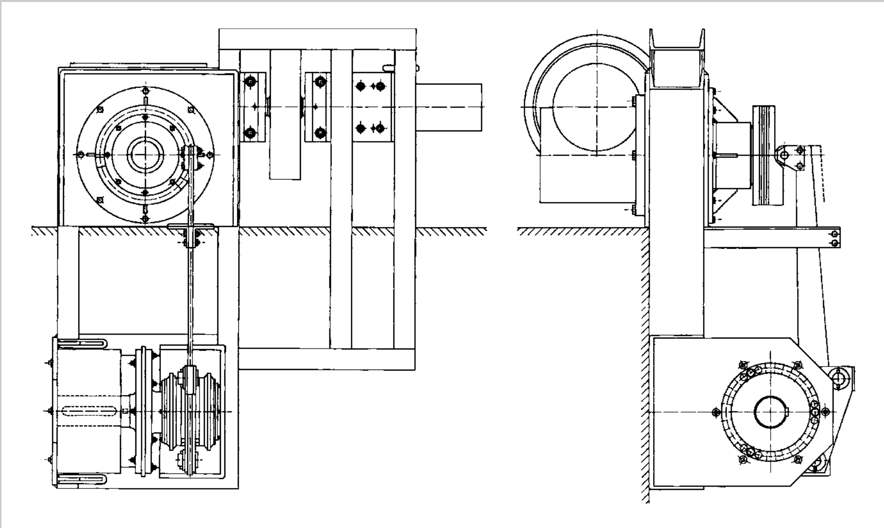


Figure 7.161. Preliminary layout drawing

Step 10: Evaluating Using Technical and Economic Criteria

Because only one final embodiment was developed, no selection was involved, only an assessment of the final embodiment based on criteria derived from the requirements list. The objective was to identify and eliminate weak spots.

The procedure involved the following steps in accordance with Section 3.3.2:

- identifying evaluation criteria
- assessing whether the parameters meet the evaluation criteria
- determining the overall rating
- searching for weak spots
- eliminating weak spots, if required.

For the evaluation we used 11 of the 13 criteria that were used to evaluate the concepts, see Figure 7.162. The use of weightings was not considered to be necessary.

The expected and calculated parameters of the test rig were evaluated against an ideal solution using a value range of 0–4, in line with VDI 2225. A more detailed evaluation did not seem worthwhile. The result is shown in Figure 7.162.

Only the technical rating was used in the calculation of the overall rating because there were no data for a formal assessment of the economic rating:

$$R = 29/44 = 0.66$$

This rating is rather low, so a search for weak spots seemed necessary. First, those parameters that had the lowest values were identified. A proposal was then made to improve those parameters that received only one or two marks:

Evaluation criteria			Parameters		Variant 4/3			Variant 4/3 impr.		
No.		Wt		Unit	Magn	Value	Weighted value	Magn	Value	Weighted value
1	Good reproducibility		Disturbing factors	–	low	4				
2				–						
3				–						
4	Tolerance of overloading		Overload reserve	%	10	3				
5	High level of safety		Danger of injury	–	average	2		see text	4	
6	Few possible operator errors		Possibilities of operator errors	–	high	1		see text	3	
7	Small number of components		No. of components	–	low	3				
8	Low complexity of components		Complexity of components	–	low	3				
9	Many standard and bought-out parts		Proportion of standards and bought-out comp.	–	high	4				
10	Simple assembly		Simplicity of assembly	–	high	3				
11	Easy change of load profile		Change of load profile	–	bad	1		see text	2	
12	Quick exchange of test connections		Estimated time needed to exchange test con.	–	average	2		see text	2	
13	Good accessibilitiy of measuring system		Accessibility of measuring system	–	good	3				
		$\Sigma W_i=1.0$				$OV_1=29$ $R_1=0.66$			$OV_2=34$ $R_2=0.77$	

Figure 7.162. Evaluation chart for embodiment based on Figures 7.161, 6.54 and 6.55

- Few possible operator errors.

  Weak spot: motor speed: (1) the speed could be set at a value higher than necessary for the maximum rate of torque increase; and (2) the run-up of the motor should only take place slowly because of the heat generated.

  Remedy: the allowed range for run-up and operation can be marked on the speed indicator of the motor. The machine can be shut down automatically if the speed becomes too high.

- Easy to change the load profile.

  Weak spot: exchange of the cylindrical cam was not possible because of the clamping pressure of the lever on the cam.

  Remedy: provide a means to lift the lever.

- High level of safety.

  Weak spot: rotating cylindrical cam was not protected.

  Remedy: provide protective cover.

- Quick exchange of test specimens (test connections).

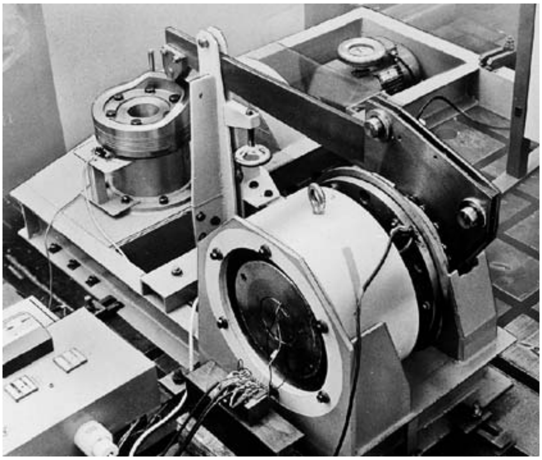


Figure 7.163. Final impulse-loading test rig, after [7.188]

Weak spot: slow because of the number of screws in the Ringfeder connection.

Remedy: no economic alternative possible.

The improved variant has been added to the evaluation chart (see Figure 7.162).

The remaining working steps used to *define the overall layout* proposed in Figure 7.1 are not discussed here. They were not very complex in the case of this test rig because it was a one-off product for a research institute and did not need a high degree of optimisation. The *detail design* of the test rig (following the working steps in Section 7.8) is also not discussed. It only involved conventional drawing and detail design steps.

Figure 7.163 shows the final impulse loading test rig. It fulfilled the main expectations and confirmed the effectiveness of a systematic approach [7.122].

7.8 Detail Design

Detail design is that part of the design process which completes the embodiment of technical products with final instructions about the shapes, forms, dimensions and surface properties of all individual components, the definitive selection of materials, and a final scrutiny of the production methods, operating procedures and costs.

Another—and perhaps the most important—aspect of the detail design phase is the elaboration of production documents, including detailed component drawings, assembly drawings, and appropriate parts lists. These activities are increasingly undertaken using CAD software. This allows the direct use of product data for production planning and the control of CNC machine tools.

Depending on the type of product and production schedule (one-off, small batch, mass production), the design department must also provide the production department with assembly instructions, transport documentation and quality

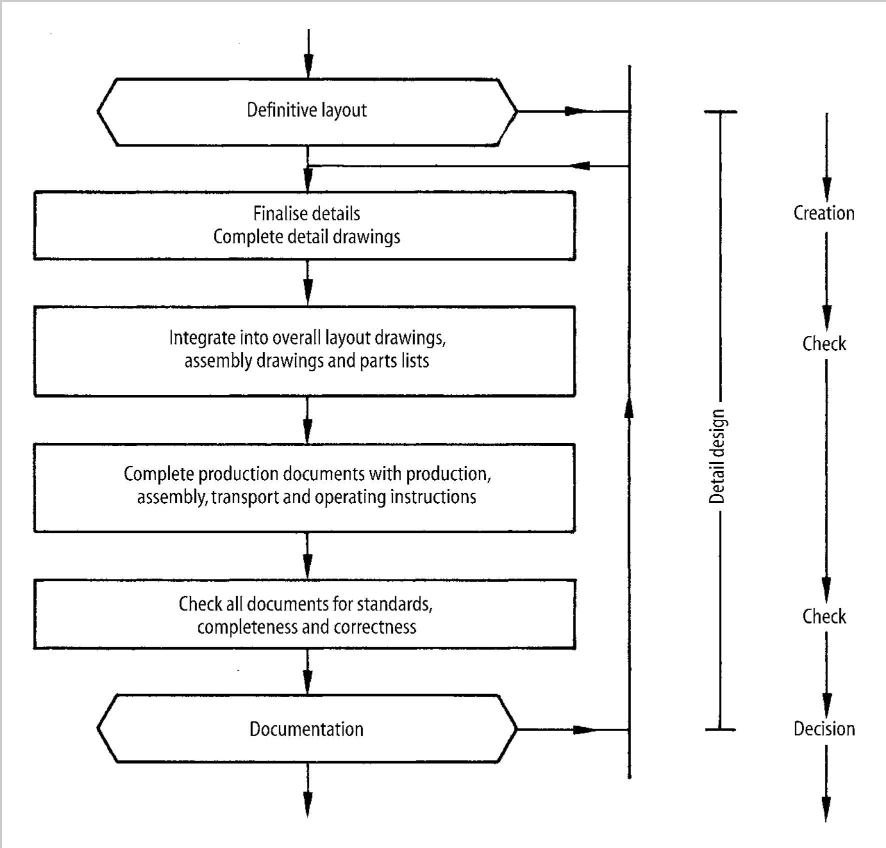


Figure 7.164. Steps of detail design

control measures (see Chapter 10), and the user with operating, maintenance and repair manuals. The documents drawn up at this stage are the basis for executing orders and for production scheduling, that is, for operations planning and control. In practice, the respective contributions of the design and production departments in this area may not be distinct.

The detail design phase involves the following steps (see Figure 7.164).

Finalise the definitive layout, comprising the detailed drawing of components, and the detailed optimisation of shapes, materials, surfaces, tolerances and fits. To that end, designers should refer to the guidelines given in Section 7.5. Optimisation aims at maximum utilisation of the most suitable materials (uniform strength), at cost-effectiveness and at ease of production, with due attention being paid to standards (including the use of standard parts and company repeat parts).

Integrate individual components into assemblies and into the overall product (fully documented with the help of drawings, parts lists and numbering systems). This is strongly influenced by production scheduling, delivery dates, and assembly and transport considerations.

Complete production documents with production, assembly, transport and operating instructions.

Check all documents, especially detail drawings and parts lists, for:

- observance of general and in-house standards
- accuracy of dimensions and tolerances
- other essential production data
- ease of acquisition, for instance, the availability of standard parts.

Whether such checks are made by the design department itself or by a separate standards department will depend largely on the organisational structure of the company concerned, and it plays a subordinate role in the actual execution of the task. The steps of the embodiment and detail design phases overlap in the same way as the steps of the conceptual and embodiment phases often do. Long lead-time parts, such as those involving forging and casting, should be dealt with first and their detail designs and production instructions are often completed before the definitive layout has been finalised. This overlapping of two design phases is particularly common in one-off production and in heavy engineering.

Detail design is very domain- and product-dependent and designers should refer to the many technical handbooks, suppliers catalogues and standards that deal with the detail design and selection of machine elements.

Corners must never be cut during the detail design phase, which has a critical effect on the technical functions, on the production processes and on the elimination of production errors. Detail design has a major influence on production costs and product quality, and hence the success of a product in the market.

8 Mechanical Connections, Mechatronics and Adaptronics

In this chapter three classes of generic solution are presented in a systematic way. Because of their overriding importance in mechanical design, mechanical connections are the first class to be discussed. The other two classes are mechatronic and adaptronic systems. These allow the realisation of new functions and improved performance using novel approaches through the integration of mechanical, electronic and software elements, and are thus changing the traditional field of mechanical engineering. Even though these developments may seem utopian or too expensive in some of the more traditional areas, their increased application will make them cheaper and more common. Automotive technology has already embraced Mechatronics and Adaptronics and their solutions will be transferred to other areas of mechanical engineering, or at least influence them.

It is only possible for mechanical designers to adopt these new types of solutions and exploit their potential if they work in interdisciplinary teams (see Section 4.3). Such teamwork can only be fruitful when all members of the team are fully knowledgeable in their own fields while at the same time possessing a shared knowledge with the other members in order to understand each other and work together effectively and efficiently [8.22].

8.1 Mechanical Connections

Assemblies and components, whether mechanical or electrical, are connected to each other in order to fulfil particular functions. The type of connection determines its basic behaviour and its application the success of a solution. Connections can be divided into those that result in a *fixed arrangement* of the components relative to one another and those that result in a *moveable arrangement*.

Connections with moveable arrangements are joints with different degrees of freedom. This could, for example, be pin joints with one rotational degree of freedom, translating joints on a square profile with only one translational degree of freedom, and ball joints with three rotational degrees of freedom [8.6]. Roth developed a matrix in which, for every possible joint, the free and restricted movements are shown in order to support a search for possible solutions [8.25].

The following sections describe the functions, working principles and some embodiments of the different types of connection for fixed arrangements.

8.1.1 Generic Functions and General Behaviour

Functions (Figure 8.1)
Connections serve to transfer forces, moments and movements between components having a clearly defined fixed arrangement. They might fulfil the following additional functions:

- taking up relative movements that are not in the loading direction
- sealing against fluids
- insulating or transmitting thermal and electrical energy.

General Behaviour
The working surface pairs at the interface are subjected to loading during the assembly process, which can produce preloading and residual stresses, or loading during operation.

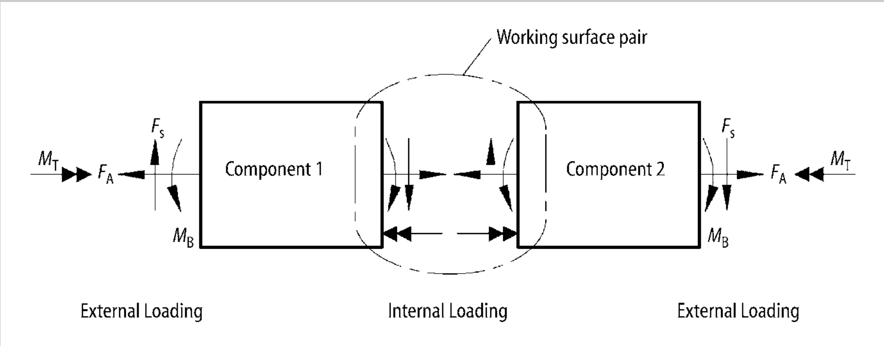


Figure 8.1. External loading and internal loading of the working surfaces of two components. F_A axial load; F_S shear load; M_B bending moment; M_T torsional moment

8.1.2 Material Connections

Working Principle (Figure 8.2)
A material connection is the result of joining components, either directly or by using additional material, utilising molecular and adhesive forces over the working surface area. These connections transmit axial and shear forces as well as bending and torsional moments.

Structural Characteristics

- form, position, size and number of mating surfaces
- stresses in the connection after production (residual stresses) and in operation
- component materials and additional materials involved
- production and operational temperatures.

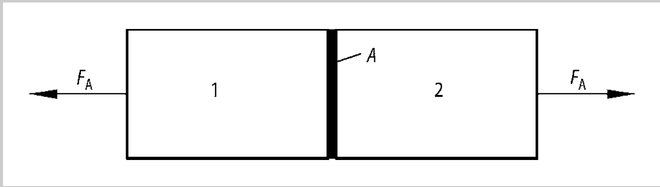


Figure 8.2. Material connection between two components subject to uniaxial loading. A working surface area, F_A axial force

Main Properties

- precise position maintained
- cannot be disconnected
- can break or deform if overloaded.

Embodiments (Figure 8.3)

- welded connections [8.5, 8.7, 8.21, 8.26, 8.27]
- soldered connections [8.6, 8.7, 8.35]
- adhesive connections [8.7, 8.15].

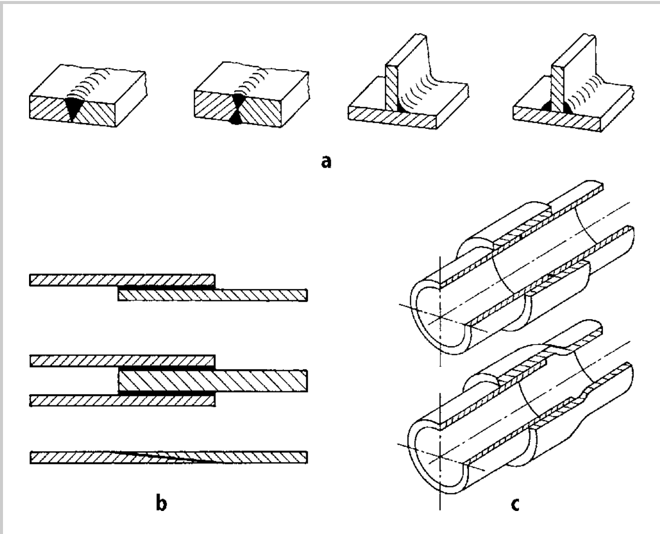


Figure 8.3. Types of material connection (selection). **a** welded connections, **b** adhesive connections, **c** soldered connections

8.1.3 Form Connections

Working Principle (Figure 8.4)
A form connection is realised by normal forces between the working surfaces of the components, which produce a surface pressure p and result in stresses at

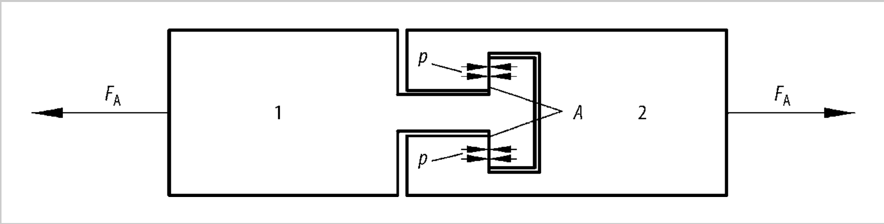


Figure 8.4. Form connection between two components subject to uniaxial loading. *A* loaded working surface area, F_A axial loading, *p* surface pressure

the mating surfaces according to Hooke's law. The pairs of working surfaces that are under pressure also fulfil additional functions such as sealing, insulating and transmitting.

Structural Characteristics

- form, position, size and number of mating surfaces (including form connection elements)
- forceflow in the connection zone
- load distribution (pressure distribution) on the form connection elements
- load distribution variations caused by material combinations involving different Young's moduli
- stiffnesses of components and form connection elements
- stresses and stress concentrations in the connection zone surrounding the working surfaces
- preloading possibilities
- arrangement of tolerances to avoid double fits
- assembly and disassembly possibilities
- loosening potential during operation and preventative measures.

Main Properties

- precise position maintained
- can be disconnected
- can break or deform if overloaded.

Embodiments (Figure 8.5)

- wedged, bolted, pinned and riveted connections [8.7]
- shaft-hub connections [8.20]
- locating elements [8.7]
- snapping, clamping and drawing connections [8.7].

The riveted connection shown in Figure 8.5a is not a pure form connection. The riveting process also causes a friction force connection between the riveted com-

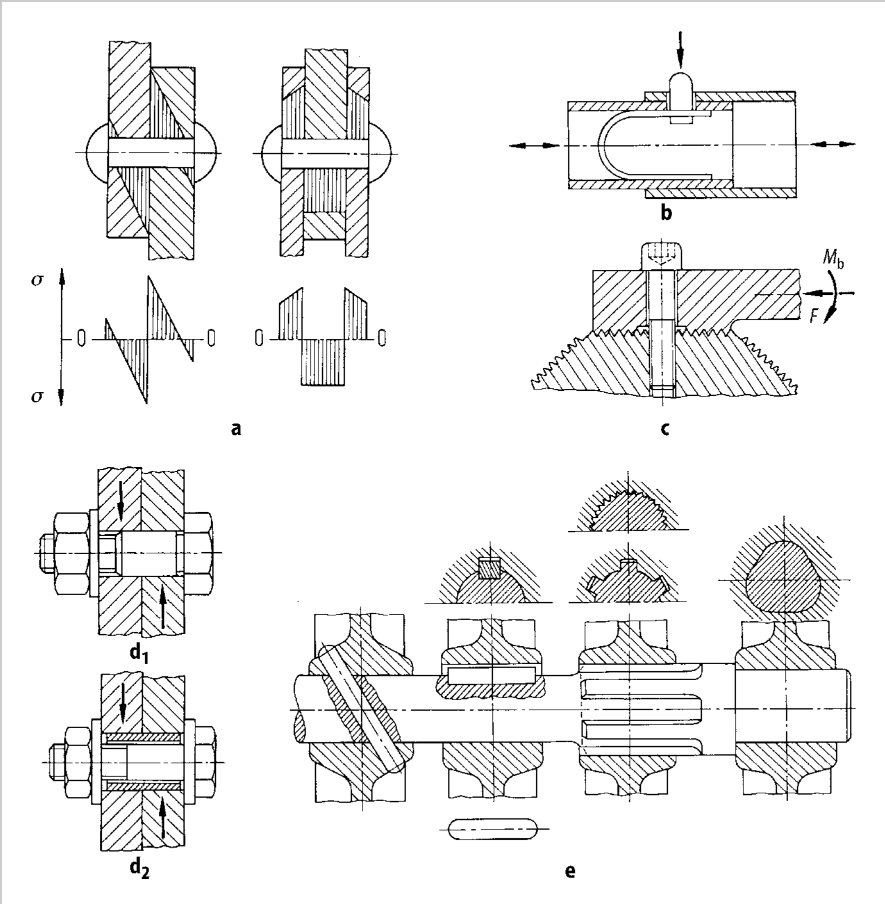


Figure 8.5. Types of form connection (selection). **a** riveted connections (disconnection difficult), **b** snap connection, **c** preloaded spline connection, **d**$_1$ shear-loaded bolted connection with fitted bolt, **d**$_2$ with shear sleeve, **e** shaft-hub form connections

ponents. How much of the transmitted force is taken up by the form connection and how much by friction cannot be determined because of the lack of clarity of the final forceflow distribution. Nevertheless, riveted connections are frequently used in structures because they do not loosen. They are also used in composite constructions of metal and plastics to avoid peeling when adhesive connections are subject to bending.

8.1.4 Force Connections

General Behaviour

A force connection is realised by forces between the working surfaces of the components. Force connections can be classified by the origin of the forces, i.e. physical effects involved.

1. Friction Force Connections

Working Principle (Figure 8.6)
A friction force connection is realised by friction forces F_F acting on the working surfaces. These are produced in response to normal forces F_N utilising Coulomb's law of friction $F_F = \mu_S \cdot F_N$. Only forces smaller than the friction force, i.e. $F \leq F_F$, can be transmitted.

Structural Characteristics

- static coefficient of friction (the main parameter that depends on the material combination)
- normal forces
- surface pressures on the working surfaces
- number of working surface pairs and distribution of the normal forces
- stiffnesses of the components and preloading elements
- relative deformations of the components during assembly and operation (friction corrosion zones, see Section 7.4.1)
- assembly and disassembly possibilities
- loosening potential during operation and preventative measures.

Main Properties

- precise position retained as long as $F_A \leq F_F = \mu_S \cdot F_N$
- can be disconnected
- relative movement (slipping) when overloaded, i.e. $F_A \geq F_F = \mu_S \cdot F_N$. Danger of fretting due to large surface pressures and of overheating in the case of continuous slipping.

Embodiments (Figure 8.7)

- shaft-hub interference connections with or without elastic inserts [8.20].
- bolted connections [8.33, 8.34]

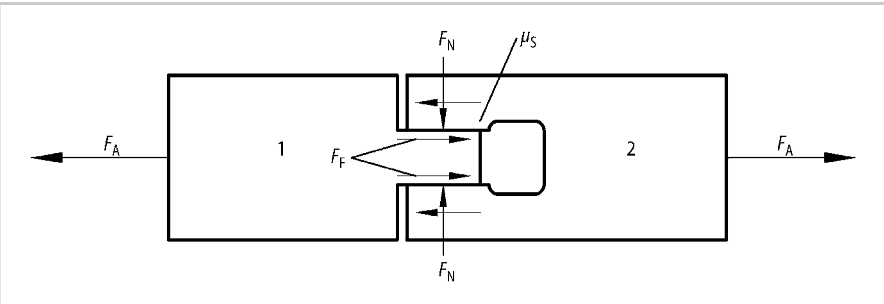


Figure 8.6. Friction force connection between two components subject to uniaxial loading. F_A axial force, F_F friction force, F_N normal force, μ_S static coefficient of friction

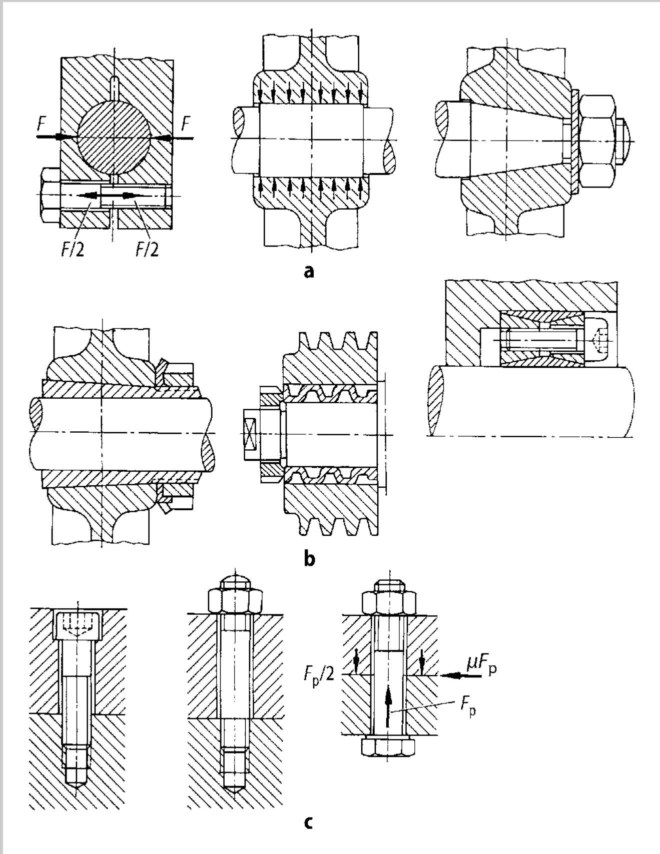


Figure 8.7. Types of friction force connection (selection). **a** shaft-hub interference connections without elastic inserts, **b** shaft-hub interference connections with elastic inserts, **c** preloaded bolted connections

2. Force Field Connections

Working Principle
A force field connection is realised by utilising force fields such magnetic force fields, hydrostatic or aerostatic pressure force fields and viscous force fields.

Structural Characteristics

- force field required
- external energy source or viscous medium
- sealing and shielding.

Main Properties

- force-displacement relationship (often stiff behaviour)
- can be disconnected

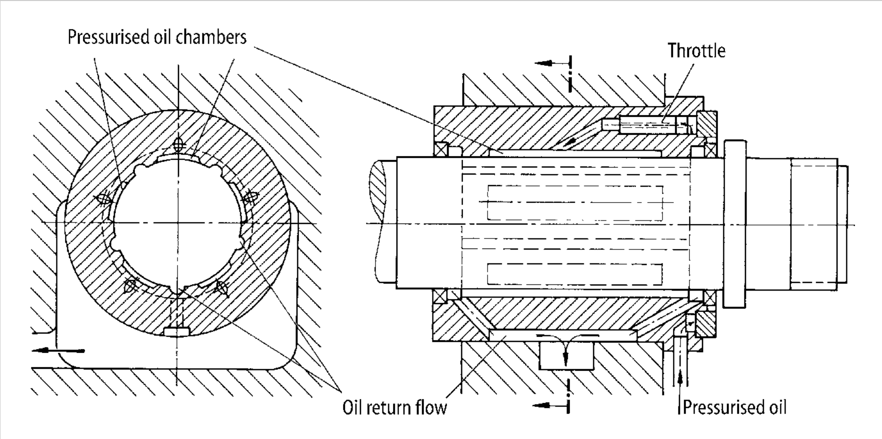


Figure 8.8. Example of a hydrostatic bearing

- in the case of overloading movement occurs until a stop is reached (usually resulting in a form connection with loss of original functionality).

Embodiments

- hydrostatic or aerostatic bearings, see Figure 8.8
- hydrostatic couplings
- magnetic bearing and closures, see Figure 8.9.

3. Elastic Force Connections

Working Principle
An elastic force connection is realised by the forces generated using elastic elements that act as energy stores when they deform. The forces of the inserted elastic elements determine the position and dynamic behaviour of the components to be connected.

Structural Characteristics

- elastic elements
- embodiment of the elastic elements within their elastic limits
- hysteresis characteristics of elastic elements, e.g. metallic springs have very low internal losses whereas rubber springs have higher losses
- durability
- possibility of introducing damping elements.

Main Properties

- force-displacement relationship
- energy storage capability through deformation work

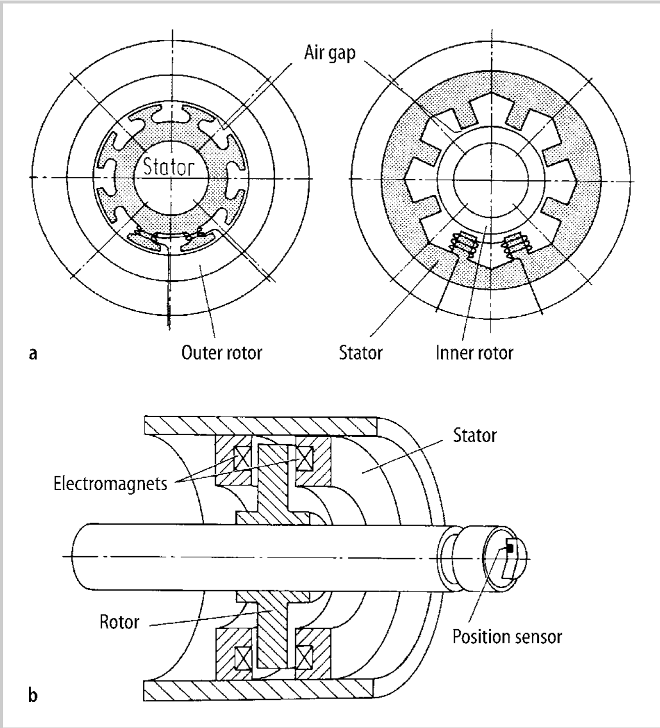


Figure 8.9. Types of magnetic bearing [8.1]. **a** radial bearing, **b** axial bearing

- sensitivity to vibrations, but with damping possibilities
- can be disconnected
- in the case of overloading movement occurs until a stop is reached (usually resulting in a form connection or compacting, such as coil binding in compression springs (see Figure 7.58), with resulting loss of elastic properties).

Embodiments

- flexible spring elements in couplings and bearings, see Figure 7.144
- elastic supports, see Figure 7.27
- elastic inserts for damping impacts [8.10, 8.12, 8.13].

8.1.5 Applications

Material connections are preferably used to:

- take up multiaxial as well as dynamic loads
- maintain relative position
- realise an economic fixed arrangement of components of the same material group

- allow easy repair through welding, soldering and gluing
- seal connected areas
- allow the use of standardised components and semi-finished materials.

Form connections are preferably used to:

- allow frequent and easy disassembly
- permit unambiguous positioning of components
- take up relatively large forces
- connect components from different material groups.

Friction force connections are preferably used to:

- allow easy and economic connection, including parts from different material groups
- permit slip when subjected to excessive loading
- set relative position of connected components
- allow components to be easily disconnected.

Force field connections are preferably used to:

- realise a connection without physical contact between components
- reduce friction losses
- control precise positioning in space
- influence dynamic behaviour.

Elastic force connections are preferably used to:

- store energy
- take up impact loads
- influence dynamic behaviour, along with damping elements where appropriate
- balance out relative movements
- balance out tolerance and dimensional differences.

8.2 Mechatronics

8.2.1 General Architecture and Terminology

The term mechatronics is made up from mechanics and electronics. By including information technology, mechatronics integrates these three fields to provide opportunities for novel solutions for products, and for their production and assembly processes, see Figure 8.10 and [8.19]. Compared to conventional systems, mechatronics permits functionality to be extended, and allows certain functions to be realised for the first time.

Mechatronic solutions are basically structured as shown in Figure 8.11. The *basic system* can be mechanical, electro-mechanical, hydraulic or pneumatic, with energy, material and signal flows. The overall function aims to fulfil a complex task. Sensors capture specific characteristic status data of the basic system. These data are then transferred to a computer system for processing, and, based on the results, actuators are instructed to perform in a pre-specified ways on the basic system. Energy has to be supplied to the computer, sensors and actuators. Humans can intervene, if necessary, to override the system.

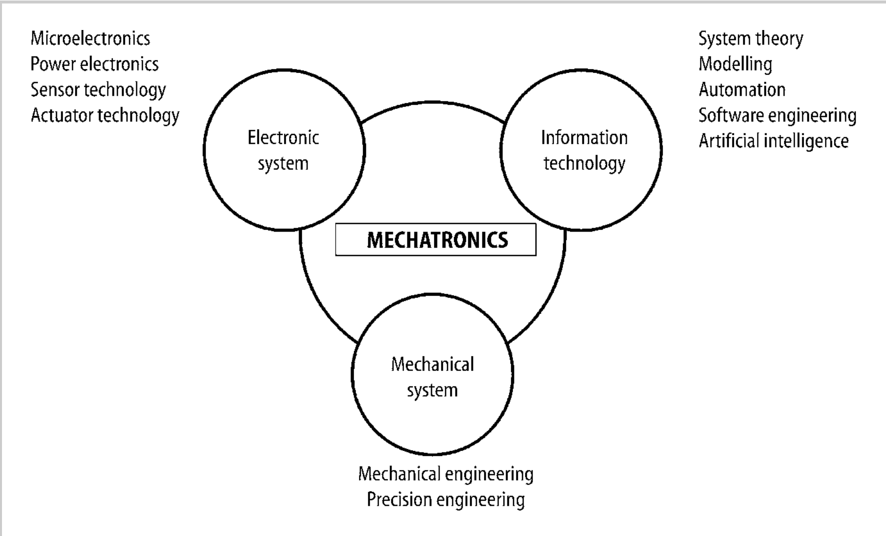


Figure 8.10. Mechatronics. Integration of the fields of mechanical engineering, electronics and information technology, after [8.19]

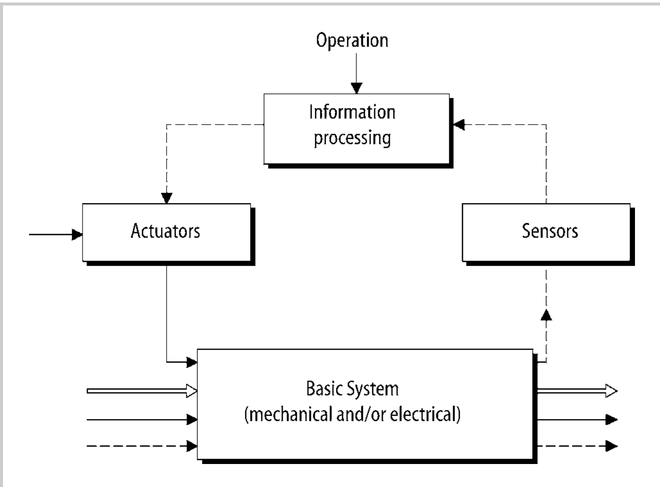


Figure 8.11. Basis structure of a mechatronic system, after [8.19]

The possibility now exists to physically integrate sensors, actuators and the data processing into the basic system, i.e. to create self-contained subsystems that require little space and are positioned at their working locations. Even when these components are only partially integrated, the term mechatronic solution is used. Increasing miniaturisation opens the way to microsystem technology and further utilisation opportunities. A draft VDI Guideline 2206 [8.32] has been published about mechatronics and its development methods.

8.2.2 Goals and Limitations

The goals of mechatronic development are to:

- realise new functions
- improve the behaviour of systems through monitoring and control without external intervention
- extend application boundaries
- realise automatic system monitoring and fault diagnosis
- achieve physical integration within a small space
- develop mechatronic subsystems as building blocks or assemblies that can be independently tested and added to existing systems
- improve operational safety.

The limitations of mechatronic solutions include:

- damage to the electronic components in the case of high surrounding temperatures or when subjected to mechanical loads, e.g. vibrations – in such cases these components cannot be integrated
- repairs are often impossible or uneconomic, requiring the replacement either of the whole mechatronic system or a major part of it
- the cost/benefit ratio is not always in line with current market economics because certain sensors, actuators or the whole system are still too expensive.

8.2.3 Development of Mechatronic Solutions

The development of mechatronic systems requires a holistic and interdisciplinary approach. It is not possible to differentiate clearly the domains and disciplines involved, nor is this desirable because the boundaries are fluid. Team members should be drawn from mechanical engineering, electronics, control, software and the relevant production disciplines. See Section 4.3 for guidance on setting up and running such teams.

The complexity and interdisciplinary nature of the process requires a systematic approach, such as the one described in this book. However, it must be applied with greater flexibility and consideration of the knowledge and terminology of the various disciplines involved.

First of all a requirements list has to be prepared (see Section 5.2) from which the necessary functions and a preliminary function structure can be derived (see Section 6.3). The starting point is the basic architecture shown in Figure 8.11. The discussion and abstract description of the subfunctions that have to be fulfilled is particularly useful in an interdisciplinary team. This helps to identify, elaborate and communicate the intentions, goals and objectives, as well as possible initial solutions. Function structures, even if they are incomplete, support the clear definition of the interfaces in the overall system. This permits the definition of independent subtasks and their allocation to the individual disciplines involved.

All the participating experts can then take responsibility for their tasks and undertake a systematic search for solutions (see Sections 4.2 and 6.4). Because of the different disciplines, the size and duration of their tasks will differ, requiring continuous coordination and adjustment of the schedule by the project manager. The solution will progress from a rough structure to a detailed embodiment through many iterative steps, similar to, but more flexible, than the methodology presented in Section 7.1. Isermann [8.19] describes the detailed steps of a mechatronic development process. Recommendations on sensors and actuators can be found in [8.19, 8.31].

An effective development process comprises an early assessment of the partial solutions using the selection and evaluation procedures discussed in Section 3.3. Every solution variant of the basic system affects the development of the sensors, actuators and the software and vice versa.

8.2.4 Examples

Early examples of mechatronic systems can be found in precision engineering and include automatic cameras and electronic office equipment. Pioneering mechatronic applications in the area of mechanical engineering can be found in the automotive industry. Antilocking braking systems (ABS), for example, are mechatronic systems that measure wheel speeds and control the braking forces to prevent the wheels locking. Such control minimises the braking distance whatever the road conditions. A further development of ABS is electronic brake distribution (EBD) to avoid the car spinning if skidding does occur by controlling the individual brakes to maintain the dynamics within preset limits. Automatic gearboxes are also controlled more and more through integrated electronic elements.

The following examples, some of which are still under development, show the possibilities that could be realised when demand exists and economic conditions are favourable.

Example 1: Friction Coupling

In a large research project on integrated mechanical and electronic systems, a standard clutch was fitted with piezo actuators. When the clutch is engaged, the actuators reduce the clutch force from its maximum value by following a specific characteristic line so that the clutching process is completed in about 0.4 s. The aim is for the clutch to follow a characteristic that at the start of engagement provides a higher coupling moment than at the end, rather than the conventional constant moment (see Figure 8.12). Following this characteristic, the maximum temperature in the friction pads, which is exponentially responsible for wear, can be reduced by up to 30%, depending on the Fourier number, see Table 9.2. Figure 8.13 shows the rotational speed, the coupling moment, the temperature and the power losses of a clutching process for a Fourier number = 1. The reduction of the maximum friction temperature is largest when the Fourier number is small, i.e. the clutch wall thickness into which the heat flows is large.

Temperature sensors in the clutch wall measure the temperature and select an appropriate clutch characteristic using, in this case, an external computer to control the piezo actuators. In addition, the rising characteristic of the clutch moment can be controlled such that the time to rise is at least as long as the period of the lowest torsional natural frequency of the systems that are coupled. This results in minimum shaft torsional vibration during the clutching process [8.14].

Example 2: Self-Reinforcing Automobile Brake

In Section 7.4.3 a type of self-reinforcing brake is discussed, which, however, can lock up. A self-weakening configuration would be preferred, provided that appropriate brake force reinforcement can be supplied. Using mechatronics brakes can

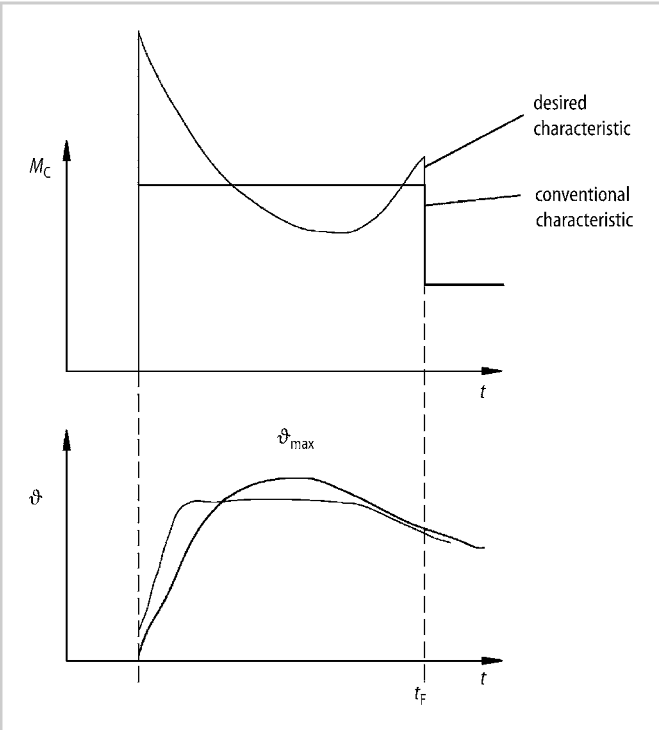


Figure 8.12. Principle correlation between coupling moment M_C, friction temperature ϑ_{max} and synchronisation point t_S, after [8.14]

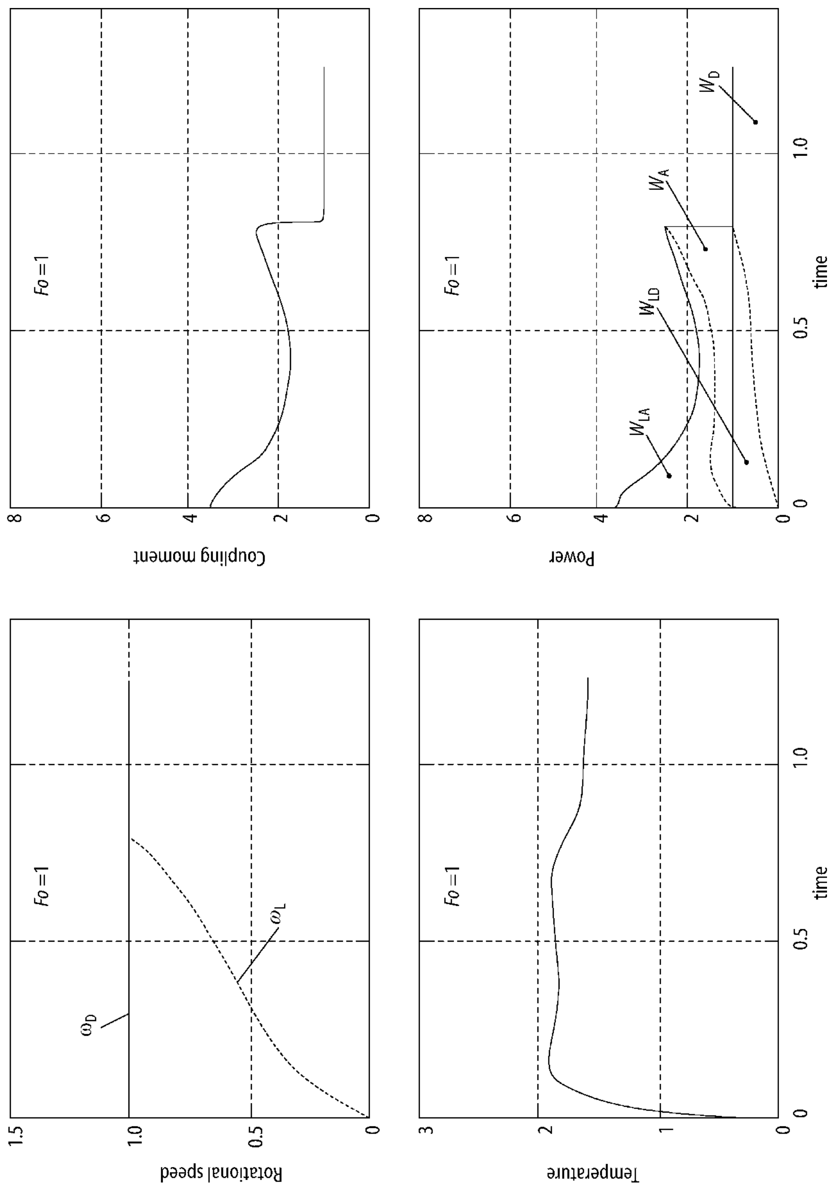


Figure 8.13. Characteristics of rotational speed, coupling moment, friction temperature and power against time for a Fourier number $Fo = 1$ (normalised values), after [8.14]

be realised that automatically provide brake force reinforcement (self-reinforcing brakes) thus saving activation energy.

New automobile concepts are tending to abandon central hydraulic systems in favour of electrical systems. This affects the braking system of an automobile. Given the overall energy availability, these systems should be as efficient as possible.

In the research project mentioned in Example 1, Breuer and Semsch [8.11] developed a self-reinforcing disc brake. This brake provides a controlled constant force and avoids self-locking [8.3, 8.28, 8.29]. Figure 8.14 shows the basic principle of the brake wedge on the brake disc. The brake force in this system would, after the activation force is applied, increase progressively until the brake locks, depending on the coefficient of friction of the brake pad. The introduction of a mechatronic solution, however, prevents the brake locking. Figure 8.15 shows the basic configuration of the new disc brake. The activation force is introduced by an electric motor with a gearbox via a lead screw. The wedge angle has been chosen such that self-loosening is always possible while at the same time providing a substantial reinforcement of the braking force.

The braking force is measured by a sensor. It would be possible to measure the normal force acting on the brake pad, but this has the disadvantage that it does not include the coefficient of friction of the pad. It would be better to measure the braking moment on the brake disc. The best solution is to measure the delay behaviour, because this also includes the coefficient of friction of the tyre. This is possible because of promising developments in tyre sensors that indicate coefficients of friction between tyre and road [8.3]. Where the sensor will be placed or whether the braking force can be measured indirectly using other available data depends on the specific electronic concepts of the automobile, e.g. making use of the ABS system. A computer controls the activation force based on the measured braking force and brake behaviour in such a way that in every wheel the required self-reinforcing braking force can be realised with relatively little energy.

The energy requirements remain within limits thanks to self-reinforcement; the brake can be ventilated at any time; and changing clearances caused by wear and thermal influences can be balanced out automatically. A version of this brake was constructed and tested in an automobile under real conditions.

Example 3: Chassis Support

In automobiles, wheels are mounted using a spring-damper system. In general, the spring and damper properties cannot be altered and are preset based on the typical operation of the automobile. The loading, the road conditions and driving behaviour influence the required spring-damper behaviour. To achieve a comfortable ride in every situation, mechatronic solutions can be used that automatically adapt the spring stiffness and damping characteristic, as well the chassis level for road clearance and roll control. To achieve this, a piston subjected to oil pressure is located in the spring leg. This is connected via a membrane with controllable air pressure that can alter the spring stiffness and length. The damper subsystem is fitted with bypasses whose cross-sections are controlled by magnetic valves to increase or decrease the damping. Sensors continuously measure the behaviour

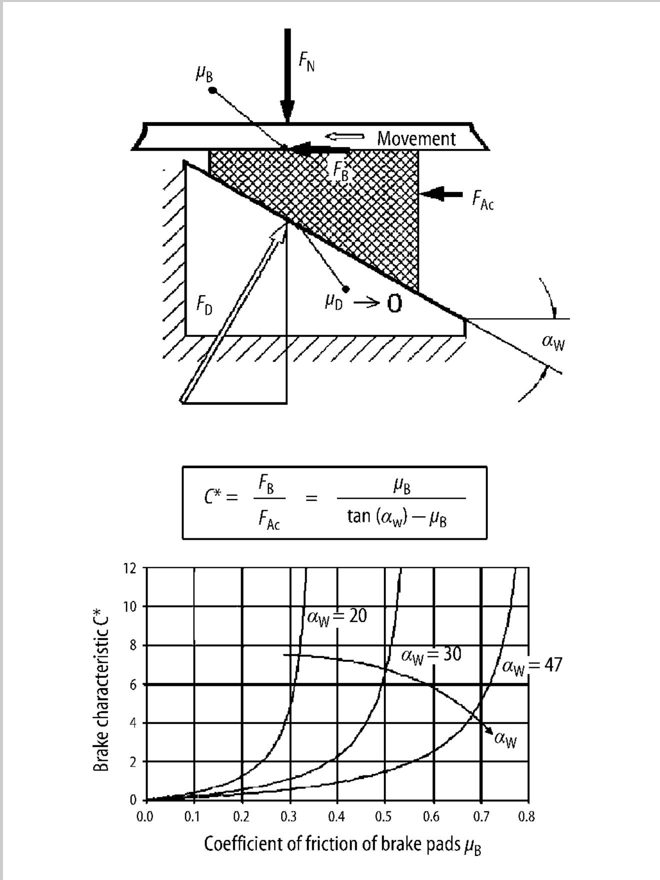


Figure 8.14. Self-reinforcing wedge on a disc brake; brake characteristic C^* = braking force F_B/activation force F_{Ac}, after [8.28, 8.29]

of the vehicle while being driven and while stationary. A processor regulates and controls the optimum spring stiffness and damping for every driving condition and adjusts the level of the chassis in accordance with the loading. The processor is connected to a diagnostic system that not only identifies the driving conditions but also faults in the measurement and regulation system itself. In the case of disturbances, the system settings go back to normal and the driver is informed [8.4].

Example 4: Self-Regulating Magnetic Bearing

Figure 8.9 shows radial and axial bearings as examples of magnetic force field connections. Magnetic bearings with active field magnets can be used as actuators as well as sensors. In combination with a digital control system, the stationary bearing position and dynamic behaviour of the shaft can be influenced. This allows new functions to be realised as demonstrated by Nordmann [8.30].

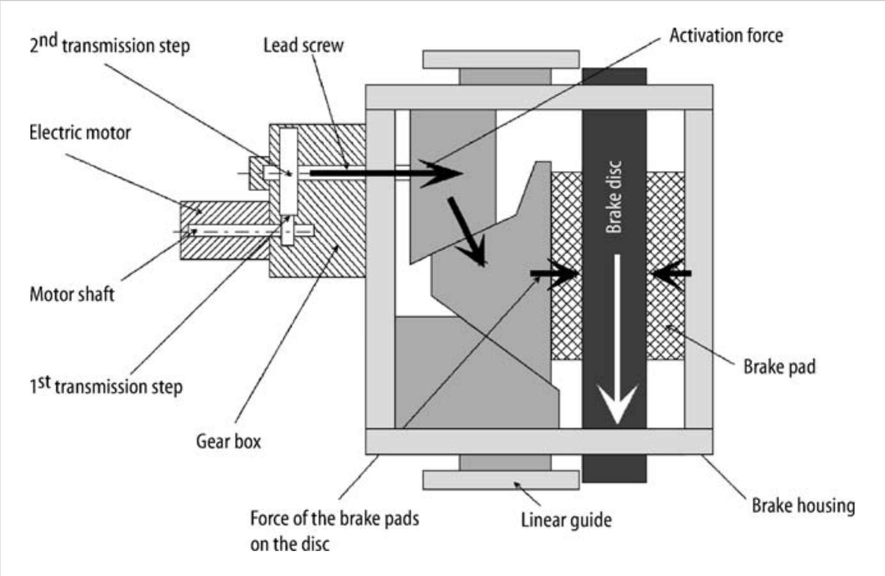


Figure 8.15. Basic configuration of the self-reinforcing disc brake, after [8.28, 8.29]

We will use a grinding drive unit for the precision grinding of small holes [8.30] as an example. Figure 8.16 shows the configuration of this unit. The grinding shaft, which is overhung from the bearings, rotates at over 100 000 rev/min. The workpiece to be ground can rotate at up to 3 600 rev/min. The grinding shaft is supported by two electromagnetic radial bearings. The axial force is taken up by an electromagnetic axial bearing. By using electromagnetic regulation it is possible to improve the grinding process by oscillating the grinding cylinder axially by a few micrometres. The normal grinding force deforms, in particular, the overhanging section of the shaft. This deformation gives the inner grinding surfaces a more or less conical shape. This phenomenon can be controlled by automatically angling the axis of the grinding shaft depending on the magnitude of the normal force. Errors in the true running of the workpiece can be corrected by a high frequency bearing control of the shaft. These measures provide for high precision and a correctly ground cylindrical surface.

Disturbances caused by unbalanced forces and abnormal grinding forces from the wear or breakage of the grinding tool produce reactions in the magnetic fields of the bearings. These can be measured and compared with a digital model in the system and immediately corrected, at least to a certain extent. If specific limiting values are exceeded, then the grinding operation is terminated.

Monitored magnetic bearings coupled with mechatronics make possible the diagnosis of failures in the rotor systems of turbines, compressors etc. Figure 8.17 shows how to build an overall model for a failure diagnosis system according to [8.2]. The rotor system is modelled in such a way that its dynamic properties are captured. Displacement sensors, e.g. on the bearings, measure the instantaneous rotor behaviour, which can change due to disturbances in the fluidic system, in the

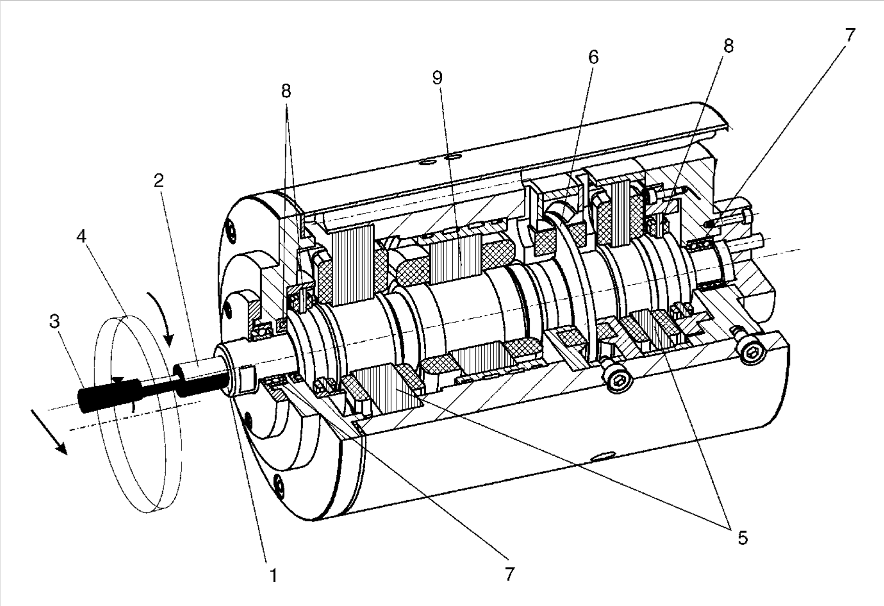


Figure 8.16. Grinding drive unit with electromagnetic radial and axial bearings. *1* grinding shaft, *2* tool, *3* grinding cylinder, *4* tools, *5* radial magnetic bearing, *6* axial magnetic bearing, *7* auxiliary bearing, *8* displacement sensors, *9* drive motor

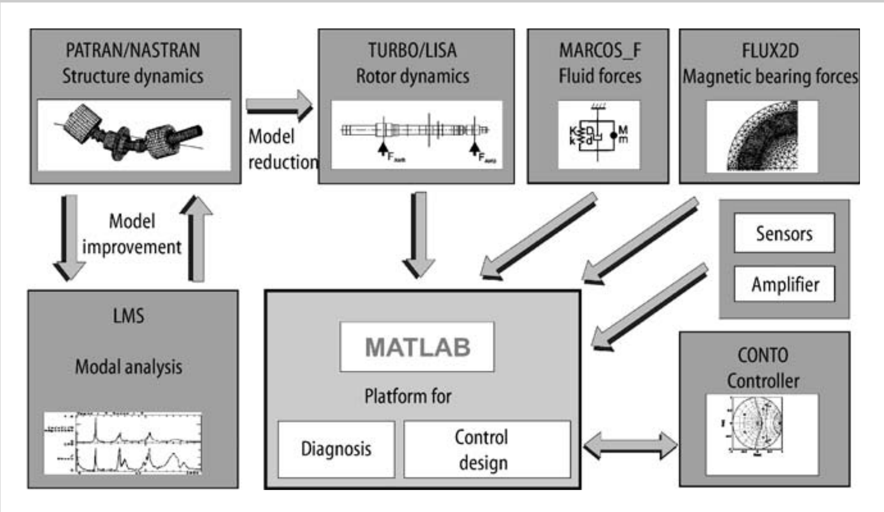


Figure 8.17. Building an overall model of a rotor system for failure diagnosis, after [8.2]

bearing system and in the rotor itself, e.g. sudden unbalanced forces caused by blade failure. The changes in the behaviour are measured and identified using the signals from the magnetic bearing sensors. Different situations give different characteristic signatures and these are analysed, the fault identified, and the appropriate measures applied.

8.3 Adaptronics

8.3.1 Fundamentals and Terminology

The term adaptronics is made up from adaptive structures and electronics. Hanselka [8.16–8.18] defines adaptronics as integrating mechanical engineering structures with the possibilities offered by electrical and electronic technology supported by control and information technology. Other authors, such as Elspass and Flemming [8.8], call these types of solution structronics and some consider adaptronics to be part of mechatronics.

The aim is to develop construction structures that continuously fulfil their tasks by actively adapting themselves to disturbances and to changes in loading and required functionality. Using adaptronics allows the construction structure to be directly influenced because the actuators and sensors are integrated in the structure as multifunctional materials. These sensors and actuators are positioned in the forceflow and via the processor react, signal, regulate and hence control the structure, which can therefore be seen as an active composite construction.

In Section 7.4.3 the principle of self-help is described. This principle refers to pure mechanical structures that through careful design can have self-reinforcing, self-balancing and self-protecting properties. The introduction of adaptronics widens and considerably improves the potential performance of these structures by incorporating the actuators and sensors as load-carrying parts, i.e. they continuously participate and do so in a coordinated way.

Compared to the concept of mechatronics (see Section 8.2), the following characteristic differences exist:

- the structure always has active material parts
- actuators can act as sensors and vice versa
- the system always contains a dynamic model of the structure that adapts, based on signals from sensors, to changes of the real structure and controls this structure through the actuators
- the reactions in the model and in the control system always take place in real time.

Multifunctional materials that can be used are: piezo ceramics, shape memory alloys, PVDF fluorothermoplastics (as films or foils), optical glass fibres, and multifunctional composites such as fibre-reinforced glued layers with embedded piezo ceramics. Piezo actuators can be produced in a multitude of shapes so that they can be integrated into a structure in the most effective way [8.8, 8.16]. Figure 8.18 shows some of the available shapes. For a stacked piezo actuator the main extension direction is in the direction of the stack, whereas for a plane one the main extension direction is parallel to the plane. Embedded in structures these actuators can provide regulated and controlled extensions. Such actuators can, for example, lengthen a bar as if tension had been applied to it. When placed pairwise in the outer surfaces of a fibre composite plate, bending effects can be produced. Configured at 45° to the main axis they are able to initiate torsional deformations.

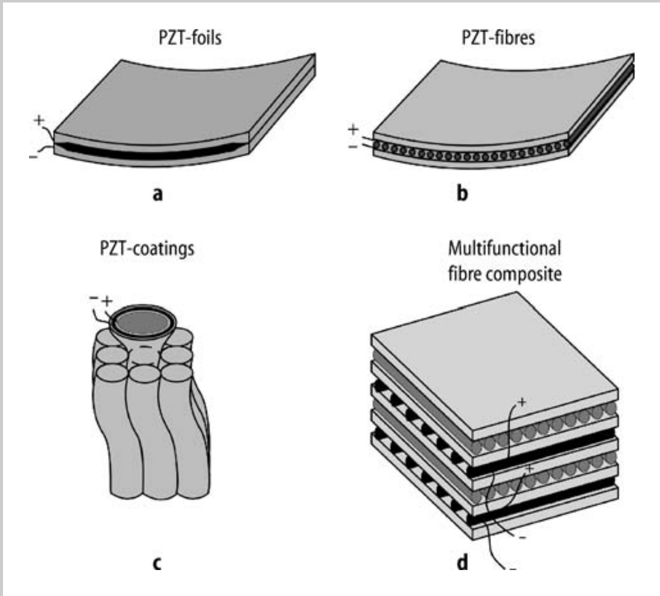


Figure 8.18. Shapes of piezo actuators as **a** foils, **b** fibres, **c** coatings and **d** integrated as a multifunctional fiber composite, after [8.16]

The general architecture of adaptronic solutions is shown in Figure 8.19. The active structure is essentially a fibre reinforced composite plate that can be complemented by a sandwich or hybrid structure. Sensors and actuators are embedded using material connections between the laminate layers of fibres and the matrix material. When a disturbance or change is sensed, signals from the sensors are sent to the computer model that simulates the structure. Depending on the goal, the control system is activated. Guided by the model, it sends correcting signals to the actuators of the structure. The structure then moves into a new state in line with the one defined by the model. This fast real-time control allows continuous adaption.

The applications described here may be considered utopian, unnecessary or too expensive given the current state of technology. However, the possibilities are fascinating and the examples that follow provide useful suggestions to trigger novel ideas for hitherto conventional areas.

8.3.2 Goals and Limitations

The goals of adaptronic systems are to:

- return a structure to its original state by undoing the effects of loads, temperatures and disturbances
- suppress actively vibration and noise
- change actively the embodiment
- realise structures with infinitely large stiffness at discrete positions

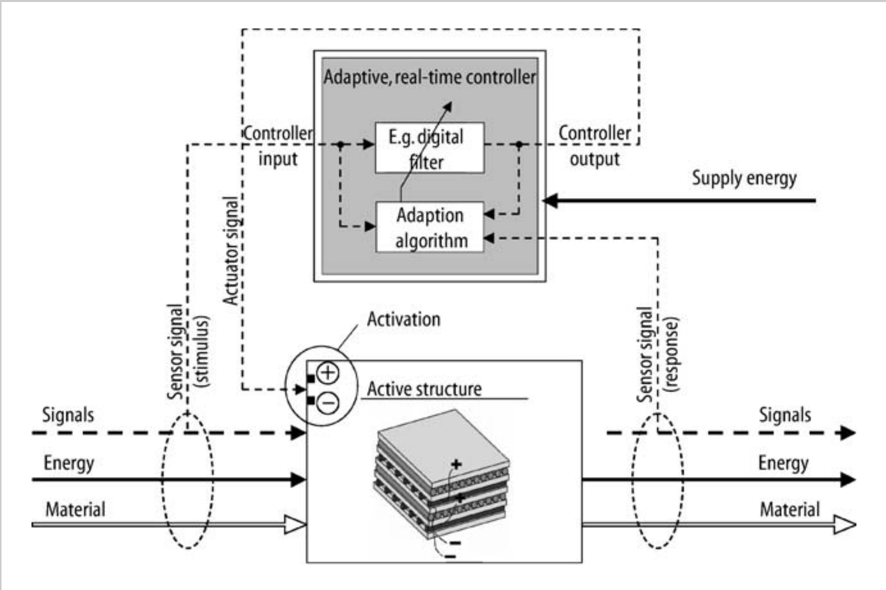


Figure 8.19. General architecture of adaptronic systems, after Hanselka [8.16]

- change actively the position
- identify damage in composites.

The limitations of adaptronics include:

- construction effort is comparatively high
- forces or movements initiated by the actuators are small
- costs for the sensors and actuators are high
- full theoretical understanding and modelling of the control process might not be possible because of the complexity
- improvements offered seem unnecessary, i.e. the cost/benefit ratio is not yet convincing.

Further research and development will overcome these limitations and extend the boundaries.

8.3.3 Development of Adaptronic Solutions

What has been said for the development of mechantronic solutions (see Section 8.2.3) applies equally to the development of adaptronic solutions. Theoretical understanding and appropriate mathematical modelling of the structures, their intelligent configuration and embodiment, and the optimal placement of sensors and actuators are essential. The development of such structures also requires a systematic approach and teamwork involving different disciplines.

8.3.4 Examples

Example 1: Non-Deforming Beams

Beam-like components subjected to external loads perpendicular to their main axes deform by bending. Adaptronic solutions can prevent this. Depending on the number and placement of piezo surface actuators, the bending can be reduced to zero at one or more discrete positions along the beam, even with differing loads. Bending due to the self-weight of a component can be compensated for in the same way. Figure 8.20 shows a beam and its deformation in a conventional arrangement and in an arrangement with embedded piezo actuators. The latter results in zero bending deformation at discrete positions [8.17]. To calculate the required "counter deformation" a model of the structure and the loading has to be built and the appropriate formulae established. Such compensation possibilities

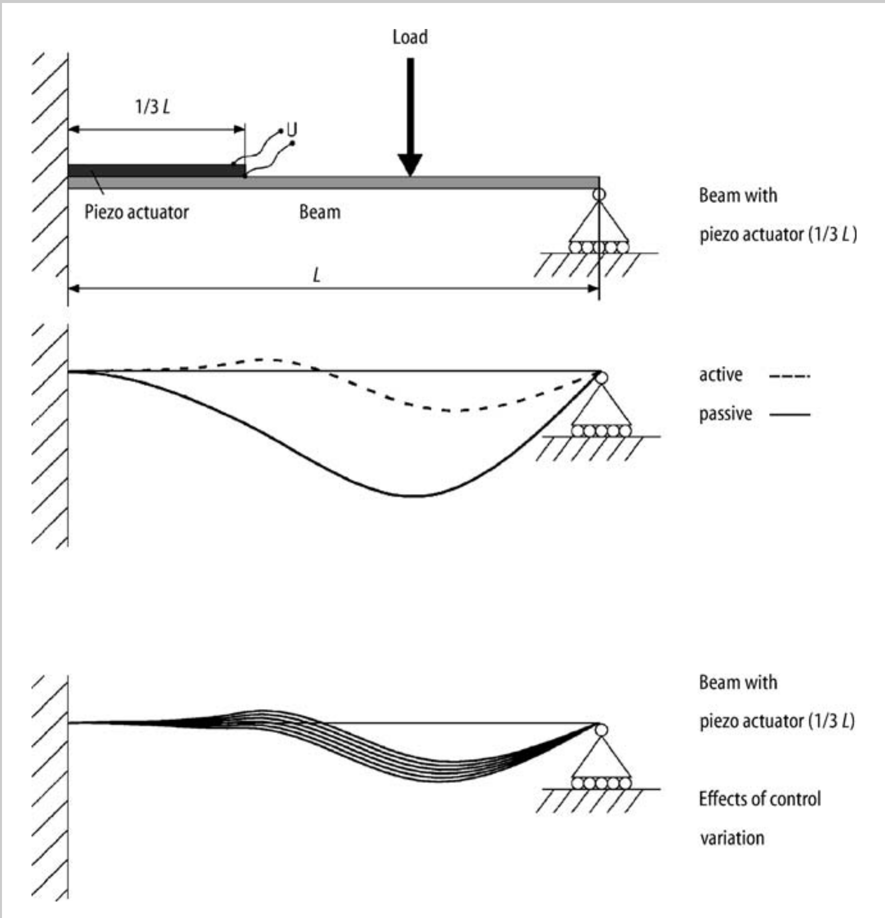


Figure 8.20. Beam with active reduction of its bending deformation, after [8.17]

are of importance for robot technology, high-precision measuring instruments, and minimal invasive surgery technology.

Example 2: Self-Correcting Antenna Reflectors

In the aerospace industry and for high-precision mirror systems, the exact shape of the reflectors is crucial. This can be realised using adaptronics. Elspass, Flemming and Paradies [8.9, 8.23] give an example for the continuous adaption of a reflector surface to compensate for the Earth's gravity. The reflector surface, see Figure 8.21, has a double wall filled with foam. The outer layers of this sandwich structure are fitted with sensors and actuators in a star-shaped arrangement. The actua-

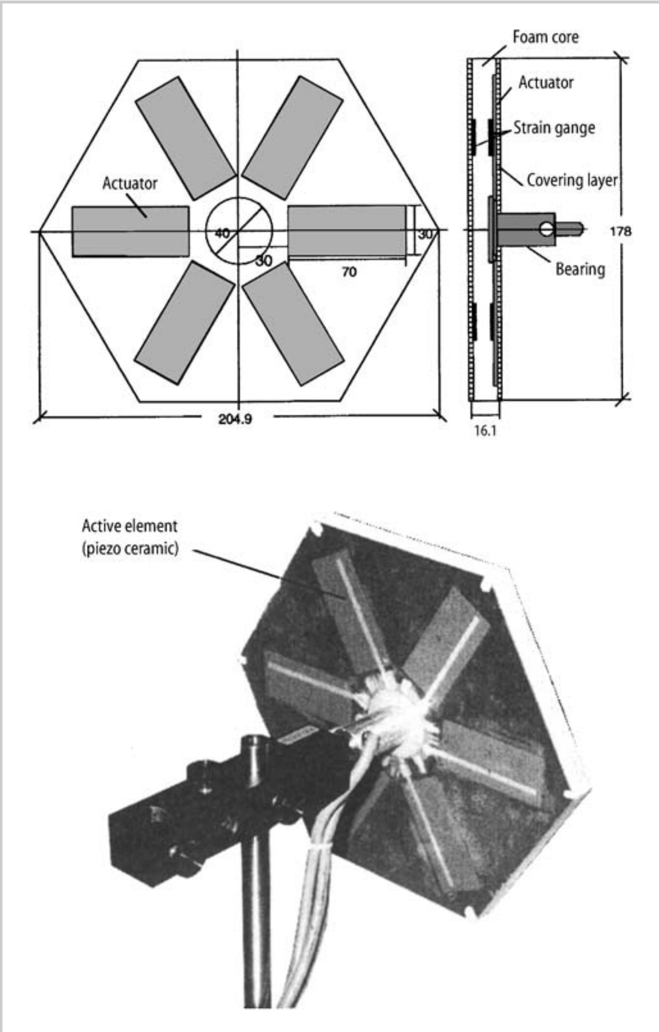


Figure 8.21. Detailed arrangement of a parabolic reflector with active sandwich structures and integration of piezo actuators, after [8.8, 8.9, 8.23]

tors are used to actively counteract the deformations caused by external effects or by the structure itself. This also allows the initiation of a deformation that is more parabolic or ellipsoidic. This principle of adaptive self-correction was used in the Hubble telescope to compensate for errors and to focus the antennae reflectors.

Example 3: Low vibration vehicle body shells

In the automobile industry there are several possible applications to improve the characteristics of body shells. Large thin-walled surfaces tend to vibrate and cause drumming. This can be counteracted by fitting piezo actuators in selected areas in order to actively reduce the vibrations, see Figure 8.22.

Such surfaces can also be used to prevent noise transmission. The surfaces are excited by piezo actuators in anti-phase to the noise vibrations thus compensating for the noise. The ride inside the vehicle thus becomes much quieter [8.8, 8.16, 8.18, 8.24].

Extending piezo actuators can be fitted in the forceflow paths of connecting and stiffening elements of a car body shell to compensate for deformations. In particular, torsional piezo actuators can be used to compensate for torsional deformations during operation. In the case of a crash, deformations that take place in opposing directions can be introduced to channel the flows of energy such that the crash deformations follow the desired paths.

Figure 8.22. Active body shell, after [8.15, 8.17]

9 Size Ranges and Modular Products

9.1 Size Ranges

Size ranges provide a rationalisation of design and production procedures [9.35].

For the *manufacturer* they have the following *advantages*:

- The design work can be done once and for all and can be used for a host of applications.
- The production of selected sizes can be repeated in batches and hence becomes more cost-effective.
- Higher quality is possible.

This implies the following *advantages* for the *user*:

- competitive and high quality products
- short delivery times
- easy acquisition of replacement parts and fittings.

Disadvantages for both manufacturer and user are:

- limited choice of sizes, not always with optimum operational properties.

By a size range we refer to technical artefacts (machines, assemblies and components) for a wide sphere of applications that:

- fulfil the same function
- are based on the same solution principle
- are made in varying sizes
- involve similar production processes.

If, in addition to the range of sizes, other associated functions have to be implemented, then *modular products* (see Section 9.2) will have to be developed side-by-side with size ranges. The development of size ranges may be original or based on an existing product but must, in either case, be carefully graded. One begins with one initial design, which is referred to as the *basic design*, from which the other sizes in the range are derived. These are referred to as *sequential designs* [9.35]. The basic design is assigned the index 0, the first successive member of the size range (sequential design) the index 1, the k-th member the index k.

In the development of a size range it is essential to make use of similarity laws and helpful to make use of decimal-geometric preferred number series. These generic tools are discussed in the next two sections.

9.1.1 Similarity Laws

Geometric similarity ensures simplicity and clarity of design. Designers know, however, that technical artefacts stepped up in geometric proportions are not satisfactory except in very rare cases. In particular, purely geometrical magnification is only permissible when similarity laws permit, which should always be checked. These laws are used very successfully in model testing [9.12, 9.18, 9.31, 9.34, 9.39, 9.42]. It is obvious to transfer this procedure to the development of size ranges. In general, however, the development of size ranges has a different objective from model technology, namely to achieve:

- the same level of material utilisation
- with similar materials if possible
- with the same technology.

It follows that, if the function is to be fulfilled equally well throughout the range, the relative stresses must remain the same.

We speak of *similarity* if the relationship of at least one physical quantity in the basic and sequential designs is constant. It is possible to define basic similarities with the help of the fundamental quantities length, time, force, quantity of electricity (charge), temperature and luminous intensity (see Table 9.1).[1]

Thus we have *geometric similarity* if the ratio of all the lengths of any sequential design to all the lengths of the basic design is constant. Here, the non-dimensional parameter to be held constant, the step factor, is $\varphi_L = L_1/L_0$ where L_1 is any length of the first member of the size range (sequential design); and L_0 the corresponding length of the basic design. For the k-th sequential design $\varphi_{L_k} = \varphi_L^k$. In the same way,

Table 9.1. Basic similarities

Similarities	Basic quantities	Invariants
Geometric	Length	$\varphi_L = L_1/L_0$
Temporal	Time	$\varphi_t = t_1/t_0$
Force	Force	$\varphi_F = F_1/F_0$
Electrical	Charge	$\varphi_Q = Q_1/Q_0$
Thermal	Temperature	$\varphi_T = \vartheta_1/\vartheta_0$
Photometric	Luminous intensity	$\varphi_J = J_1/J_0$

[1] Fundamental physical quantities are as listed in the German text. The basic physical quantities selected for the SI system differ slightly. These, along with their basic units shown in brackets, are: length (metre); time (second); mass (kilogram); electric current (ampere); thermodynamic temperature (Kelvin); and luminous intensity (candela). The differences do not affect the principles described.

we can describe similarities in time, force, electricity, temperature and luminous intensity.

If two or more of the basic quantities are in constant proportion, then we have special similarities. Model technology has defined dimensionless parameters for important and recurring similarities. Thus, in the case of simultaneous invariance of length and time, we have *kinematic similarity*, and in the case of simultaneous invariance of length and force we speak of *static similarity*.

A very important similarity, namely *dynamic similarity*, appears when a constant force relationship is combined with geometric and temporal similarities. Depending on the forces involved, we arrive at different dimensionless parameters. *Thermal similarity* deserves special mention because, in the case of geometrically similar size ranges and the same utilisation of materials, it is not compatible with dynamic similarity [9.37].

Table 9.2 lists important similarity relationships in the development of size ranges for mechanical systems. They are by no means exhaustive and must be supplemented from case to case, for instance in bearing developments by Sommerfeld's number and in hydraulic machines by the cavitation number and pressure index.

Table 9.2. Special similarity relationships

Similarities	Invariants	Group names	Definitions	Descriptions
Kinematic	φ_L, φ_t			
Static	φ_L, φ_F	Hooke	$Ho = \frac{F}{E \cdot L^2}$	Relative elastic force
Dynamic	$\varphi_L, \varphi_t, \varphi_F$	Newton	$Ne = \frac{F}{\rho \cdot v^2 \cdot L^2}$	Relative inertia
		Cauchy *	$Ca = \frac{Ho}{Ne} = \frac{\rho \cdot v^2}{E}$	Inertia force/elastic force
		Froude	$Fr = \frac{v^2}{g \cdot L}$	Inertia force/gravitational force
		NN **	$\frac{E}{\rho \cdot g \cdot L}$	Elastic force/gravitational force
		Reynolds	$Re = \frac{L \cdot v \cdot \rho}{\eta}$	Inertia force/frictional force in liquids and gases
Thermal	$\varphi_L, \varphi_\vartheta$	Biot	$Bi = \frac{h \cdot L}{\lambda}$	Supplied or removed/conducted quantity of heat
	$\varphi_L, \varphi_t, \varphi_\vartheta$	Fourier	$Fo = \frac{\lambda \cdot t}{c \cdot \rho \cdot L^2}$	Conducted/stored quantity of heat

* In some texts, we find $Ca = \sqrt{\rho/E}$. This is appropriate if Ca is intended as a velocity ratio relationship

** Not named

Example – Similarity at Constant Stress

In heavy engineering systems, inertia forces (forces due to mass, acceleration, etc.) and elastic forces resulting from the stress-strain relationship play a predominant role.

If the stresses are to remain constant throughout a size range, then $\sigma = \varepsilon \cdot E =$ constant. In that case the stress step factor becomes:

$$\varphi_\sigma = \frac{\sigma_1}{\sigma_0} = \frac{\varepsilon_1}{\varepsilon_0}\frac{E_1}{E_0} = 1$$

With the same material, that is $\varphi_E = E_1/E_0 = 1$, we need:

$$\varphi_\varepsilon = \varepsilon_1/\varepsilon_0 = 1\,, \quad \text{or} \quad \varphi_\varepsilon = \frac{\Delta L_1}{\Delta L_0}\frac{L_0}{L_1} = 1\,, \quad \text{or} \quad \varphi_{\Delta L} = \varphi_L$$

With this so-called Cauchy condition, all changes in length must increase with the same step factor as the appropriate lengths (geometric similarity). The elastic force step factor then becomes:

$$\varphi_{FE} = \frac{\sigma_1 A_1}{\sigma_0 A_0} = \varphi_L^2\,, \quad \text{with} \quad \varphi_0 = \varphi_\varepsilon \cdot \varphi_E = 1 \quad \text{and} \quad \varphi_A = \varphi_L^2$$

The inertia force step factor is:

$$\varphi_{FI} = \frac{m_1 a_1}{m_0 a_0} = \frac{\rho_1 V_1 a_1}{\rho_0 V_0 a_0}$$

With

$$\varphi_\rho = \rho_1/\rho_0 = 1\,, \quad \varphi_V = V_1/V_0 = L_1^3/L_0^3 = \varphi_L^3$$

and the acceleration step factor

$$\varphi_a = \frac{L_1 t_0^2}{t_1^2 L_0} = \frac{\varphi_L}{\varphi_t^2}$$

we have

$$\varphi_{FI} = \varphi_L^4/\varphi_t^2$$

A dynamic similarity, that is a constant ratio between inertia and elastic forces with geometric similarity, can only be attained if $\varphi_t = \varphi_L$:

$$\varphi_{FE} = \varphi_L^2 = \varphi_{FI} = \varphi_L^4/\varphi_L^2 = \varphi_L^2$$

Hence the velocity step factor becomes:

$$\varphi_v = \varphi_L/\varphi_t = \varphi_L/\varphi_L = 1$$

With the same material, the same result can also be derived from the Cauchy number (see Table 9.2), for when ρ and E remain constant then the dynamic similarity will only remain constant if the velocity v also remains constant.

For all important quantities such as power, torque etc., and with $\varphi_L = \varphi_t =$ constant and $\varphi_\rho = \varphi_E = \varphi_\sigma = \varphi_v = 1$, it is now possible to establish the similarity relationships shown in Table 9.3.

Table 9.3. Similarity relationships for geometrical similarity and equal stresses: dependence of important quantities on length

With $Ca = \rho v^2/E$ = constant and the same material, that is ρ and E = const., v = const. In the case of geometrical similarity the following relationships occur	
Speeds, n, ω Bending and torsional critical speeds n_{cr}, ω_{cr}	φ_L^{-1}
Strains ε, stresses σ, surface pressures p due to inertia and elastic forces, speeds v	φ_L^0
Spring stiffnesses s, elastic deformations ΔL Strains ε, stresses σ, surface pressures p due to gravity	φ_L^1
Forces F Powers P	φ_L^2
Masses M, torques T, torsion stiffnesses s_t Section moduli W, W_t	φ_L^3
Second moments of area I, J	φ_L^4
Mass moments of inertia I', J'	φ_L^5

Note: The utilisation of the materials and safety levels are only constant if the influence of the dimensions on the material properties can be ignored

It should be remembered that the utilisation of the materials and the safety levels only remain constant if the influence of the dimensions on the material properties can be ignored throughout the size range.

Size ranges developed in accordance with these laws are geometrically similar and provide for the identical utilisation of the materials. Such developments are possible whenever gravity and temperature have no decisive influence on the design. If they have, the use of semi-similar series is advisable (see Section 9.1.5).

9.1.2 Decimal-Geometric Preferred Number Series

Once we are familiar with the most important similarity relationships, we still have to determine the best method of choosing the step factor of a size range. Kienzle [9.24, 9.25] and Berg [9.5–9.9] have argued that a decimal-geometric series is the most useful.

A *decimal-geometric series* is based on multiplication by a constant factor φ and is developed within one decade. The constant factor φ is the step factor that determines the step sizes of the series and can be expressed as:

$$\varphi = \sqrt[n]{a_n/a_0} = \sqrt[n]{10}$$

where n is the number of steps within a decade. For 10 steps, the series would then have a step factor:

$$\varphi = \sqrt[10]{10} = 1.25$$

and is called R 10. The number of terms in the series is $z = n + 1$.

Table 9.4 sets out the main values of four preferred number series as defined by DIN 323 [9.13, 9.16].

The need for geometric scaling is often found in daily life and in technical practice. The resulting series conform with the Weber–Fechner law which states that the physiological sensation produced by a stimulus is proportional to the logarithm of the stimulus, e.g. sound and illumination.

Reuthe [9.40] has shown how, in the development of friction drives, designers instinctively choose the main dimensions by means of geometrical scaling. Our own work on turbine shaft oil scraper rings has confirmed these findings. In Figure 9.1, shaft diameters are plotted using a logarithmic scale against the number of oil scraper rings designed over a period of 10 years. The results show that there were 47 diameters with peaks at more or less regular intervals, which clearly demonstrates a geometrical scaling. However, the number of nominal sizes was disturbingly large—some differed by only a few millimetres and gave rise to very small production batches. Luckily, as Figure 9.1 also shows, if preferred sizes are selected with the help of the R 20 series, the number of variants can be reduced to less than half, giving a considerably more balanced and higher requirement per nominal size. Had the designers chosen such preferred numbers deliberately, a much more suitable size range would have emerged by itself.

The use of preferred number series thus provides the following *advantages* [9.13]:

- Appropriate scaling leads to the selection of nominal sizes in accordance with demand. The finer series have common numerical values with the coarser.

Table 9.4. Main values of preferred numbers

Basic series R 5	R 10	R 20	R 40	Basic series R 5	R 10	R 20	R 40
1.00	1.00	1.00	1.00		3.15	3.15	3.15
			1.06				3.35
		1.12	1.12			3.55	3.55
			1.18				3.75
	1.25	1.25	1.25	4.00	4.00	4.00	4.00
			1.32				4.25
		1.40	1.40			4.50	4.50
			1.50				4.75
1.60	1.60	1.60	1.60		5.00	5.00	5.00
			1.70				5.30
		1.80	1.80			5.60	5.60
			1.90				6.00
	2.00	2.00	2.00	6.30	6.30	6.30	6.30
			2.12				6.70
		2.24	2.24			7.10	7.10
			2.36				7.50
2.50	2.50	2.50	2.50		8.00	8.00	8.00
			2.65				8.50
		2.80	2.80			9.00	9.00
			3.00				9.50

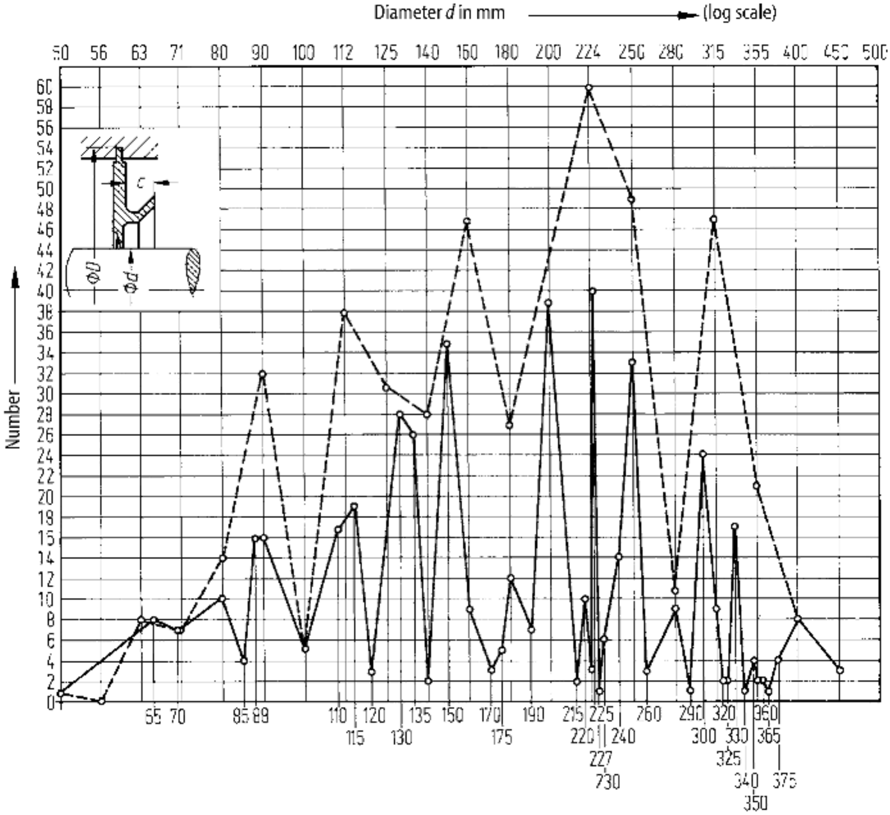


Figure 9.1. Frequency of seal diameters d of scraper rings for turbine shafts; *continuous line*: actual situation; *broken line*: suggested size range

With proper gradation it is possible to approximate an arithmetical series. This facilitates jumping from row to row and hence provides the different steps needed for matching the distribution of the market requirement. The preferred number series contain both decimal powers and also doubles and halves (see Section 9.1.3).

- There is a reduction of the dimensional variants by the choice of dimensions based on preferred numbers with a consequent saving in production documents, equipment and measuring tools.
- Since the products and quotients of terms of the series are in turn terms of a geometrical series, analyses and calculations reduce mainly to multiplication and division. As π is contained in the preferred number series with a good approximation, geometric gradation of component diameters will generate circumferences, circular areas, cylinder contents and spherical surfaces that are, in their turn, terms of the preferred number series.
- If the dimensions of a component or of a machine are terms of a geometrical series, then linear magnifications or diminutions will give rise to preferred num-

bers in the same series provided, of course, that the magnification or diminution factor is also selected from the series.

- Automatic growth of the size range will be compatible with existing or future ranges.

9.1.3 Representation and Selection of Step Sizes

1. Preferred Number Diagram

For the following discussion *preferred number diagrams* are useful. Preferred numbers in a size range can be represented as logarithms to the base 10 by means of their powers (see the derivation in Section 9.1.2). That is, every preferred number PN can be expressed by $PN = 10^{m/n}$ or:

$$\log(PN) = m/n$$

where m is the step number in the PN range and n the number of steps within one decade.

On the other hand, nearly all technical relationships can be expressed in the general form:

$$y = cx^p$$

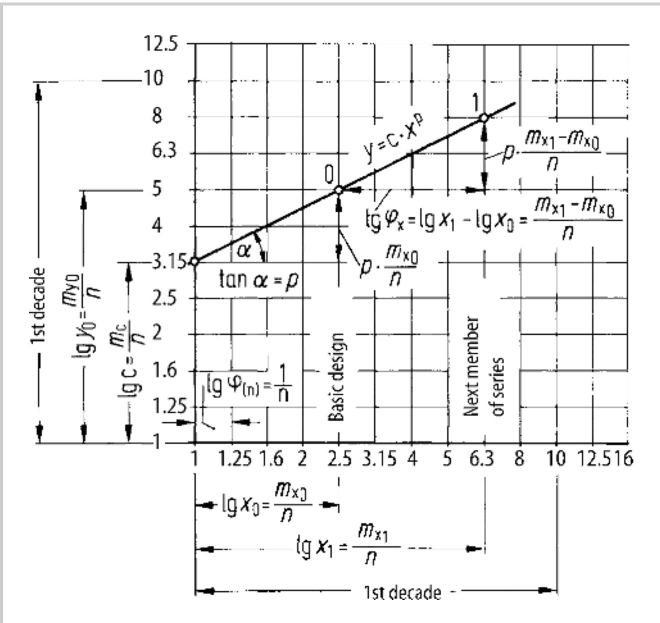


Figure 9.2. Technical relationships in the PN diagram; n step number in the finest underlying PN series; every intersection is a preferred number of this series; every integral exponent leads back to another preferred number

or in its logarithmic form as

$$\log y = \log c + p \log x$$

Hence the technical relationship can also be expressed by:

$$\frac{m_y}{n} = \frac{m_c}{n} + p\frac{m_x}{n}$$

Entering this into a coordinate graph and labelling the axes directly with natural numbers rather than logarithms, one obtains a preferred number diagram as shown in Figure 9.2. Every preferred number of a certain range (in this case R 10) is then located along each axis at equal spacings, each space representing the step factor (in this case 1.25).

If the dependent and independent quantities are associated by a power law $y = cx^p$ (see Figure 9.2) then both preferred numbers can be graded by a preferred number series, either with exponent $p = 1$ (linear growth, 45° line) or with $p \neq 1$ (non-linear growth, slope $p = 0.5, 2, 3 : 1$ or similar).

This type of representation of preferred numbers and number series is very useful, as we will show in the examples in Sections 9.1.4 and 9.1.5.

2. Selection of Step Sizes

In general, when trying to rationalise a product size range, designers will select their increments once and for all. To that end they make an *appropriate selection of step sizes*, for instance in respect of power and torque. That selection can be based on several considerations. First of these is the market situation, which as a rule requires small increments so that the varied demands of customers can be met most effectively. The second consideration is efficient design and production. For technical and economic reasons, the selected step sizes must be fine enough to meet the technical demands (for instance, power), and yet coarse enough to allow large-batch production based on a simplified range.

The selection of optimum step sizes thus involves an integrated approach to the "market – design – production – sales" system, and requires information about:

- market expectations (sales) in respect of individual sizes
- market behaviour in respect of simplified ranges and the resulting gaps
- production costs and times of the various step sizes (see Section 11.3.4) and the effect on the overall production costs [9.36]
- constant properties of each product in the size range.

Since the optimum selection of step sizes must be based on all the factors we have mentioned, it is not always possible to opt for a constant step factor; more often technical and economic considerations will demand the break up of a particular range of sizes into several sets.

If we define a *characteristic number N* of a range such that:

$$N = \frac{\text{Greatest term of the range}}{\text{Smallest term of the range}} = \varphi^n$$

where n is the number of the steps in any particular range and $z = n + 1$ is the number of terms, then the step factor:

$$\varphi = \sqrt[n]{N}$$

The range can be split up by means of a *constant* or a *variable step factor*, that is, by jumps within and between preferred number series (R 5–R 40). The resulting step characteristics are shown in Figure 9.3.

Type A has a constant step factor (for instance $\varphi = 1.25$ corresponding to R 10) over the entire range.

In Type B, the lower part of the range is divided up coarsely (for instance $\varphi = 1.6$ corresponding to R 5) and the upper part more finely (for instance $\varphi = 1.25$ corresponding to R 10). Such degressive geometrical product ranges should be used whenever a coarser grading for the smaller product sizes is economically justifiable, e.g. because of smaller batch sizes.

Type C has a greater increment in the upper range and is used if demand is concentrated on smaller sizes. It is also known as a progressive geometrical range.

Type D has a smaller step factor in the middle part of the range, which is characteristic of situations where demand is concentrated there.

Type E a larger step factor in the middle part of the range, however this is hardly ever required.

We can generally take it that the size gradation must be finer the greater the demand and the more precisely certain technical stipulations have to be met. A different gradation can be chosen easily whenever the market demands and without great design effort if a decimal-geometric preferred number series is used. Needless to say, the effects on production must be taken into account as well.

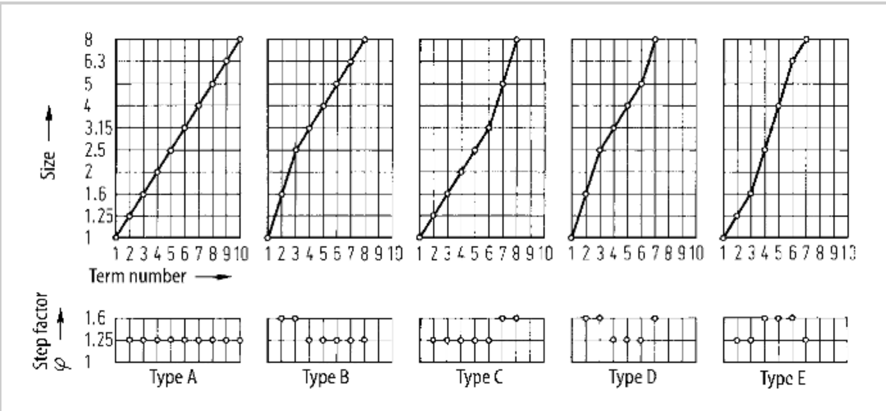


Figure 9.3. Step characteristics of size ranges. Factors assigned to each step

For economic reasons, it is often advisable to split the range into parts and to replace several sizes with just one for each part (semi-similar size range). Such a gradation leads to a stepped line.

In grading, a distinction must be made between *independent* and *dependent quantities*. As a rule, the task itself determines which sizes must be treated as dependent and which as independent. For example, geometric grading of the power output may be advantageous for market reasons and grading of sizes by preferred number series for production reasons.

In Figure 9.4, the dependent and independent quantities have been plotted logarithmically. If the preferred numbers have the same factor, then the spacing is constant (see Figure 9.2).

However, technical systems may not involve power relationships between dependent and independent quantities. In that case, not all the sizes can be geometrically graded. Here designers must decide, depending on the task, whether they grade the independent or the dependent quantities in accordance with a preferred number series.

The following example illustrates this situation. Independent sizes I_{12}, I_{23} etc. have been assigned to the geometrically graded parts of the range D_1D_2, D_2D_3 etc. (see Figure 9.4). This correlation is obtained by replacing the D_1D_2, D_2D_3, etc. with their geometric mean values $D_{12} = \sqrt{D_1 \cdot D_2}$ and then drawing the stepped line accordingly. This is preferable to fixing the line intuitively. It can be seen that the dependent relationships based on curve *a* once again result in a geometric grading of the steps, while the non-linear relationships based on curve *b* do not (in other words, the I'-values are not geometrically graded). Here designers must again decide for what sizes a gradation based on preferred numbers is still appropriate.

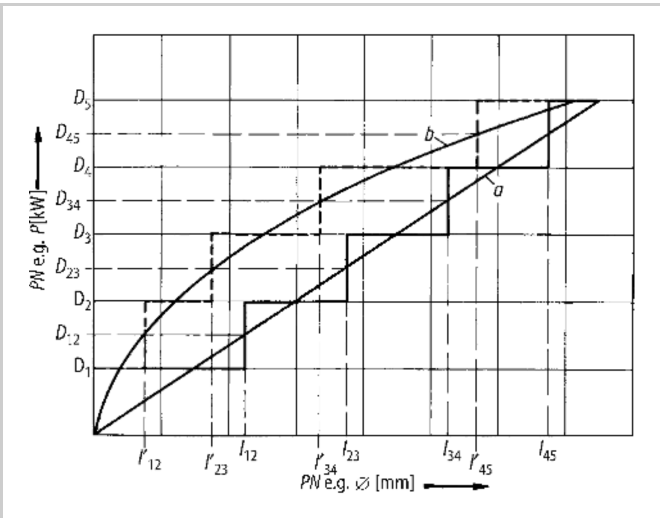


Figure 9.4. Grading of independent (I) and dependent (D) quantities. For a power function there is a linear relationship on the *PN* (preferred number) diagram (*curve a*); for others there is a non-linear relationship (*curve b*)

Deviations from strictly geometric gradings may, as we have already said, be imposed by production considerations. Practice has shown that it may be more economical to provide arithmetic or even irregular increments for some component dimensions, so that, in a product size range, semi-finished materials, which are not usually geometrically graded, can be exploited more fully, or the production process can be simplified. This leads to semi-similar size ranges (see Section 9.1.5). Even though grading based on preferred number series is generally advisable, designers should not use it rigidly, but decide each case individually after cost analysis (see Section 11.3.4).

9.1.4 Geometrically Similar Size Ranges

If the basic design, the choice of materials and the necessary calculations are to hand, and if the nominal dimensions lie roughly in the middle of the intended size range, then, as already discussed (see Section 9.1.3), nearly all technical relationships can be expressed in the general form:

$$y = cx^p$$

or in its logarithmic form as

$$\log y = \log c + p \log x$$

All dependencies can be represented on a *preferred number diagram* (double logarithmic graph) as straight lines. The slope of each line corresponds to the exponent p of the technical relationship (dependence) (see Figure 9.2). For simplicity, we enter the preferred numbers instead of the logarithms and so obtain a very practicable visual tool for the development of size ranges, as Berg [9.7, 9.9] has pointed out. Every intersection represents a preferred number, and is always produced by lines with integral exponents. If the abscissa gives the nominal size x, then the step factor $\varphi_x = x_1/x_0$. In geometrically similar size ranges it is equal to the length factor φ_L. Once the basic design has been fixed, all other magnitudes—dimensions, torques, power, speeds, etc.—can be derived from the known exponents of their physical or technical relationships (see Table 9.3) and can be drawn as straight lines with the appropriate slope (thus weight, $\varphi_W = \varphi_L^3$, will have a slope of 3:1).

As a result, the main dimensions of the product can be expressed in diagram form without the need for further drawings. Figures 9.5 and 9.6 provide an example for a gear coupling.

Such data sheets (preferred number diagrams) enable designers, starting from the basic design, to provide the sales department, the purchasing department, the planning department and the production department with crucial information on every size in the range.

It should, however, be remembered that the measurements cannot be transferred directly from the data sheets to the drawings and other production documents, which need only be made once an order has been received, unless the following factors have also been taken into consideration:

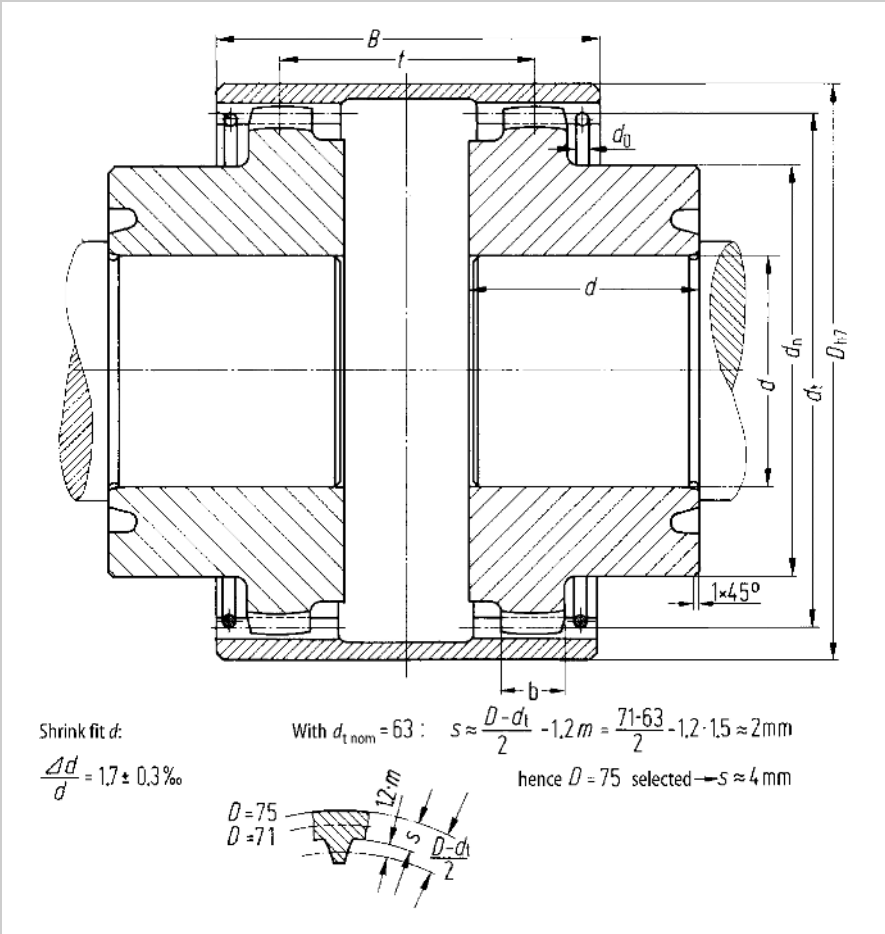


Figure 9.5. Basic design ($d_t = 200$ mm) for gear coupling size range

1. *Fits and tolerances* are not in geometric step with the nominal sizes, the size of a tolerance unit i for a dimension D being given by $i = 0.45 \times \sqrt[3]{D} + 0.001\,D$, that is, the factor for the tolerance unit being determined by the relationship $\varphi_i = \varphi_L^{1/3}$. Particularly in the case of shrink and interference fits, but also of function-determined bearing clearances etc., the tolerances must, because the elastic deformations tend towards φ_L, be adapted accordingly. In other words, smaller dimensions make more, and larger dimensions less, severe demands (see Figure 9.6).
2. *Technological limitations* often demand deviations. Thus a cast wall cannot be reduced below a minimum thickness, and certain thicknesses cannot be completely hardened by quenching. In all such cases, the limiting dimensions must be ascertained, as was done, for instance, with the smallest sleeve for the gear coupling shown in Figure 9.6, which had to be strengthened by an

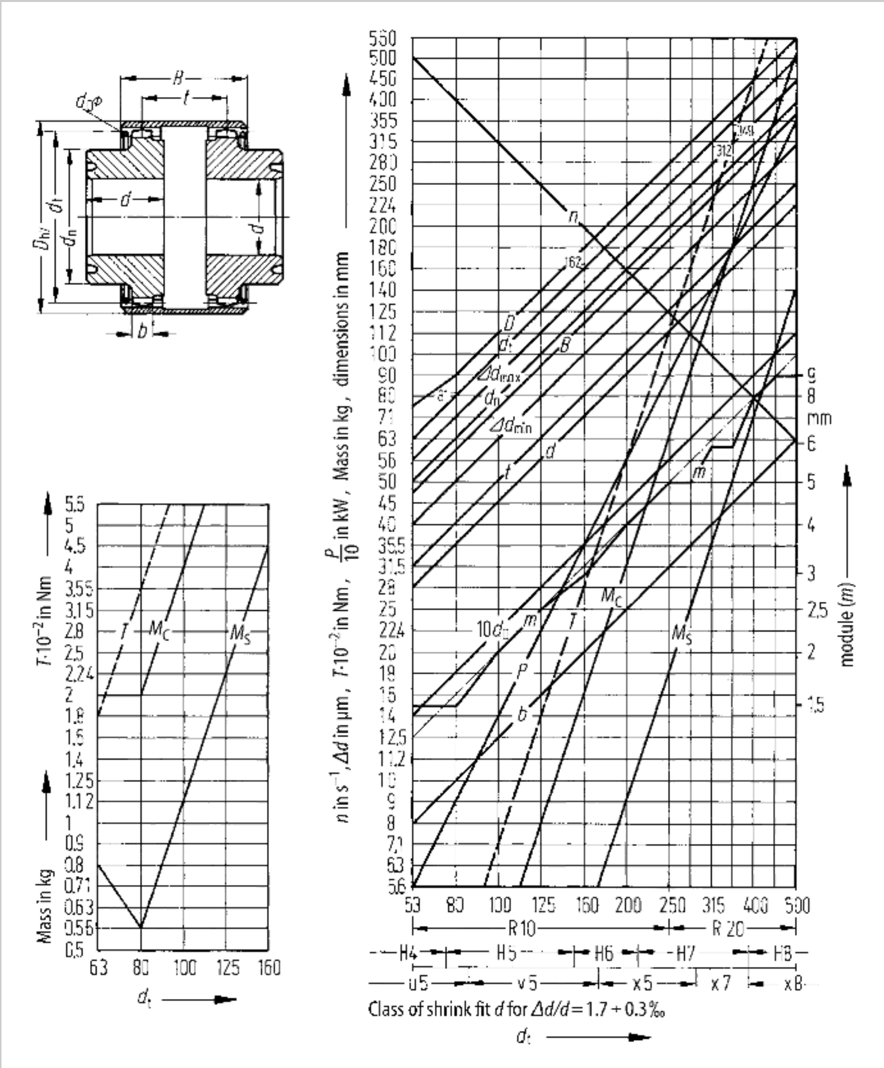


Figure 9.6. Data sheets for the gear coupling size range plotted for the range of nominal diameters d_t corresponding to the basic design shown in Figure 9.5. Dimensions geometrically similar. Exceptions: outer sleeve diameter D of the smallest member for reasons of stiffness; the standardised gear moduli m cannot be stepped in accordance with preferred numbers; and these moduli in combination with the need for an integral, even number of teeth require a slight adaptation of the pitch circle diameters of some steps

increase in the wall thickness (D = 71 mm to D = 75 mm). The same principle applies to measurement and machining provisions (see Figure 9.5).

3. *Overriding standards* are not always based on preferred numbers, so the relevant components must be adapted accordingly (see Figure 9.6 fixing the module).

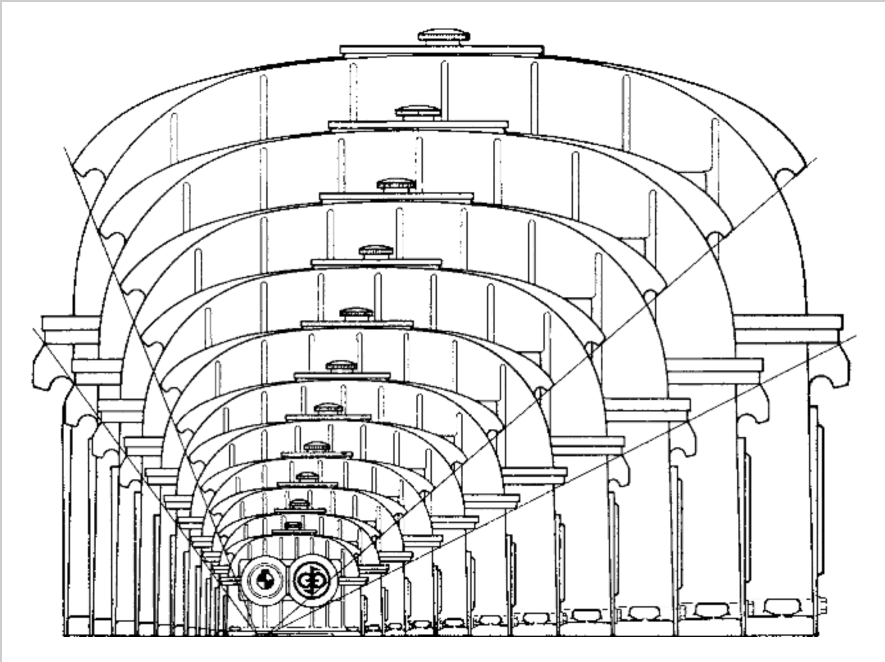


Figure 9.7. Display of a gearbox size range [9.15] (Flender)

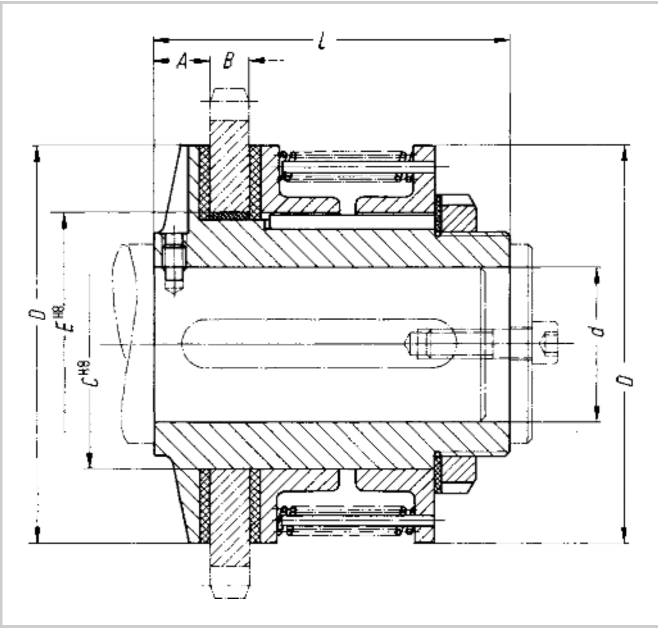


Figure 9.8. Basic design of a torque-limiter (Ringspann KG)

4. *Overriding similarity laws* or *other requirements* may impose a more pronounced deviation from geometric similarity, in which case semi-similar series should be used (see Section 9.1.5).

Once the necessary deviations from geometric similarity have been determined, if necessary by checking drawings of the critical areas, they are entered in the data sheet. Production documents need not be prepared until actually required. To illustrate the size range, say in catalogues or advertisements, displays of the type previously reserved for technical drawings are being increasingly used [9.7, 9.25]. Figure 9.7 shows an example based on a gearbox size range.

Figure 9.8 shows the basic design of a geometrical range of torque-limiters, providing for equal utilisation of materials, paying due heed to overriding standards. If the lining wears, the drop in torque must be kept as small as possible. This is done by means of a large number of peripheral coil springs with relatively flat characteristic curves. All sizes of the torque-limiter fulfil the similarity conditions mentioned in Table 9.3: relationships between forces are kept constant over the

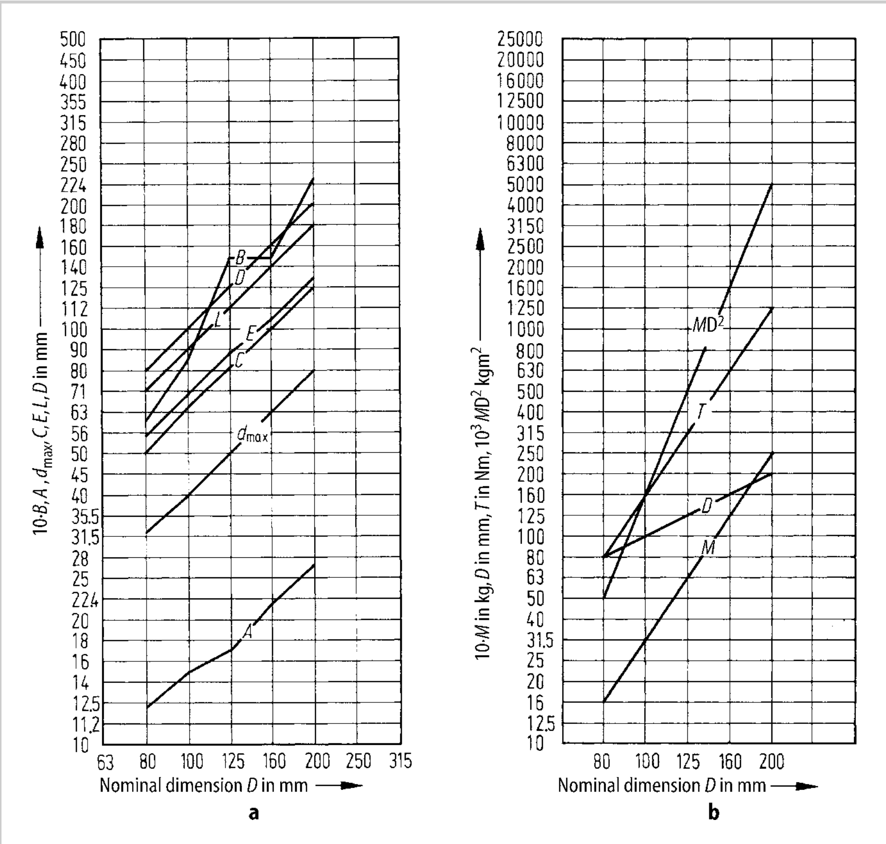


Figure 9.9. Data sheets for torque-limiter shown in Figure 9.8: **a** Dimensions adapted to overriding standards and the sizes of bought-out parts; **b** Main parameters: torque T, mass M and moment of inertia MD^2

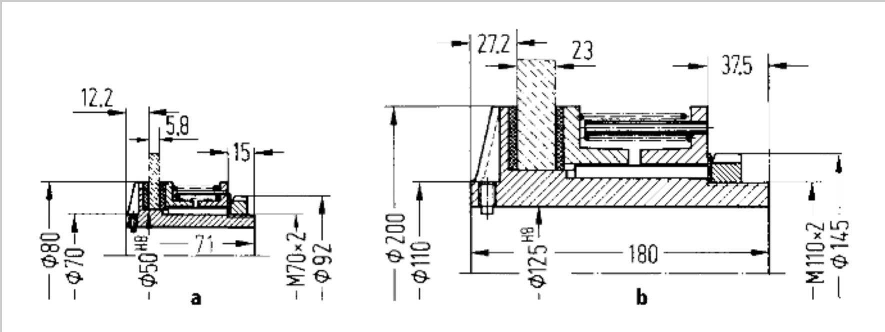


Figure 9.10. Layouts from the size range shown in Figure 9.9 (Ringspann KG): **a** smallest; **b** largest

entire range and the utilisation of the materials is constant. Figures 9.9a and 9.9b show the relevant data sheets. The identifiable deviation of dimension B is determined by the overriding standard width of the chain wheels (bought-out parts); the deviation of A by the use of standard screws and taps and also by technological factors (wall thickness). Figures 9.10a and 9.10b show the smallest and largest members of the size range respectively.

9.1.5 Semi-Similar Size Ranges

Geometrically similar size ranges based on a decimal-geometric series cannot always be realised. Significant deviations from geometrical similarity may be imposed by the following factors:

- overriding similarity laws
- overriding task requirements
- overriding production requirements.

In all such cases, *semi-similar* size ranges must be developed.

1. Overriding Similarity Laws

Influence of Gravity

If inertia forces, elastic forces and weight act together, and if the latter cannot be neglected, then the relationships derived from the Cauchy condition no longer apply. This, as we have explained, is because, while the inertia and elastic forces at constant speed depend on the length factor ($\varphi_{\mathrm{FI}} = \varphi_{\mathrm{FE}} = \varphi_{\mathrm{L}}^2$), the weight increases as

$$\varphi_{\mathrm{F_w}} = \rho_1 \cdot g \cdot V_1/(\rho_0 \cdot g \cdot V_0) = \varphi_\rho \varphi_{\mathrm{L}}^3 \quad \text{and for} \quad \varphi_\rho = 1 \quad \text{as} \quad \varphi_{\mathrm{F_w}} = \varphi_{\mathrm{L}}^3$$

Table 9.2 shows that, if all other material properties and the speed remain constant, length is the only variable dimension. If it does vary, the relevant dimensionless parameter cannot remain constant—that is, the relationship of the forces must change. Hence with similar cross-sections the stresses change as well and geometric similarity cannot be maintained. This is the case, for instance, with the construction of electrical machines and conveyor systems.

Influence of Thermal Processes

A similar series of problems arises with thermal processes. Constant temperature relationships φ_ϑ only apply when there is thermal similarity, regardless of whether the heat-flow is steady or fluctuating. The first case is represented by the so-called Biot number, $Bi = hL/\lambda$ [9.20], where h is the heat transfer coefficient and λ the coefficient of thermal conductivity of the heated wall. Here too it is obvious that, with approximately equal heat transfer coefficients (the velocity remaining the same) and with the same materials, only the length can vary, and indeed must vary in a size range. As a result the dimensionless parameter governing thermal similarity cannot itself remain unchanged [9.37]. The same is true of fluctuating heating and cooling processes represented by the Fourier number, $Fo = \lambda t/(c\rho L^2)$, where λ is the coefficient of thermal conductivity, c the specific heat and ρ the density of the material. If the material remains the same, the time t and the length L are variable. For the Cauchy number to remain constant, the time must vary as a function of the length. Once again we are left only with the length, which must be variable in a size range. Hence the Fourier number can only remain constant if the time step factor $\varphi_\mathrm{t} = \varphi_\mathrm{L}^2$, that is, if the time varies as the square of the length.

All other things being equal, therefore, thermal stresses due to temperature variations increase as the square of the wall thickness.

Other Similarity Relationships

If the function of a device is determined by physical processes that do not involve inertia or elastic forces, then the physical relationships must be taken into consideration in all designs based on similarity laws [9.18, 9.34, 9.39, 9.42].

In a plain bearing, for instance, the operating conditions are set by the Sommerfeld number:

$$So = \bar{p}\psi^2/(\eta\omega)$$

where $\bar{p}$ is the mean pressure, ψ the non-dimensional clearance, η the dynamic viscosity and ω the rotational speed.

In a machine that otherwise obeys the Cauchy number, we have

$$\varphi_\mathrm{So} = \frac{\bar{p}_1\psi_1^2\eta_0\omega_0}{\bar{p}_0\psi_0^2\eta_1\omega_1} = \varphi_{\bar{\mathrm{p}}}\varphi_\psi^2\frac{1}{\varphi_\eta}\frac{1}{\varphi_\omega}$$

With elastic forces we have $\varphi_{\bar{p}} = 1$, with weight we have $\varphi_{\bar{p}} = \varphi_\mathrm{L}$; for the rest, we have:

$$\varphi_\psi = 1\,,\quad \varphi_\omega = 1/\varphi_\mathrm{L}\,,\quad \varphi_\eta = 1 \quad \text{at} \quad \vartheta = \text{constant}\,.$$

With elastic forces, therefore, we have $\varphi_{So} = \phi_L$ with weight $\varphi_{So} = \varphi_L^2$. As the Sommerfeld number increases with the overall size, the bearing becomes increasingly eccentric and, at a given size, may take up the clearance necessary for lubrication.

In a pipe with laminar flow, the loss of pressure is expressed by:

$$\Delta p = f \frac{l}{d} \frac{\rho}{2} v^2 = 32\eta \frac{l}{d^2} v$$

where $f = 64/Re$ in the laminar region, $Re = dv\rho/\eta$, l = length of pipe, d = diameter of pipe, v = velocity in the pipe, ρ = density of the fluid, and η = dynamic viscosity of the fluid.

With η = constant, the pressure loss function becomes:

$$\varphi_{\Delta p} = \varphi_v / \varphi_L$$

Thus, if the pressure loss is to remain constant, the velocity in the pipe must increase in proportion to the size. As a result, the Reynolds number may increase to such an extent that the transition region for turbulent flow is reached, in which case the above equations no longer hold.

Electric AC motors that have a discrete speed depending on the pole number cannot be used to adjust the speed of a finely stepped range of machines (for instance pumps) to maintain a constant Cauchy number. The consequences would be varying stresses and different outputs and the remedy is a suitably adapted semi-similar series.

2. Overriding Task Requirements

The choice of a semi-similar size range may be imposed, not only by similarity laws but also by overriding task requirements. This situation often arises in an ergonomic context. All components with which human beings come into contact in the course of their work—especially the controls, handles, standing and sitting places, and safety features—must fit physiological needs and physical dimensions. In general, none of these components can be changed with the nominal size of the range.

An overriding requirement may also appear for purely technical reasons, inasmuch as inputs and outputs may vary widely in size, as happens with paper and print products.

Figure 9.11 is a schematic representation of a lathe. Here, the size of the human-operated controls cannot be increased with the size of the range; indeed some cannot be altered at all. Thus the operating height must always be adapted to human dimensions, and there are some operations that require an exceptionally long turning length or an exceptionally large turning diameter. In all such cases the machine as a whole must be designed on semi-similar principles, while individual assemblies such as spindle drives, tail-stocks, etc. can be developed as geometrically similar series.

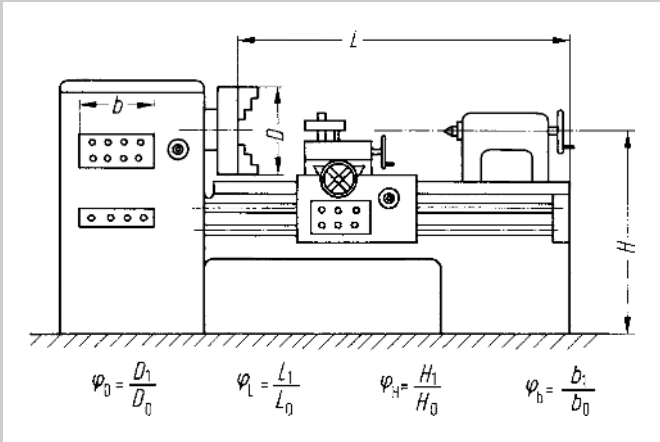


Figure 9.11. Lathe with main dimensions and controls shown schematically; the diameter/length/height ratio may have to be varied to suit particular groups of products, that is $\varphi_D \neq \varphi_L \neq \varphi_H$, but if possible $\varphi_H = \varphi_b = 1$ for ergonomic reasons

3. Overriding Production Requirements

The development of a size range is aimed at high cost-effectiveness. Within the range, especially if it is finely stepped, individual components and assemblies may be more coarsely stepped to provide larger batch sizes for even greater cost effectiveness.

Figure 9.12 is the data sheet of a geometrically similar turbine range consisting of seven sizes. Stuffing boxes and locating bolts are stepped more coarsely than the rest, ensuring greater batch sizes and greater economy. Figure 9.13 shows the increase in batch sizes for an assumed sales projection.

All these examples make it clear that it is not always possible to adhere to geometrically similar size ranges; instead, designers must strive, with the help of similarity laws, to arrive at that size range which provides the highest overall utilisation of the strength of every component. Depending on the physical constraints, each size will have to be individually selected. This is best done with the help of exponential equations, as we shall now go on to show.

4. Adaptation with the Help of Exponential Equations

Exponential equations are a simple means of dealing with the requirements mentioned under the previous three sections and of developing semi-similar size ranges.

As we have pointed out, nearly all technical relationships can be expressed by power functions. When using preferred number diagrams only the exponent is important if one starts from a basic design.

A physical quantity of the k-th member of a size range can often be represented by:

$$y_k = c_k x_k^{p_x} z_k^{p_z}$$

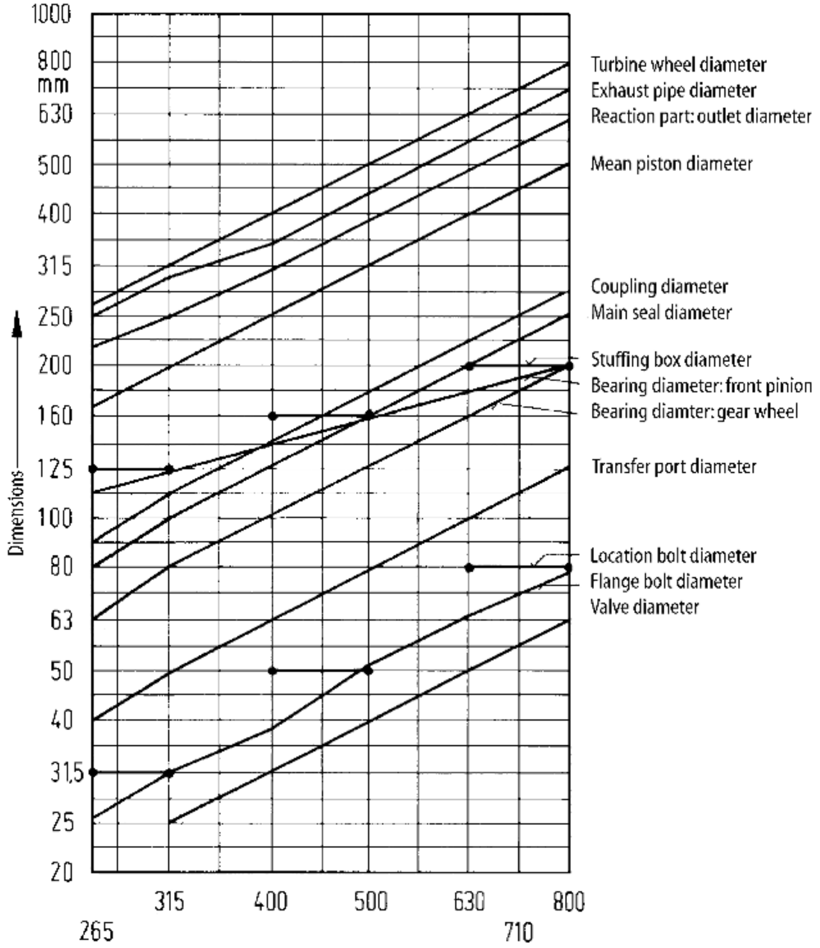


Figure 9.12. Data sheet for turbine size range: main dimensions are geometrically similar, deviations are determined by standards; stuffing boxes and locating bolts are in larger steps than the other components

The dependent variable y and the independent variables x and z can always be expressed by preferred numbers starting from the basic design (Index 0):

$$y_k = y_0 \varphi_L^{y_e k} \quad ; \quad x_k = x_0 \varphi_L^{x_e k} \quad ; \quad z_k = z_0 \varphi_L^{z_e k}$$

where φ_L is the chosen step factor of the dimension chosen as nominal in the size range, y_0, x_0, z_0 are the appropriate values of the basic design, k is the k-th step, and y_e, x_e and z_e are the associated step exponents. Since c_k is a constant, we have for all elements $c_k = c$:

$$y_k = y_0 \varphi_L^{y_e k} = c \left(x_0 \varphi_L^{x_e k} \right)^{p_x} \left(z_0 \varphi_L^{z_e k} \right)^{p_z}$$

$$y_k = c x_0^{P_x} z_0^{P_z} \cdot \varphi_L^{(x_e k p_x + z_e k p_z)}$$

Sales forecast

Type	255	315	400	500	630	710	800
Number	6	9	9	6	3	2	1

3 locating bolts per turbine

Size	Φ25	Φ31.5	Φ40	Φ50	Φ63	Φ71	Φ80
Number	18	27	27	18	9	6	3

Combined to:

Size	Φ31.5	Φ50	Φ80
Number	45	45	18

Figure 9.13. Sales forecast in respect of turbine size range (Figure 9.12) and the associated bolts. Because of the large step sizes, larger batch sizes are possible

With $y_0 = cx_0^{p_x} z_0^{p_z}$ we have:

$$y_0 \varphi_L^{y_e k} = y_0 \varphi_L^{(x_e k p_x + z_e k p_z)}$$

By equating the exponents, we obtain:

$$y_e = x_e p_x + z_e p_z$$

which is independent of k.

Here y_e, x_e and z_e are the exponents to be determined, and p_x and p_z the physical exponents of x and z. The exponent y_e depends on x_e and z_e.

Let us now consider a practical example: the provision of sprung elastic pipeline supports for a range of geometrically similar valves (see Figure 9.14). The following requirements must be met:

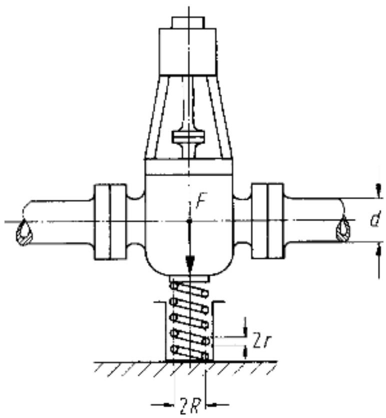


Figure 9.14. Valve supported in pipeline by means of coil springs

- The stress in the spring due to the weight of the valve must be constant throughout the range.
- The stiffness of the spring must increase as the bending stiffness of the pipe.
- The mean spring diameter $2R$ must preserve geometrical similarity with the increasing valve size (nominal dimension d).

What law must the spring wire diameter $2r$ and the number of active coils n obey? First of all the appropriate relationships must be set down, so that the exponential equation can be determined (the subscript e shows that only the exponent of the corresponding quantity is involved):

$$F = Cd^3 \quad (1) \qquad F_e = 3d^3 \quad (1')$$

$$\tau = \frac{F \cdot R}{r^3\pi/2} \quad (2) \qquad \tau_e = F_e + R_e - 3r_e = 0 \quad (2')$$

$$s = \frac{Gr^4}{4nR^3} \quad (3) \qquad s_e = 4r_e - n_e - 3R_e \quad (3')$$

Let d be the independent variable. Since the spring stress must remain constant, the step factor $\varphi_\tau = 1$, and the step exponent $\tau_e = 0$. The stiffness s of the spring must correspond to the bending stiffness of the pipes. According to Table 9.3, this is ensured by $\varphi_s = \varphi_L$. Since the basic dimension d of the valves increases geometrically, $\varphi_s = \varphi_d$, so that the step exponent of s becomes:

$$s_e = d_e \quad (4')$$

The loading is equal to the weight of the valve F; the weight dimension is related to the basic size d by $\varphi_F = \varphi_d^3$. The exponent of F referred to d is therefore:

$$F_e = 3d_e \quad (5')$$

If the mean spring diameter is to increase in geometrical similarity, we must have $\varphi_R = \varphi_d$ or:

$$R_e = d_e \quad (6')$$

Substituting equations (5′) and (6′) into equation (2′) we obtain:

$$3d_e + d_e - 3r_e = 0$$

or

$$r_e = (4/3)d_e \quad (7')$$

Substituting equations (4′), (6′) and (7′) into equation (3′), we obtain:

$$4r_e - n_e - 3d_e = d_e$$

$$n_e = 4r_e - 4d_e = 4(4/3)d_e - 4d_e = (4/3)d_e$$

Result: Spring wire diameter $2r$ and the number of active coils n must increase as $d^{4/3}$. In that case, the step factor is:

$$\varphi_r = \varphi_n = \varphi_d^{4/3}$$

The spread of the individual sizes is shown qualitatively in the data sheet reproduced in Figure 9.15.

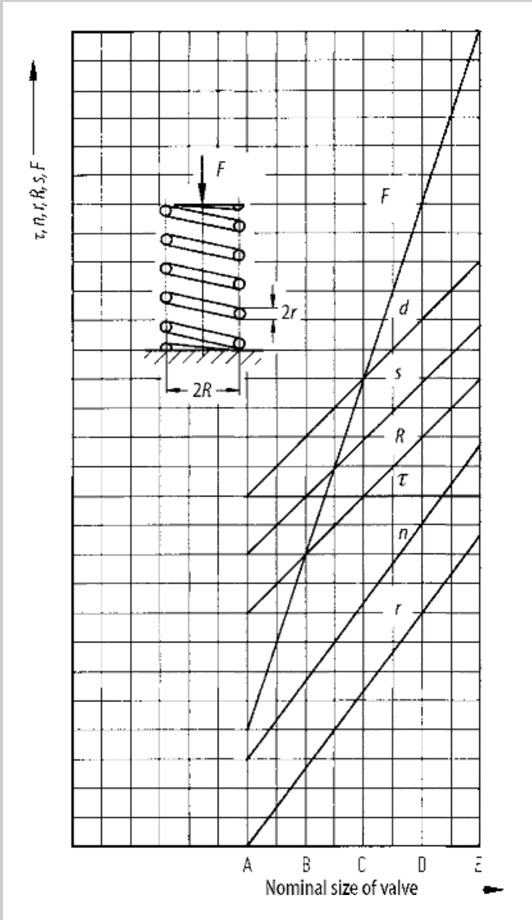


Figure 9.15. Data sheet for semi-similar coil springs

5. Examples

Example 1

A range of high-pressure gear pumps is to consist of six sizes giving delivery volumes ranging from 1.6 to 250 cm^3 per revolution at a maximum operating pressure of 200 bar and a constant input speed of 1500 rev/min. In the preferred number diagram shown in Figure 9.16, the steps laid down for the six sizes are plotted against the delivery volume, gear tooth width and pitch circle diameter. The following relationships are involved:

- The pitch circle diameters d_0 (each pump size has only one) are graded in accordance with R 10 with a step factor of $\varphi_{d_0} = 1.25$, the sizes deviating very slightly from the preferred numbers by virtue of the constant, integral number of teeth and also because the standard values of the modules m differ very slightly from the R 10 series.

- The volume delivered per revolution resulting from the tooth geometry is

$$V = 2\pi\, d_0 m b\,, \quad \text{where } b = \text{gear tooth width}\,.$$

From one size to the next, and at geometrical similarity, the volume delivered therefore increases as:

$$\varphi_V = \varphi_{d_0}\varphi_m\varphi_b = \varphi_L^3 = 1.25^3 = 2$$

that is, the volume delivered doubles from step to step (see Figure 9.16). The pump power $P = \Delta p \cdot \dot{V}$ increases as:

$$\varphi_P = \varphi_{\Delta p}(\varphi_V/\varphi_t)$$

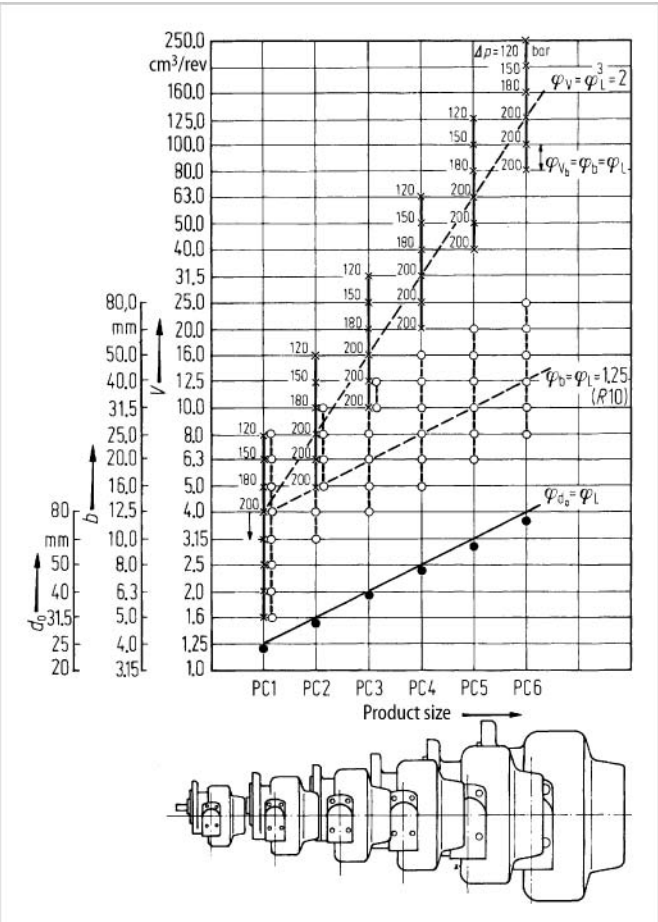


Figure 9.16. Data sheet for a size range of high-pressure gear pumps: V volume delivered per revolution; b gear-tooth width; d_0 pitch circle diameter of gears (Reichert, Hof)

which, with $\varphi_{\Delta p} = 1$ and $\varphi_t = 1$ becomes:

$$\varphi_P = \varphi_V = 2$$

Because of the constant rotational speed, the torque is stepped up accordingly.

- Every pump size, i.e. every pitch circle diameter, has been provided with six tooth widths b, except the smallest size which has eight, so that smaller steps in the volume delivered can be obtained. This means that for each pump size the geometrical volume delivered, $V = 2\pi d_0 mb$, will have a step factor of $\varphi_{V_b} = \varphi_b = 1.25$, d_0 and m being constant and the chosen tooth width step factor being $\varphi_b = 1.25$ (R 10). The power curve for any one pump size then becomes:

$$\varphi_{P_b} = \varphi_{V_b} = \varphi_b = 1.25$$

- To cope with the mechanical stresses (resulting from the increasing torques and the increasing bending moments due to increases in tooth width) with a shaft of constant diameter, the three pumps with the greatest tooth width in each size group must have their output pressure reduced. For overriding economic reasons (identical shaft diameter, identical bearings), the first two pumps of each size group do not have their strengths fully exploited.
- The delivery volumes of the top three pumps in any size group correspond to the bottom three of the next group up. A delivery pressure of 200 bar can therefore be obtained over the entire delivery-volume range.

This particular size range was conceived as a semi-similar series with a small number of housing sizes and several tooth width sets, so that, at the same drive speed and pressure over the entire range (overriding task requirements) and also at constant gear tooth size, constant gearwheel and shaft diameters per housing size (overriding production requirements), the maximum possible range of delivery volumes could be provided.

Example 2

In Figure 9.17 the output P of a size range of electric motors with varying pole numbers (speeds) has been plotted against the various product sizes (shaft heights H). The shaft heights are in accordance with R 20 and have a step factor of $\varphi = 1.12$. The output of the electric motor is governed by $P \sim \omega JBbhtD$, that is, at constant angular velocity ω or speed n, current density J and magnetic flux density B, the output is proportional to the conductor dimensions b, h, t and also to the distance $D/2$ of the conductor from the shaft axis.

The output step factor is therefore given by:

$$\varphi_P = \varphi_L^4 = 1.12^4 = 1.6 \quad \text{(R 5)}$$

In the 4-pole motor (1500 rev/min) the output range is therefore 500–3150 kW. Because power output varies with speed, and also because the dimensions of the conductor, the diameter of the rotors, and the heat removed by ventilation have to be varied, the slower 6-pole version must be reduced by three steps (355 to

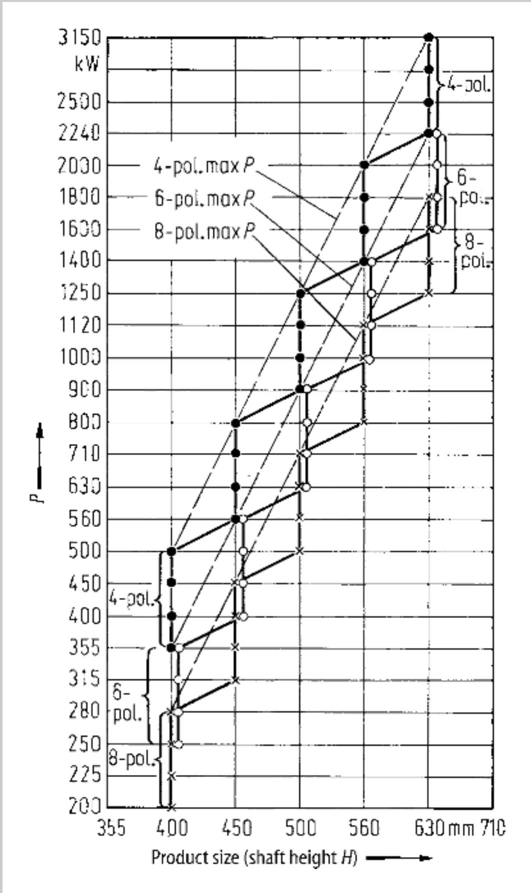


Figure 9.17. Output data sheet for a electric motor size range (AEG Telefunken) [9.1]

2240 kW), and the even slower 8-pole version by a further two steps (280 to 1800 kW).

To provide marketable and finer output steps and also to satisfy the overriding production requirements, four outputs are provided per shaft height or motor size, so that the output curve assumes the form of a stepped line. Smaller outputs are obtained by varying the size of the electrically active parts and fitting them into the same size of housing. In contrast to what happened in Example 1, the outputs for the different size groups (fixed pole number) do not overlap, although this has been done with other motor designs so as to maintain certain performance properties, e.g. efficiency.

Figure 9.18 shows the welded housings of this motor range in greatly simplified form. The stepped sizes of several important dimensions are entered in a data sheet (see Figure 9.19). It can be seen that the shaft height *H*, the housing height *HC* and the distance between the foundation bolts *B* and *A* are all stepped up by the factor $\varphi_L = \varphi_H = 1.12$. The values of *H*, *HC* and *B* follow the R 20 series, whereas *A* and *DB*

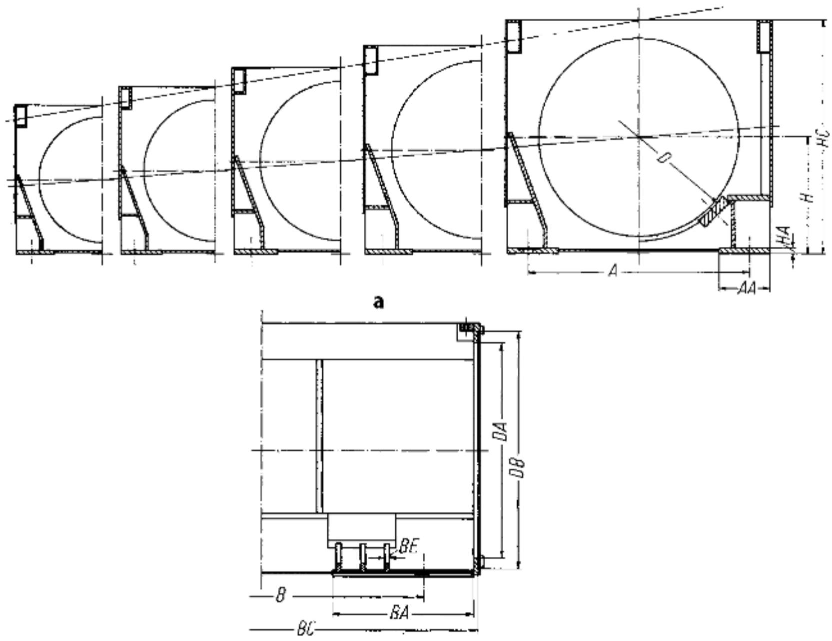


Figure 9.18. Housing for the electric motor size range (simplified) shown in Figure 9.17 (AEG Telefunken): **a** cross sections; **b** elevation

follow the same series, but with their positions slightly shifted. Just one housing length *BC* is provided for the four outputs per shaft size (see Figure 9.18). This is possible because different sizes of the electrically active parts can be fitted easily into one housing size. Without this separation of the housings from the electrical components, the layout would not be economic and several housing lengths would have to be provided for each shaft height [9.30].

Because of overriding similarity laws on the electrical side (for instance in respect of the windings) the housing length step factor φ_{BC} cannot be kept constant over the entire range of shaft heights. Figure 9.19 shows the increase in step factor for *BC* with increasing shaft height, the step size only approaching R 20 for the last two housings of the range.

Let us now look at a few detailed measurements of this housing design. The baseplate dimensions *AA* and *BA* have been graded by a single step factor which lies between R 20 and R 40. This was done to save material while maintaining the minimum dimensions needed to assemble the fixing bolts. The baseplate thickness *HA* has been stepped in accordance with the usual semi-finished material dimensions, but by and large follows R 20. For the strengthening ribs an equal thickness *BE* is provided for four housing sizes. Only for the largest housing are thicker ribs required.

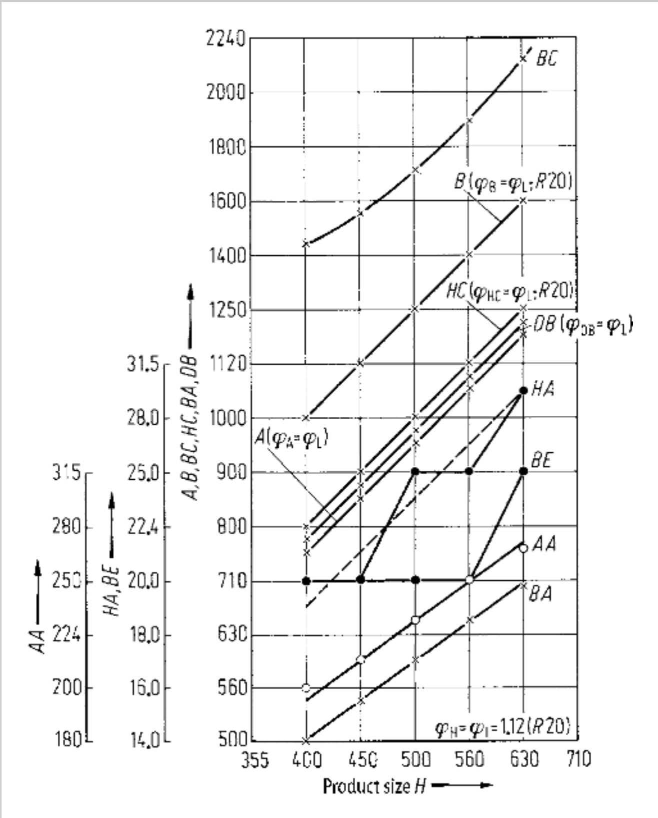


Figure 9.19. Data sheet for housing dimensions of the electric motor size range in Figure 9.17. (symbols as in Figure 9.18)

Because of overriding similarity laws, overriding task requirements and overriding production requirements, individual dimensions and nominal sizes may have to be stepped in accordance with laws that differ from those leading to geometric similarity. In every case, however, designers must, in the first instance, aim at size ranges based on the appropriate similarity laws and the preferred number series and only deviate from them after careful consideration of the particular task and the costs involved.

9.1.6 Development of Size Ranges

Size-range development can be summed up as follows:

1. Prepare the basic design for the range. This can be completely new or derived from an existing product.
2. Determine the physical relationships (exponents) in accordance with similarity laws, using Table 9.3 for geometrically similar product ranges, or using exponential equations for semi-similar product ranges. Put down the results as preferred number diagrams in the form of data sheets.

3. Determine the step sizes and the scope of application, and add them to the data sheets.
4. Adapt the theoretically obtained ranges to satisfy overriding standards or technological requirements and record the deviations on the data sheets.
5. Check the product range against scale layouts of assemblies paying particular attention to critical areas for extreme dimensions.
6. Improve and complete what documentation may be needed to determine the range and prepare production documents (at the time they are needed).

The need for developing a semi-similar size range may not always appear from the requirements list or from a first survey of the physical relationships, but may only become clear during an actual development. Section 9.1.5 describes how the individual components and dimensions can be determined during the development of semi-similar size ranges using exponential equations. The number of parameters and the number of equations to be solved may be quite large in complex applications. For that reason Kloberdanz [9.26] has developed a computer-aided size range program. After formulating the physical relationships involved and adding the constraints, the program automatically determines the scaling rules and represents the results in the form of preferred number diagrams and data sheets. These can then be adapted interactively to other constraints such as company standards and stock lists.

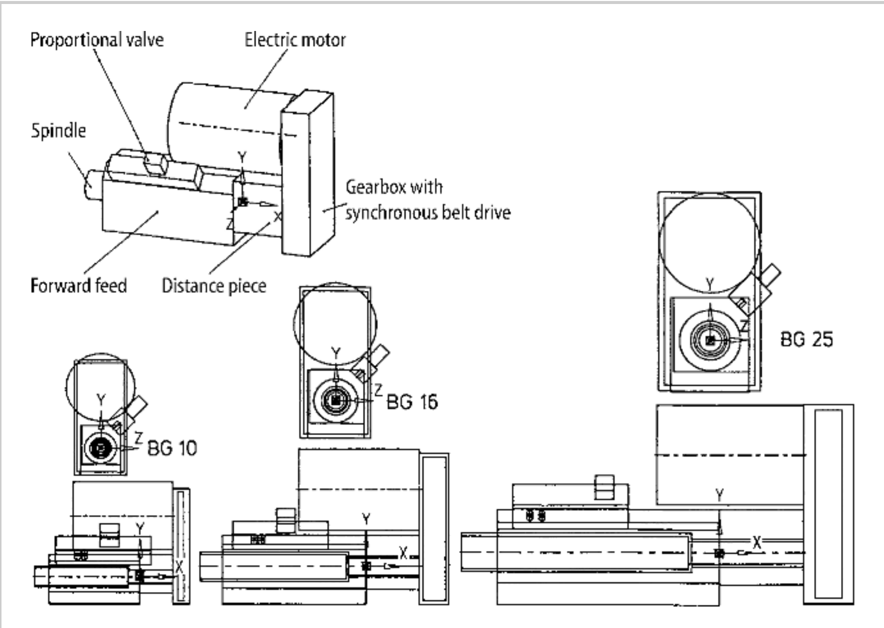


Figure 9.20. Example of computed-aided development of a semi-similar size range of hydropneumatic forward feed units, after [9.26, 9.38]

Using parametric macros, the scaling rules are used to generate automatically preliminary geometrical layouts of sequential designs for a semi-similar size range (see Figure 9.20). After the final size range has been determined, the details can then be defined using single part macros [9.8, 9.26].

9.2 Modular Products

In Section 9.1 we discussed the features and design potential of size ranges. Their aim is the rationalisation of product development by the implementation of the *same* function with the same principle solution and, if possible, with the same properties over a wide range of sizes.

Modular systems provide rationalisation in a different situation. If a product is to fulfil *different* functions, then many variants will have to be provided, at great cost in design and production. Rationalisation is, however, possible if the particular *function variant* at any one time is based on a combination of fixed individual parts and assemblies (function units), and this is precisely what a modular system sets out to achieve.

By *modular products* we refer to machines, assemblies and components that fulfil various overall functions through the combination of distinct function units (building blocks) or modules.

Because such modules may come in various sizes, modular products often involve size ranges. The modules should be produced by similar methods whenever possible. Since in a modular system the overall function results from a combination of building blocks, the development of modular products demands the elaboration of a corresponding function structure and this calls for greater design effort during the conceptual and embodiment phases than does the development of a pure size range.

A modular system can provide a favourable technical and economic solution whenever all or some function variants of a product series are required in small batch sizes only, and whenever they can be based on a single or only a few basic modules, along with additional modules.

Besides fulfilling a variety of functions, modular systems can also serve to increase the production batch size of identical parts for use as building blocks in a variety of products. This additional objective, which greatly helps to rationalise the production procedure, is attained by the breakdown of the product into module-like units, as was the done for differential construction described in Section 7.5.8. Which of the two objectives is paramount depends largely on the product and on the task it has to perform. With a wide-ranging overall function, what matters most is the resolution (divisibility) of the product into function-oriented modules. On the other hand with a small number of overall function variants, a production-oriented resolution is the paramount consideration.

Often, modular development is only initiated when what was originally conceived as an individual or size-range development is expected to yield a large number of variants. To that end, product series that have already been marketed are often redesigned as a modular system. The disadvantage here is that the products are more or less predetermined. Whereas the advantage is that their essential properties have already been tested so that an expensive new development can be dispensed with.

9.2.1 Modular Product Systematics

Modular product systematics are discussed in [9.10,9.11,9.29]. Basing ourselves on these findings, we shall first of all examine the principles and the most important concepts, and merely add a few amplifications [9.4].

Modular product systems are built up of separable or inseparable units, i.e. *modules*. We must distinguish between *function modules* and *production modules*. Function modules help to implement technical functions independently or in combination with others. Production modules are designed independently of their function and are based on production considerations alone. Function modules in the narrower sense have been divided into equipment, accessory, connecting and other modules [9.10, 9.11]. This division is neither clear-cut nor adequate for the development of modular systems.

1. Classification of Modules

For the classification of function modules it seems advantageous to define the various types of function that recur in modular systems and can be combined as subfunctions to fulfil different overall functions (overall function variants), see Figure 9.21.

Basic functions are fundamental to a system. They are not variable in principle. A basic function can fulfil an overall function simply or in combination with other functions. It is implemented as a basic module which may come in one or several sizes, stages and finishes. Basic modules are “essential modules”.

Auxiliary functions are implemented by locating or joining *auxiliary modules* that are kept in step with the basic modules and are usually “essential modules”.

Special functions are complementary and task-specific subfunctions that need not appear in all overall function variants. They are implemented by *special modules* that are additions to or accessories for the basic modules. They are “possible modules”.

Adaptive functions are necessary for adaptation to other systems and to boundary conditions. They are implemented by *adaptive modules* whose dimensions are not fully fixed in advance and hence allow for unpredictable circumstances. Adaptive modules may be “essential modules” or “possible modules”.

Customer-specific functions not provided for in the modular system will recur time and again even in the most careful development. Such systems are implemented by *non-modules* which have to be designed individually for specific tasks. If they are used, the result is a *mixed system*, that is, a combination of modules and non-modules.

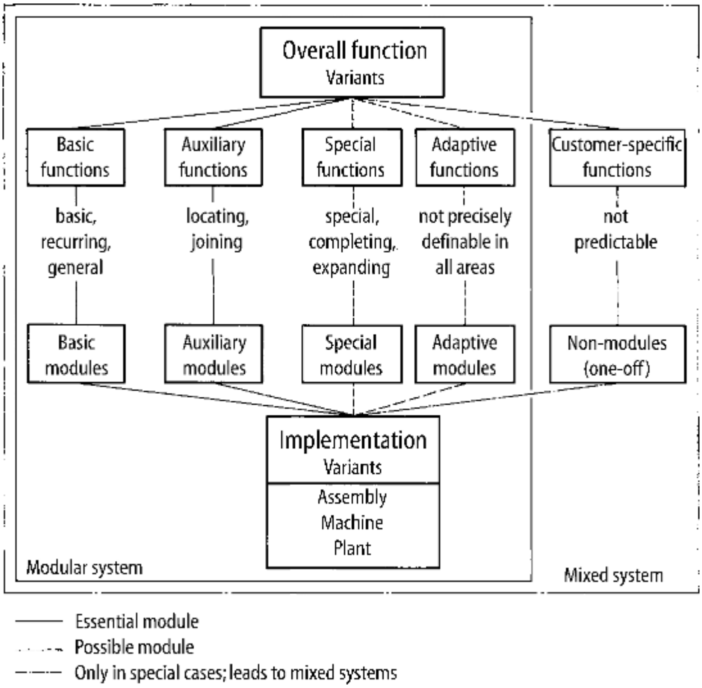


Figure 9.21. Function and module types in modular and mixed product systems

By the *importance of a module* we refer to its ranking within a modular system. Thus, function modules can be ranked as essential modules or as possible modules [9.14].

A production-oriented characteristic is the *complexity of a module*. Here we distinguish between *macro modules* which, as assemblies, can be subdivided into components, and *micro modules* that are components themselves.

A further aspect of module characterisation is their *type of combination*. Designers should always aim for technically advantageous combinations of similar modules. In practice, however, the combination of similar with different modules, and also with customer-specific non-modules, is often unavoidable. The latter, as mixed systems, can meet market requirements very economically.

For the characterisation of modular systems we can also consider their *resolution*—in other words, the extent to which a particular module can be broken down into individual parts for functional or production reasons. For the modular system as a whole, the resolution defines the number of individual units and their possible combinations.

2. Concretisation of Modules

One-off products, such as turbines, pumps and compressors, often demand significant variations in performance and efficiency. They require their working zones, for example blade passages and cylinder dimensions, to be adapted. However, many parts remain identical, for example the bearings, seals, and input and output sections. In such cases a division into modules is advantageous (see Figure 1.9, working step 4 and Figure 7.1, working step 3). The overall product is thus developed as a combined approach, that is, as a size range partially made up from modules (see Figure 9.22). The modules are generated in suitable step sizes. For the manufacturer, these modular systems do not really exist until, based on specific requirements, the appropriate sets of drawings are combined as modules into an overall machine (see Figure 9.23). Such a "fictitious" modular product is not only useful for the product development department; it can also provide the basis for fixed production modules that can be used to prepare production plans and software for CNC machines. Another use of the modules is to plan the optimum stock of casting patterns. These patterns can be divided into modules that are combined, where necessary, into more complex castings, such as housings. Depending on the need, the level of concretisation can be selected between having product modules available either in software (and paper) or in hardware.

For the application of closed modular systems, their *range* and *potential* can be expressed by *combinatorial plans* with a finite and predictable number of variants. Such plans make it possible to choose desired combinations directly. By contrast, open modular systems contain a great multiplicity of combinatorial possibilities, which cannot be fully planned or represented (see Figure 9.32). A *specimen plan* provides examples of typical applications of the modular system.

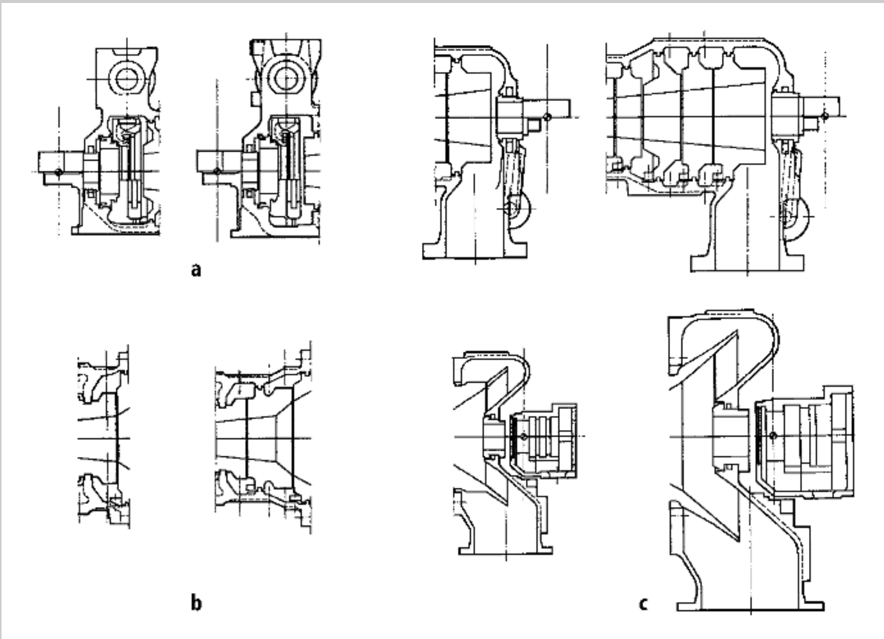


Figure 9.22. Modules for an industrial turbine size range generated using geometric sections (Siemens): **a** Entry section; **b** Middle section; **c** Exit section

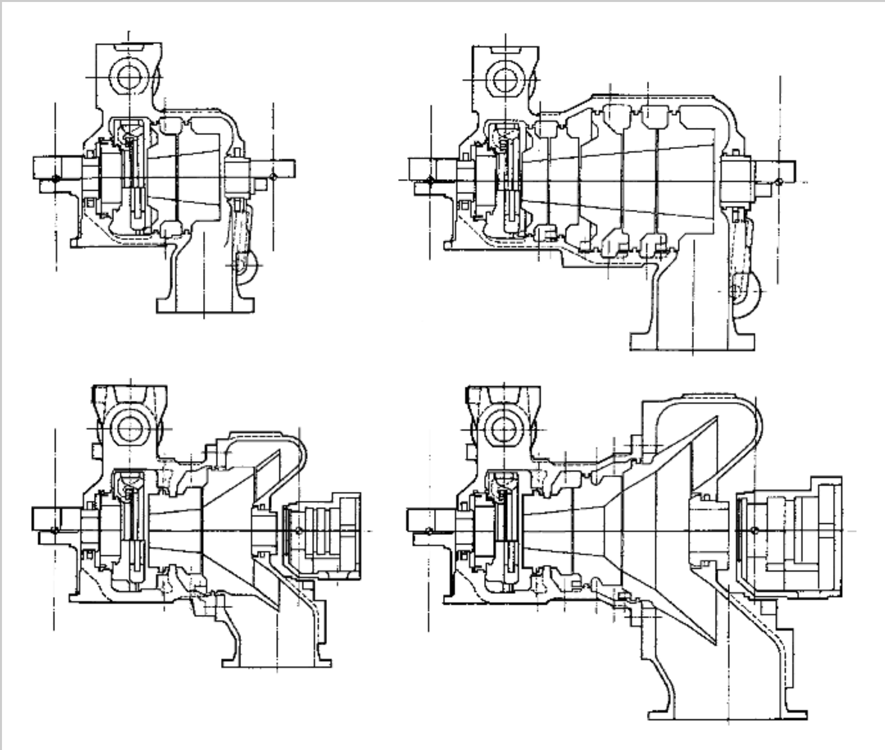


Figure 9.23. Complete turbine design for different pressure and flow requirements produced by combining the modules shown in Figure 9.22 (Siemens)

The above-mentioned concepts of module development are summarised in Table 9.5.

9.2.2 Modular Product Development

In what follows the development of modular products will be presented in accordance with the steps listed in Figure 4.3.

1. Clarifying the Task

In their formulation of demands and wishes, for instance with the help of the checklist (see Figure 5.3), designers must pay careful attention to the clarification of the various tasks to be performed by the product series. A characteristic demand of the specification of a modular product is that it must fulfil several overall functions. This results in the *variants of the overall function* that a specific modular product has to fulfil.

Of particular importance for the economic analysis and application of modules is data about the market expectations of particular variants. Friedewald [9.17]

Table 9.5. Concepts of modular systematics

Classifying criteria	Distinguishing features
Types of module	– Function modules • Basic modules • Auxiliary modules • Special modules • Adaptive modules • Non-modules – Production modules
Importance of modules	– Essential modules – Possible modules
Complexity of modules	– Large modules – Small modules
Combination of modules	– Similar modules only – Different modules only – Similar and different modules – Modules and non-modules
Resolution of modules	– Number of parts per module – Number of units and their possible combinations
Concretisation of modules	– Software/paper modules only – Mix of hardware and software modules – Hardware modules only
Application of modules	– Closed system with combinatorial plan – Open system with specimen plan

speaks of the quantification of function variants for the technical and economic optimisation of modules. Whenever the implementation of rarely demanded variants increases the overall cost of the modular system, an attempt must be made to remove such variants. The more searching these analyses are before the actual development is begun, the greater are the chances of arriving at a cost-effective solution. However, the reduction of types by the removal of infrequently demanded and costly function variants cannot be finalised until the elaborated solution concept or even the embodiment design provides reliable information about the cost of the different variants and also about the influence of every individual variant on the cost of the modular system as a whole.

2. Establishing Function Structures

The establishment of function structures is of particular importance in the development of modular systems. With the function structure—that is, the splitting up of the required overall function into subfunctions—the structure of the system is already laid down, at least in principle. From the outset, designers must try to subdivide the overall function variants into a minimum number of similar and recurring subfunctions (basic, auxiliary, special and adaptive functions, see Figure 9.21). The function structures of the overall function variants must

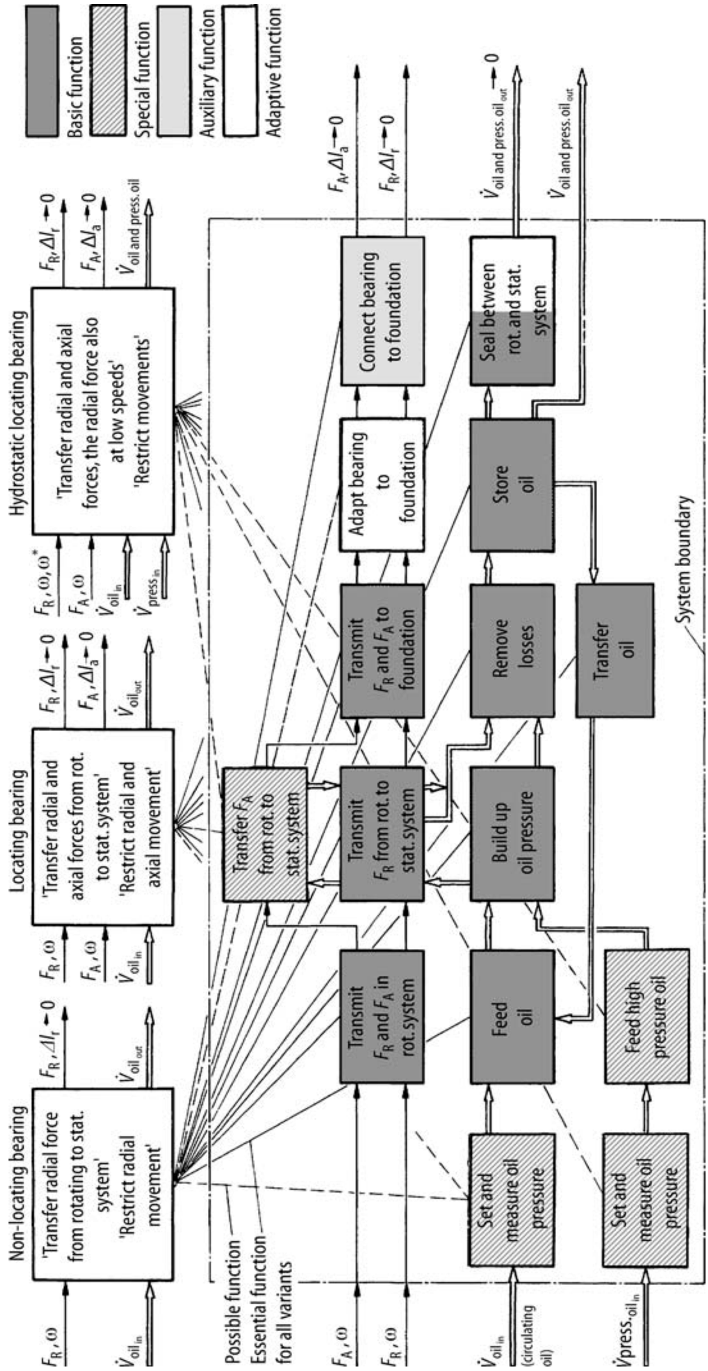


Figure 9.24. Function structure for a modular bearing system, after [9.23]

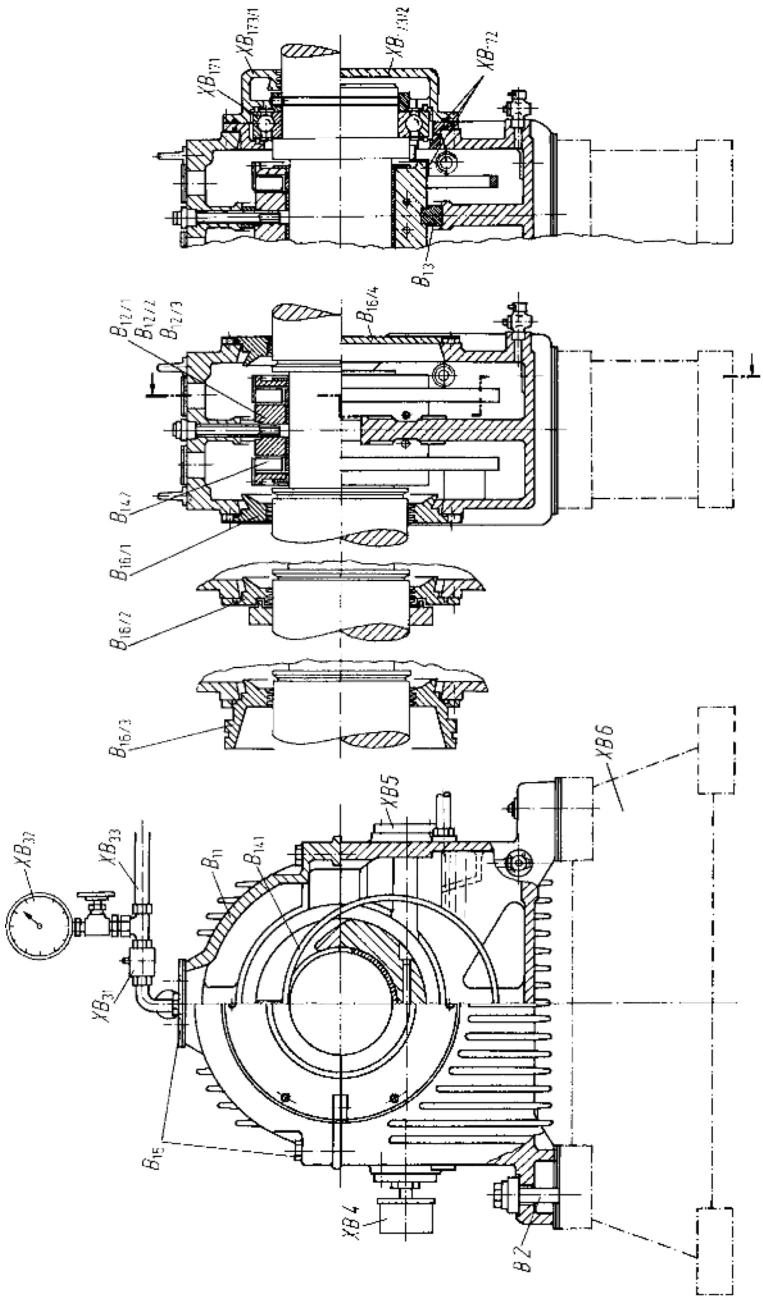


Figure 9.25. Layout of the modular bearing system shown in Figure 9.24 (AEG Telefunken)

be logically and physically compatible, and the subfunctions determined by them must be interchangeable. To that end, it is useful if, depending on the particular task, the overall function can be achieved by essential modules and by additional task-specific possible modules.

Figure 9.24 shows the function structure for the modular bearing system discussed in [9.3, 9.23]. The most frequently demanded overall functions, namely "non-locating bearing", "locating bearing" and "hydrostatic locating bearing", together with the appropriate basic, special, auxiliary and adaptive functions, are represented. By means of the subfunction "seal between rotating and stationary systems", we can show that it is often more cost-effective to combine several functions into one complex function; thus in the present case, the sealing function was combined with an adaptive function to satisfy various interface conditions. The production module "shaft seal", which performs this complex function, was accordingly specified as an unfinished one that could be completed during production as: (1) a simple line seal, (2) as a line seal with an additional labyrinth, or (3) as a seal with an additional coupling adapter (see Figure 9.25). It should also be stressed that there are special functions (special modules) that occur in at least one overall function variant (here: "transfer axial force F_A from rotating to stationary system"), others that represent possible modules for all overall function variants (here: "set and measure oil pressure"), and yet others that only become necessary at a certain size (here: "feed high pressure oil").

In the setting up of function structures the following objectives should be borne in mind:

- Aim for the implementation of the required overall functions by the combination of the minimum number of easily implementable basic functions.
- Try to divide the overall functions into basic functions and if necessary into auxiliary, special and adaptive functions in accordance with Figure 9.21, in such a way that variants in high demand are predominantly built up with basic functions; and more rarely demanded variants with additional special and adaptive functions. For very rarely demanded function variants, mixed systems with additional functions (non-modules) are often more cost-effective.
- Try to combine several subfunctions into a single module if this increases cost-effectiveness. Such combinations are particularly recommended for the implementation of adaptive functions.

3. Searching for Working Principles and Concept Variants

The next step is to find working principles for the implementation of the various subfunctions. To that end, designers should, above all, look for such principles as provide variants without changes in working principle and basic design. As a rule, it is advantageous to stipulate similar types of energy and similar physical working principles for the individual function modules. Thus it is more cost effective and technically advantageous, in the combination of subsolutions into overall solutions (solution variants), to implement various drive functions with a single type of energy rather than provide a single modular system with separate electrical, hydraulic and mechanical drives.

A satisfactory production solution is also ensured by the implementation of several functions by a single unfinished module that can be completed in various ways depending on the requirements.

However, so complex are the technical and economic factors involved that it is impossible to lay down hard and fast rules. Thus, in the case of the bearing system (see Figure 9.25) it seems technically and economically advantageous to provide the bearing shell with lateral locating surfaces for taking up small axial forces. With larger axial forces, however, rolling bearings must be provided instead; it would be a mistake to try, for purely theoretical reasons, to transfer the radial and axial forces over the entire size range by means of plain bearings. The plain bearing system must be designed during the conceptual phase with two alternative lubrication systems (free ring or fixed ring) because their respective advantages and disadvantages can only be determined by later experiments [9.23]. The design of the ultimately chosen modular bearing system is shown in Figure 9.25.

4. Selecting and Evaluating

If several concept variants have been found during the previous steps, each must now be evaluated with the help of technical and economic criteria so that the most favourable solution concept can be selected. Experience has shown that, since the properties of any one variant are not yet sufficiently clear at this stage, such selections are very difficult to make.

Thus, in the case of the bearing system, preliminary evaluations have to be made even in the conceptual phase, for instance as to whether the axial forces should be taken up by plain or rolling bearings. However, the final choice of lubricating system can only be taken after the building of prototypes and experimentation with them.

Apart from the determination of the technical rating of individual concept variants, economic factors are of crucial importance in the design of modular systems. To come to grips with them, designers must estimate the production costs of the individual modules and their relative effect on the cost of the modular system as a whole. To that end, they will first of all determine the expected "function costs" of the subfunctions or of the modules fulfilling them. At a low level of concretisation, which is characteristic of the conceptual phase, they cannot usually hope to come up with more than very rough estimates. Since basic modules appear in all sorts of variants, they will select such solution principles as provide the most cost-effective basic modules. Special and adaptive modules take second place in the minimisation of costs.

For minimising the costs of a modular system, not only the modules themselves but also their interaction must be taken into account; in particular, the influence of special, auxiliary and adaptive modules on the *cost of the basic modules*. The influence of the cost of every overall function variant on the cost of the modular system as a whole must be fully determined. This may prove a complex task. Thus, in the bearing system we have been considering, the function variant "cool oil internally" would greatly influence the cost of the basic module "bearing housing", because the dimensions of the special module "water cooler" determine the dimensions of the housing and hence the overall cost. If there is only a small demand for this variant, then it is certainly more cost-effective to fit the oil cooler to the outside of the housing and to put up with the extra cost of an oil pump.

In short, the layout of the basic modules must be adapted to the function variants with the highest expected demand. To that end, the influence of the remaining modules is of great importance. In [9.27, 9.28] a method using Neural Nets is proposed to identify and assess such complex relationships.

If it is impossible to provide a marketable adaptation of the basic concept, the least cost-effective function variants should be eliminated from the modular system. It will often be more economical to replace unusual variants, which render the overall system more expensive, by making individual adaptions than to impose such adaptions on the whole modular system. An alternative is the use of mixed systems.

5. Preparing Dimensioned Layouts

Once a solution concept has been selected, the individual modules must be designed in accordance both with their functions and their production requirements. In the design of modular systems, production and assembly considerations are of paramount economic importance. By paying heed to the embodiment design guidelines laid down in Sections 7.5.8 and 7.5.9, designers must try to provide basic, auxiliary, special and adaptive modules with the maximum number of similar and recurring parts and the minimum number of unfinished parts and production processes.

When selecting step sizes, designers should aim at the optimum resolution of modules (modularity), and to that end they may well adopt the differential construction approach. The determination of the optimum number of modules is, however, a complex task, for it is influenced by the following factors:

- Requirements and quality must be maintained and the propagation of errors must be taken into account (see Section 7.4.5: the principle of fault free design). Thus the greater the number of individual components, the greater the number of fits, and this may have untoward repercussions on the function, for instance on the vibration of a machine.
- Overall function variants must be created by simple assembly of modules (individual parts and assemblies).
- Modules may only be broken down to the extent that functions and quality permit and costs allow.
- In modular products marketed as overall systems, variants of which clients can assemble themselves by combinations of the modules [9.33], the most common modules must be designed for equal wear and tear and for easy replacement.
- In determining the most efficient modularity with regard to costs and production times, designers must pay special heed to the costs, not only of the design itself,

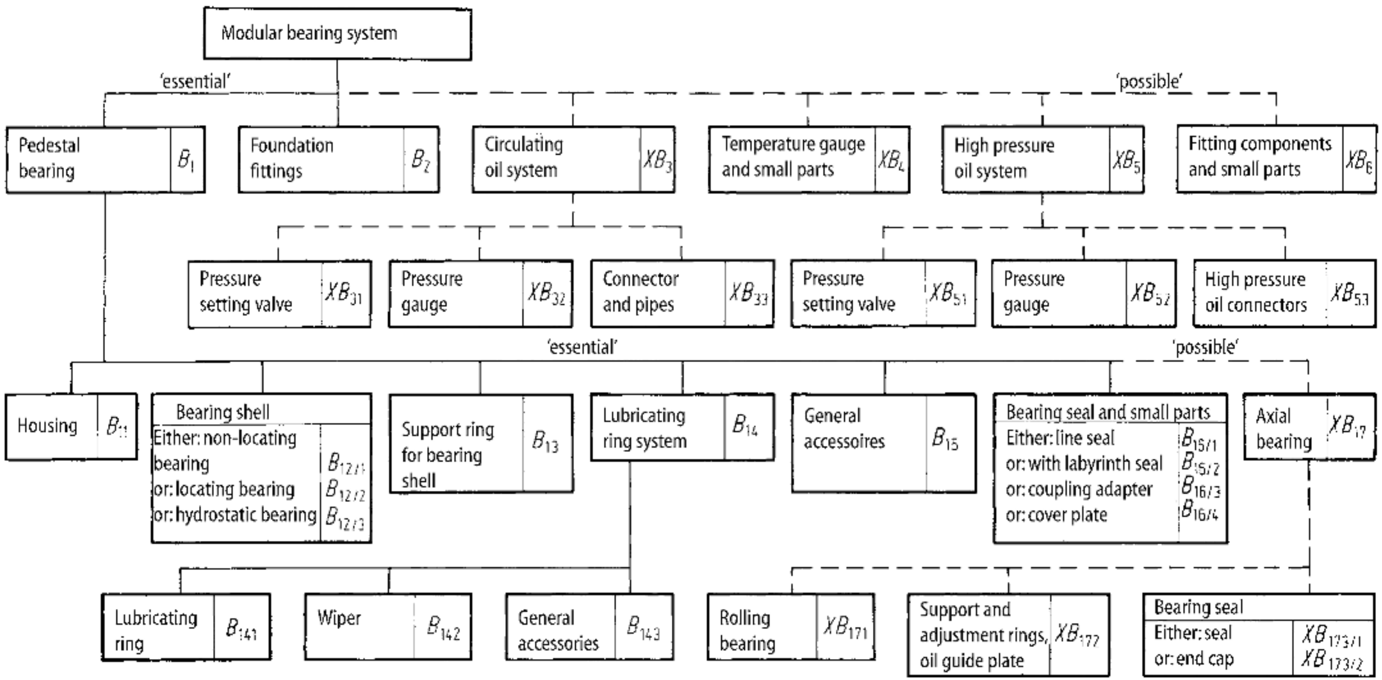


Figure 9.26. Family tree of the modular bearing system in accordance with Figures 9.24 and 9.25 (prefix X indicates possible modules)

but also of production, including production planning, production processes, assembly, handling and distribution.

Figure 9.25 shows the scale layout of the bearing system we have been discussing. In Figure 9.26 the structure of the overall function variants (see Figure 9.24) is shown in the form of a family tree. In both these figures, only the most important assemblies and individual parts of the bearing system have been entered; the actual modularity is greater. If the function structure, which only shows the main function variants, is compared with the final modular structure, it becomes clear

Table 9.6. Modules in bearing system shown in Figure 9.26

Modules	Nos.	Types	Functions
Housing	B_{11}	Basic module	'Transmit F_R and F_A to foundation', 'Remove losses', 'Store oil'
Bearing shell	$B_{12/1}$	Basic module	'Transmit F_R from the rotating to the stationary system', 'Build up oil pressure'
	$B_{12/2}$	Variant of $B_{12/1}$	additionally: 'Transfer F_A from the rotating to the stationary system'
	$B_{12/3}$	Variant of $B_{12/1}$	additionally: 'Transfer hydro-static oil pressure to shaft'
Support ring between housing and bearing shell	B_{13}	Auxiliary module	'Connect bearing shell with housing'
Lubricating ring	B_{141}	Basic module	'Transfer oil'
Wiper	B_{142}	Basic module	'Feed oil'
General accessories	B_{143}	Basic module	'Control oil level' and 'Remove oil'
General accessories	B_{15}	Basic module/ auxiliary module	'Accessory and connecting functions'
Bearing seal and small parts	$B_{16/1}$	Basic module	'Seal between rotating and stationary systems'
	$B_{16/2}$	Basic module/ adaptive module	additionally: 'adapt to labyrinth seal'
	$B_{16/3}$	Basic module/ adaptive module	additionally: 'Provide coupling adapter'
	$B_{16/4}$	Special module	'Seal housing in the absence of shaft'
Foundation fittings	B_2	Auxiliary module	'Connect bearing to foundations'
Pressure setting valve	XB_{31}	Special module	'Set pressure for circulating oil'
Pressure gauge	XB_{32}	Special module	'Measure oil pressure'
Connectors and pipes	XB_{33}	Auxiliary module	'Transfer circulating oil'
Temperature gauge and small parts	XB_4	Special module	'Measure temperature'
Pressure setting valve	XB_{51}	Special module	'Set pressure for high pressure oil'
Pressure gauge	XB_{52}	Special module	'Measure oil pressure'
High pressure oil connectors	XB_{53}	Auxiliary module	'Feed high pressure oil'
Fitting components and small parts	XB_6	Adaptive module	'Adapt bearing to foundation'
Rolling bearing	XB_{171}	Special module (for large axial forces)	'Transfer F_A from the rotating to the stationary system'
Support and adjustment rings, oil guide plate	XB_{172}	Auxiliary module	'Connect rolling bearing with housing', 'Supply oil to rolling bearing'
Bearing seal	$XB_{173/1}$	Special module	'Seal between rotating and stationary systems in case of rolling bearing variant'
	$XB_{173/2}$	Special module	'Seal housing in the absence of shaft'

that in the given modular system several functions are fulfilled by a single module or its variants. Table 9.6 shows the modules used and their assigned functions.

6. Preparing Production Documents

Production documents must be prepared in such a way that the execution of orders can be based on the simple, and if possible computer-aided, combination and further elaboration of modules for the required overall function variants.

Drawings require an appropriate part-numbering system and classification, two prerequisites of the optimum combination of modules (individual parts and assemblies).

The combination of individual modules into product variants must be recorded in the parts list. To build up a parts list, designers can refer to the so-called variant parts list [9.14] which is based on the structure of the product and in which a distinction is made between essential modules and possible modules.

Particularly suited to the numeration of drawings and parts lists is the method of parallel encoding, which assigns identification numbers for the unequivocal and unmistakable description of components and assemblies, and classification numbers for the function-oriented recording and retrieval of these components and assemblies. The classification number is of particular importance in a modular system, because it helps to identify functional and other similarities between components.

9.2.3 Advantages and Limitations of Modular Systems

For the *manufacturer*, modular systems provide *advantages* in nearly all areas of the company:

- Ready documentation is available for tenders, project planning and design. Design is done once and for all, though it may be more costly for that very reason.
- Additional design effort is needed for unforeseeable orders only.
- Combinations with non-modules are possible.
- Overall scheduling is simplified and delivery dates can be improved.
- The execution of orders by the design and production departments can be cut short through the production of modules in parallel; in addition parts can be supplied quickly.
- Computer-aided execution of orders is greatly facilitated.
- Calculations are simplified.
- Modules can be manufactured for stock with consequent savings.
- More appropriate subdivision of assemblies ensures favourable assembly conditions.

- Modular product technology can be applied at successive stages of product development, for example, in product planning, in the preparation of drawings and parts lists, in the purchase of raw materials and semi-finished materials, in the production of parts, in assembly work, and also in marketing.

For the *user* there are the following *advantages*:

- short delivery times
- better exchange possibilities and easier maintenance
- better spare parts service
- possible changes of functions and extensions of the range
- almost total elimination of failures thanks to well-developed products.

For the *manufacturer* the *limit* of a modular system is reached whenever the subdivision into modules leads to technical shortcomings and economic losses:

- Adaptations to special customer wishes are not as easily made as they are with individual designs (loss of flexibility and market orientation).
- Once the system has been adopted, working drawings are made on receipt of orders only, with the result that the stock of drawings may be inadequate.
- Product changes can only be considered at long intervals because once-and-for-all development costs are high.
- The technical features and overall shape are more strongly influenced by the design of modules and the modularity than they would be by individual designs.
- Production costs are increased, for example because of the need for accurate locating surfaces and production quality must be higher because re-machining is impossible.
- Increased assembly effort and care are required.
- Since the interests of both the users and the producers have to be taken into consideration, the determination of an optimal modular system may prove very difficult.
- Rare combinations needed to implement unusual requirements may prove much costlier than tailor-made designs.

For the *user* there are such *disadvantages* as:

- Special wishes cannot be met easily.
- Certain quality characteristics may be less satisfactory than they would be with special-purpose designs.
- Weights and structural volumes of modular products are usually greater than those of specially designed products, and so space requirements and foundation costs may increase.

Experience has shown that, while modular production helps to make significant reductions in general overheads (administrative staff costs in particular), the effect on production and material costs can be less significant, because, as mentioned earlier, greater weights and volumes tend to be involved. Only if a modular system is developed with the express intention of rendering every function variant more cost-effective than a specially designed product can there be a significant reduction in overall costs.

9.2.4 Examples

Gearboxes

Gearboxes are another familiar example of modular systems. They involve a multiplicity of market-determined function variants, for instance, the attachment of different input and output devices, various shaft positions and different gear ratios. However, the basic overall construction structure is known and fixed. Several examples can be found in [9.21, 9.22, 9.43].

Modular Tram System

We will now use the example of a modular tram system to illustrate how the right selection of module parameters, in combination with an appropriate design strategy making use of CAx tools, can produce a high degree of flexibility and, at the same time, reduce costs.

The outer shape of a tram is, apart from visual aspects, determined by the required transportation capacity and the existing infrastructure of the operator. The *length* of the tram is mainly determined by the required number of passengers to be carried. The *width* is determined by the maximum allowable values set out in transport regulations and by the infrastructure, e.g. the existing distances between tracks in the case of twin-track layouts. The arrangement of the tram, that is, the *number* and *length* of the tram sections, and the configuration of the chassis are also determined by the infrastructure. Relevant issues here are, among others, the radius of the curves in the tracks, the buildings along the route, proximity of pavements, etc.

Because the abovementioned influences on the external shape of a tram differ for each operator and the required transportation tasks, a very large number of tram concepts have been generated over time. In this example, the task was to cover all existing tram applications with a very limited number of different tram sections, i.e. modules (basic modules) with not more than three widths and two lengths. After an extensive market analysis and a study of the trams produced in the past, the three basic modules shown in Figure 9.27 were defined. These are an end module, a chassis module and a middle module.

The end module is in two variants, with a driver cabin and without one; the chassis module with a driven variant and non-driven one; and the middle module in two lengths. The longer variant permits two different door arrangements. All modules come in three widths. The modules are shown in Figure 9.28.

The design of the body shell is based on a strict systematic approach. It can be represented using a parametric 3-D modeller and modified within predetermined

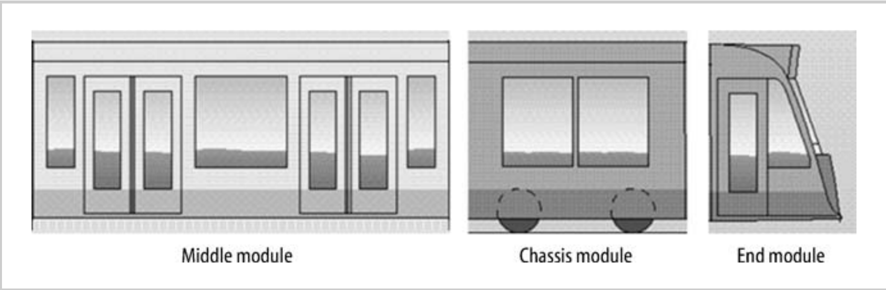


Figure 9.27. Basic modules of a modular tram

parameter ranges. The lengths of the individual design elements of the modules, such as the linking cross members, the roof supporting members, etc., have a clear geometric interdependency. By setting the parameters for the external dimensions of the modules, such as module length and width, number of doors, etc., the dimensions of the remaining elements of the module follow directly. Figure 9.29 shows, as an example, the body shell of the middle module.

The end module is a special module. The body shell of the tram consists of aluminium and extruded profiles that are bolted together. To realise the market requirement for different end module designs, the structure of the end module was produced using a GRP sandwich construction. The interfaces to the body shell, however, remain unchanged for each particular class of tram width. The resulting high flexibility and cost effectiveness, along with a wide range of configuration options, was partly due to the coupling of CAD and CAM. The 3-D

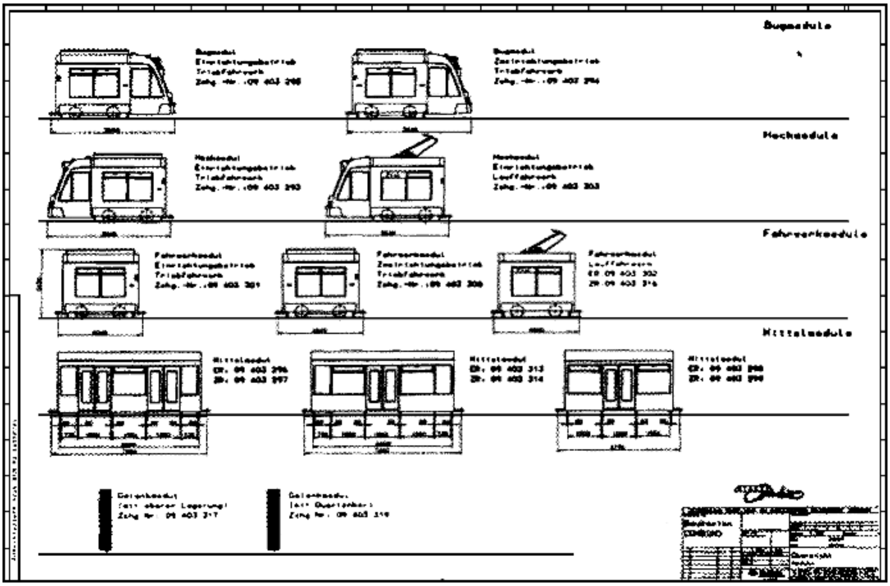


Figure 9.28. Modular tram system

CAD data for the end module can be sent directly to form milling machines that produce the foam cores for the GRP sandwich structure. It is essential that such possibilities, in addition to the previously mentioned structural and visual imperatives of the body shells, are taken into account when planning such modular products.

The selected tram modularisation only allows three sensible tram types of different lengths, namely a three, five and seven section tram. In Figure 9.30 the trams of the series are shown.

The basic configuration of the trams can be recorded as standard product structures in a Production Planning System (PPS). The design strategy behind the modules can be described in a Configuration Management System (CMS). This system can be used in the following way. In a first step, using the appropriate requirements, the structure of the tram, with three, five or seven sections, is selected. The parameters of the tram are then entered into the CMS. This system retrieves from the digital archive the required drawings, along with their ID numbers, and enters these at the appropriate positions in the product structure. In a second step, the assemblies and components that are not pre-defined, i.e. the customer-specific ones, are designed as special modules or non-modules using a conventional design approach. In this way, the product structure is completed (see Figure 9.31). More details of the approach adopted for this modular design task can be found in [9.32].

Further examples taken from hydraulics, pneumatics and machine tool construction can be found in the literature [9.2, 9.19, 9.29, 9.41].

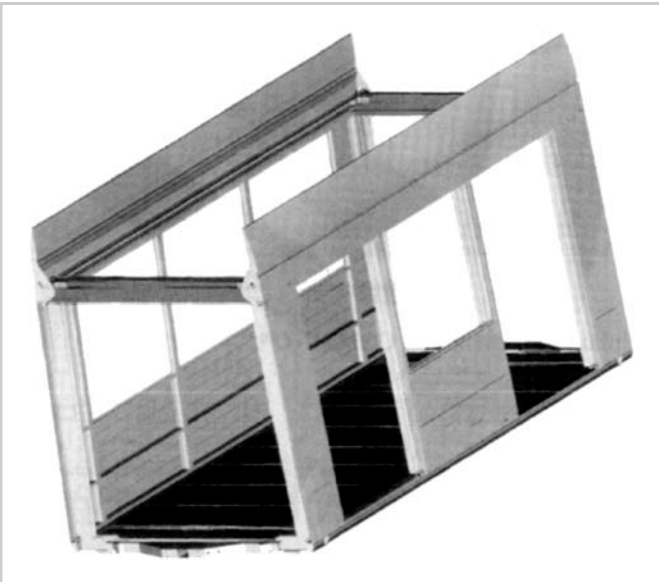


Figure 9.29. The parameterised body shell of the middle module

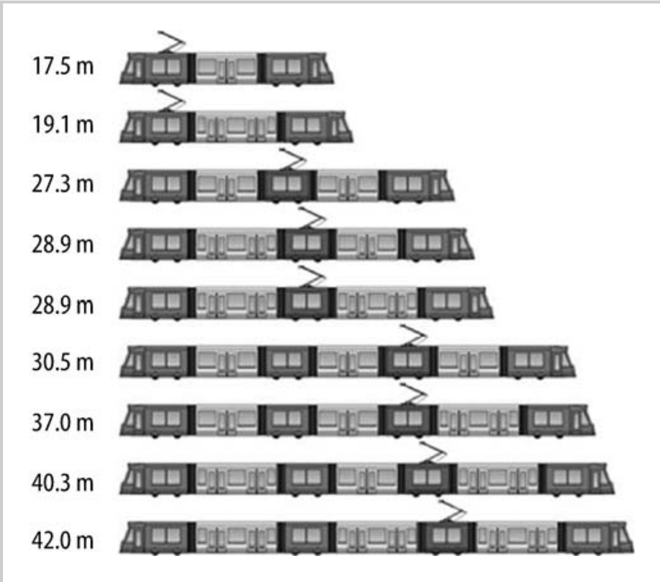


Figure 9.30. The trams of the COMBINO series: closed modular system [9.32]

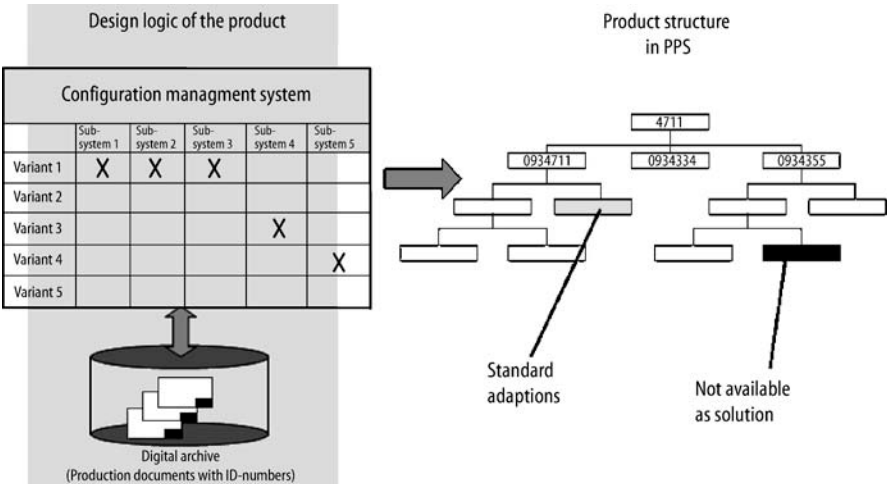


Figure 9.31. Configuration management system and product structure [9.32]

Modular Conveyor System

While all the systems discussed above are examples of "closed" modular systems, Figure 9.32 shows the modules and a specimen plan of an "open" modular system. The fixed modules are shown under *a* and a sample combination under *b*.

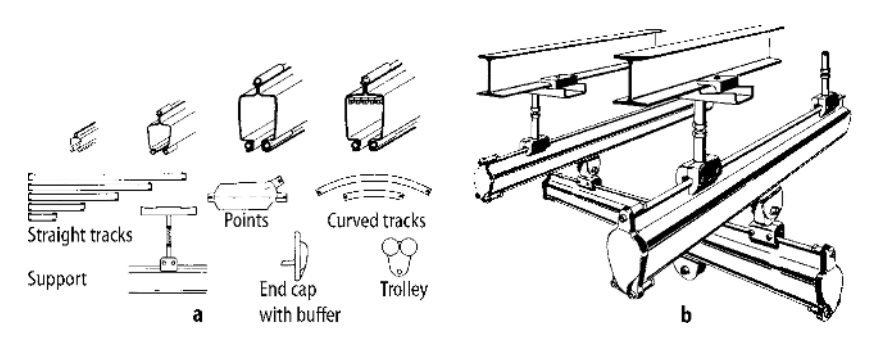


Figure 9.32. Open modular system for conveyors (Demag, Duisburg), **a** fixed modules **b** sample combination

9.3 Recent Rationalisation Approaches

9.3.1 Modularisation and Product Architecture

According VDI Guideline 2221 (see Section 1.2.3) after identifying the principle solution it has to be divided into modules. This results in a construction structure (see Figure 2.13), often referred to as a *product architecture* [9.44].

The product architecture is a scheme showing the relationship between the function structure of a product and its physical configuration. The particular importance of the product architecture is described by Ulrich [9.44]. According to Göpfer [9.45] the development of a product architecture is an essential task of product development and involves the transformation of a functional description of a product into a physical one. The relationships between these two descriptions characterise the product architecture, see Figure 9.33.

A product architecture can be used to describe the modularity of a product, which can be classified according the functional and physical independence of its components. A component is functionally independent if it fulfils exactly one

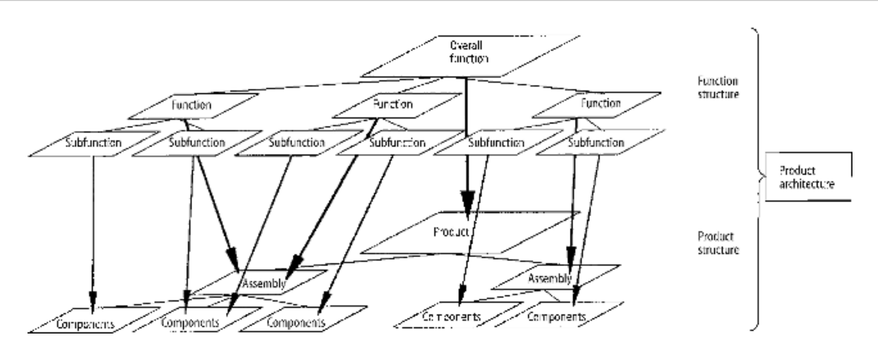


Figure 9.33. Product architecture [9.45]

subfunction. There is therefore and unambiguous relationship between function and component. In terms of product modularisation, a component is physically independent when it represents a coherent unit before the product is assembled. This means, for example, that it can be tested independently of the rest of the product. The objective of product modularisation is not the maximisation of modularity, which would mean an unnecessary increase of interfaces, but optimising the opportunities to meet different objectives.

Based on the previous descriptions, the terms related to product modularisation can be defined as follows:

Modularity is the degree of purposeful structuring of the product architecture.

Modularisation is the purposeful structuring of a product in order to increase its modularity. The aim is to optimise an existing product architecture to meet product requirements [9.46] or to rationalise production processes.

Modules are units that can be described functionally and physically and are essentially independent [9.46].

9.3.2 Platform Construction

The concept of platform construction comes from the automotive industry [9.47]. Platform construction is an approach for developing variant-rich products with short cycle times. It utilises the rationalisation potential of identical structures and components in a planned manner [9.48, 9.49]. A platform product consists of a basic variant-neutral product platform and product-specific additions (design elements) [9.48]. The product platform is determined from a functional perspective and is the lowest common denominator of a product series. A characteristic of platform construction is that the similarity between the products sharing a common product platform cannot easily be recognised from the appearance of the products [9.50].

Platform construction and modular construction are not identical. This is essentially because, unlike modular construction, the product variants based on a platform construction are not principally configured out of predefined modules.

10 Design for Quality

10.1 Applying a Systematic Approach

Nowadays product quality is defined in a much broader sense than it used to be. Apart from fulfilling the required technical functions, careful attention has to be paid to the requirements of safety, use, ergonomics, recycling and disposal [10.4], as well as production and operating costs (see Section 2.1.7, Figures 2.15 and 7.2). It is important to recognise that poor product quality can result from shortcomings in design as well as in production.

Achieving product quality appropriate for the market starts with the design process [10.2, 10.19]. Quality cannot be achieved simply though testing and improving a product—it has to be built in from the beginning of the design process and maintained throughout the production process. Just as design commits a large proportion of a product's costs (see Chapter 11), up to 80% of all faults can be traced back to insufficient planning, design and development [10.26]. Furthermore, up to 60% of all breakdowns that occur within the warranty period are caused by incorrect or incomplete product development.

Ensuring quality and improving quality are team activities. These activities have to address all aspects of product development, starting with product planning and marketing. Quality is influenced decisively during design and development, and has to realised during production. The basis for quality procedures and terminology is the international standard DIN ISO 9000–9004 [10.12–10.16].

The systematic approach along with the selection and evaluation methods described in this book support quality assurance in product design and development [10.2, 10.3, 10.33].

Introducing the steps of the systematic approach into the overall product creation process, with its project management and project teams, supports a holistic approach to product quality (see Section 4.3). The process chain shown in Figure 4.5 presents an integrated product creation process with overlapping phases undertaken by project-specific teams made up of specialists recruited from the areas shown and from supplier organisations. This brings together expert knowledge, ensures continuous consideration of customer requirements and, in particular, provides short and direct information transfer paths. The latter ensure an iterative and continuous coordination of the design activity. Interdisciplinary project-specific teams also guarantee balanced assessments and decision making, both of which are important prerequisites for achieving high quality.

Of the basic rules, principles and guidelines of embodiment design, the following contribute directly to quality assurance.

Clear and simple solutions help the reliable prediction of the effects of working principles and the behaviour of construction structures, thereby reducing the risks from unintended disturbing factors (see Sections 7.3.1 and 7.3.2).

The principles of *direct safety* (safe-life, fail-safe, redundancy) and of *indirect safety* (safety systems, safety devices) provide important opportunities to achieve durability, reliability, accident prevention and environmental protection (see Section 7.3.3).

Fault free design supports failure reduction through design measures such as compensating for disturbing factors (principle of balanced forces), selecting working principles and working structures in which the properties are largely independent of the disturbing factors (principle of division of tasks, see Section 7.4.2), and choosing interfacing elements that do not require close tolerances (see Section 7.4.5).

Force transmission between parts often results in mismatched deformations (differences in magnitudes and directions) causing additional stresses. These can be avoided by applying the *principle of matched deformations*, i.e. force directions and geometries are determined such that the interfacing surfaces deform in the same directions and with the same magnitudes, thus ensuring a uniform load transmission (see Section 7.4.1).

The *principle of stability* ensures that when a system or component is subjected to disturbing factors, the effects of these are compensated for or reduced (see Section 7.4.4).

The *principle of self-help* attempts to utilise the operating and disturbing effects to support the main function. It can also produce a self-protecting solution that compensates for excess stresses or alters the load paths when overloading occurs (see Section 7.4.3).

Design to allow for expansion and creep means that thermal and load related expansions of parts, with or without the effects of time, are reduced by the appropriate selection of materials or allowed for by suitable guides. These measures ensure that there are no residual stresses, no jamming and no other disturbances to the operation (see Sections 7.5.2 and 7.5.3).

Design against corrosion and to minimise wear attempts to avoid or minimise corrosion and wear—or at least make them safe for operation—by preventing the causes (primary measures); or by selecting appropriate materials, by applying surface finishes, and by specifying simple maintenance measures (secondary measures) (see Sections 7.5.4 and 7.5.5).

Careful *design for production and assembly* not only reduces production costs and times but also provides an essential basis for quality assurance. Production and assembly are the areas on which quality methods and measures have traditionally focused (see Sections 7.5.8 and 7.5.9).

Design for minimum risk attempts to anticipate possible future problems, due to either gaps in knowledge or unforeseen disturbing factors, in such a way that should such problems arise during testing, they can be dealt with easily using simple additional measures (see Section 7.5.12).

Design to standards strongly supports quality assurance, because the application of standards ensures the use of proven technology and procedures, supports maintenance, and introduces internationally agreed quality features (see Section 7.5.13).

When considering product quality in its broadest sense, embodiment design guidelines such as *design for ergonomics, design for aesthetics and design for recycling*, are also important (see Sections 7.5.6, 7.5.7 and 7.5.11).

By rigorously applying systematic design methods, product quality is positively influenced, with hardly any additional costs, through: the avoidance of failures and disturbing factors; the provision of simple and clear working and construction structures; and the unambiguous realisation of the desired product properties. Such *primary measures* are to be preferred over extensive analysis and testing.

In addition to these design methods, a range of systematic tools support quality. The *requirements list*, for example, ensures that none of the essential demands and wishes are overlooked. This list is therefore of particular importance for quality assurance (see Section 5.2). For a preliminary selection of solutions, a *selection chart* is available (see Section 3.3.1), for a more detailed assessment and for identification of weak spots, *Cost-Benefit Analysis* or a similar procedure can be used (see Section 3.3.2). *Fault tree analysis* can be used to assess the effects of disturbing factors and possible failures (see Section 10.3).

Procedures and computer-based tools have been developed to help designers *analyse and define tolerances* that maximise the quality and minimise the cost of complex parts and assemblies (see Section 7.5.8 and [10.29]).

Computer-supported *reliability analyses* are used to predict component and machine lives and the likelihood of failures, thus supporting quality improvement [10.5, 10.24].

Computer-based *optimisation procedures* are important for optimising technical systems to meet complex sets of objectives and constraints.

To analyse the stresses and deformations of structures under mechanical and thermal loads in order to optimise them for safety, material utilisation and other characteristics, the *Finite Element Method* (FEM) has been widely introduced. FEM and all analytical procedures to verify calculations and define preliminary embodiments support quality assurance.

Despite the possibilities that systematic design offers designers to improve quality, companies have introduced additional quality management procedures. *Total Quality Management* (TQM) and *Total Quality Control* (TQC) represent a quality philosophy that engages all those involved in the product creation process in a continuous and holistic *quality engineering* process [10.20–10.22, 10.25–10.27]. TQM is foremost an organisational management instrument focusing on the following areas of operation: quality aware management, staff development, customer relations management, supplier integration, responsibility to society, process-orientated organisation structures, quality-directed auditing, and goal planning that encourage quality [10.25]. TQM also provides individual methods that complement the systematic design approach.

First of these is *Failure Modes and Effects Analysis* (FMEA), which is used to analyse possible failures and the risks involved in a more extensive way than can be done with Fault-Tree Analysis. Because of its importance, FMEA is discussed separately (see Section 10.4).

A further method is *Quality Function Deployment* (QFD), which is used to translate the often vague customer requirements into ones that are clearly formulated, and where possible quantified, and that are related to the different company departments [10.3, 10.9, 10.10, 10.17, 10.23, 10.25]. QFD thus helps to refine and complete the requirements list, making it an important part of a systematic product planning process. Because of its importance in industrial practice the method is described in more detail in Section 10.5.

Another systematic approach is the *design review*, which is a team-based activity used at the end of the various design phases to check results and assess progress [10.33]. These checks and assessments are also used to estimate and reduce risks.

Figure 10.1 summarises the main product- and process-related failures that can occur along with some of the essential measures that can be used to mitigate them.

It can be concluded that the systematic approach proposed in this book contains all the fundamentals for applying quality engineering. The special methods of TQM should be seen as complementary to this systematic approach and not the other way round [10.6, 10.8, 10.18, 10.33]. If the search for suitable principle solutions has not been undertaken rigorously and if the appropriate rules, principles and

Product-related failures	**Possible mitigating measures**	
Geometry · Space problems · Faulty interface configuration	· 3D modelling · Design reviews · Statistical tolerancing	 [10.33] [10.33]
Function · Inadequate or deficient function fulfilment · Inadequate breakdown behaviour · Interfacing problems	· Fault-Tree Analysis · Failure Mode and Effect Analysis (FMEA) · Quality Function Deployment (QFD) · ISO 9001 (Validation)	(see 10.3) (see 10.4) (see 10.5) [10.5]
Layout · Kinematic problems · Strength problems	· Experiments · Field tests · Simulations - Finite Element Method (FEM) - Multi-Body Simulation (MBS)	
Process-related failures		
· Inadequate document management · Inadequate configuration management · Inadequate variant management · Inadequate change management · Inadequate version management	· ISO 9001 · Engineering Data Management System (EDMS) · Product Data Management (PDM) · Digital archive	[10.5]

Figure 10.1. Possible failures of design and development with measures to mitigate them

embodiment guidelines have not been applied to their full extent, the methods of TQM will not be able to rectify these fundamental deficiencies.

10.2 Faults and Disturbing Factors

The design process involves a series of creative and corrective steps. Selection and evaluation methods (see Section 3.3) as well as tests and calculations help to identify and remove weak spots. Even so designers can make mistakes, or their knowledge may not be sufficient to identify or exclude links that are faulty or prone to disturbances. When designers are aware of the information they lack and the uncertainty in their decisions, they can avoid severe technical and economic consequences by designing to minimise risk (see Section 7.5.12).

Often malfunctions are not caused by design faults but by *disturbing factors*. According to Rodenacker [10.28] disturbing factors can be caused by variations in the input variables, that is, by quality differences in the material, energy and signal flows entering the system (see Figure 2.14). When these influence the output of a system adversely, it may be necessary to compensate for them by modifying the type of solution, e.g. through a control system. The basis for this is determined by the selected working principles and the way they are combined. One should always aim for a robust concept, in which the outputs are independent of the quality of the inputs. The efficiency of a friction wheel drive, for example, strongly depends on the quality of the friction surfaces, which can have a negative effect on the quality of the overall product.

Disturbing factors can be identified in the *function structure* when the allocation and connection of the subfunctions lack clarity. They show up in the *working principle* when the selected physical effects do not produce the expected results. Because of variations in *material properties* along with shape, position and surface deviations introduced during *production* and *assembly*, the selected *embodiment* can result in unexpected effects. Finally, *external disturbing factors* such as temperature, humidity, dust, vibration, etc. can cause effects that should not be neglected. It may therefore be necessary to suppress the effects of disturbing factors to avoid the danger of fault propagation.

Preventative measures can reduce the malfunctions caused by disturbing factors but cannot exclude them altogether. Examples of measures include the principles of fault-free design (see Section 7.4.5 and [10.30]) and the other embodiment principles (see Section 7.4) and guidelines (see Section 7.5).

Extensive suggestions to achieve improved precision in machines are given by Spur [10.29]. He defines a machine as a "precision system" that is determined by the precision of: the material properties; the component geometry; the assembly geometry; the machine motions; the control system; along with its precision during operation.

Important prerequisites to prevent faults and disturbing factors, or at least limit their effects, are the identification and estimation of possible faults and disturbing factors as early as possible in the product development process. The following sections describe some established methods.

10.3 Fault-Tree Analysis

The influence of faults and disturbing factors can be determined systematically by *Fault-Tree Analysis* [10.11]. The Fault-Tree Analysis uses Boolean algebra to make an estimate of faults, their consequences and causes in safety critical systems. This method is based on causality, i.e. every event has to have at least one cause. An event (disturbance) only occurs when its cause arises.

From the conceptual phase, designers know what overall function and individual subfunctions have to be fulfilled. The established function structures can thus be used to identify all the functions to be checked. These functions are then negated one by one, that is, assumed to be unfulfilled. By reference to the checklist (see Section 7.2), designers can seek out the possible causes of these potential faults or disturbances. The OR or AND relationships of these causes and their effects can then be examined.

The conclusions help designers improve their designs and, if necessary, re-examine the solution concept or modify production, assembly, transport, operation and maintenance procedures. Let us take a concrete example.

The design of a safety blow-off valve for a gas container (see Figure 10.2) must be checked for possible design faults during the *conceptual phase*. From the requirements list and the function structure, it is possible to specify the operating conditions depicted in Figure 10.3. The blow-off valve is intended to open when the operating pressure p_{op} exceeds 1.1 times the nominal working pressure p_{nom}, and to close again when the container is under nominal pressure. The main func-

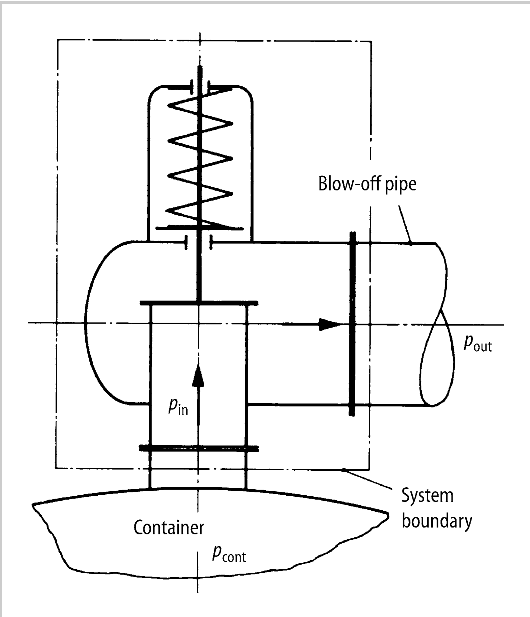


Figure 10.2. Safety blow-off valve for a gas container

tions are therefore "open valve" and "close valve". The overall function can also be described as "limit pressure". Let us now assume a possible failure of the overall function, namely "valve does *not* limit pressure" (see Figure 10.4). The valve functions shown in Figure 10.3 and their timing are negated. Each has an OR relationship with the overall function. Each fault thus identified is next investigated in terms of its possible causes. The fault we have chosen to investigate in more detail is "does not open" (see Figure 10.5).

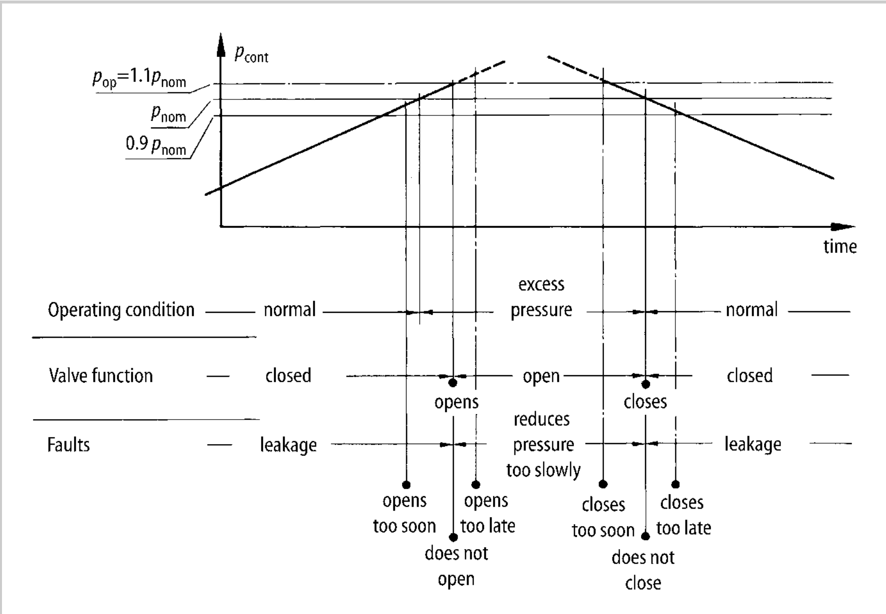


Figure 10.3. Operating conditions, valve main functions and faults of the safety valve

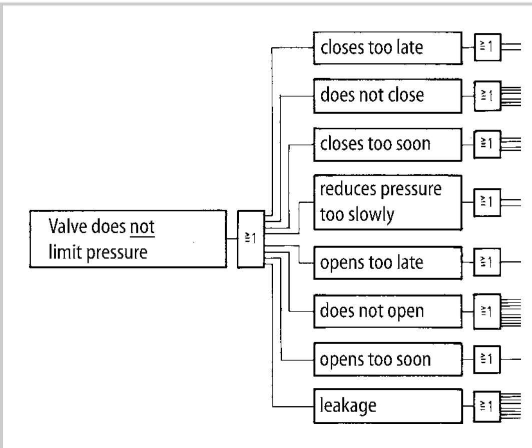


Figure 10.4. Construction of fault-tree based on faults identified from Figure 10.3

An identified cause may be associated with further causes with which it has an OR or an AND relationship, and these may have to be scrutinised accordingly.

Figure 10.6 shows a selection of further causes of malfunctions and some of the remedies identified at this stage. Often these cannot be clarified in more detail until the embodiment phase. Grouping the remedial measures according to the

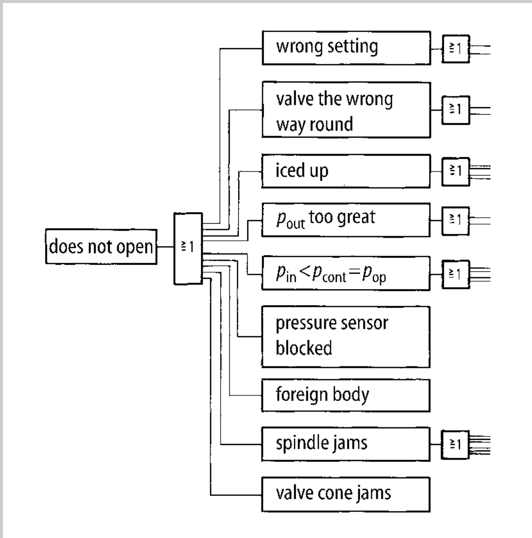


Figure 10.5. Detail from completed fault-tree (Figure 10.4) for the fault "does not open"

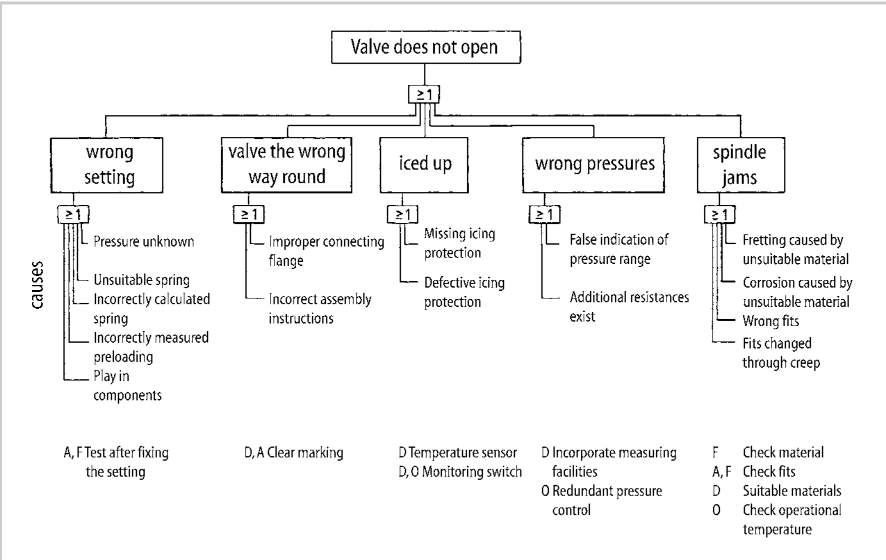


Figure 10.6. Causes of and remedies of malfunctions, after Figure 10.5: D = design; P = production; A = assembly; O = operation (use and maintenance); F = formal procedure required

departments involved simplifies their execution. On the basis of the information gained from a fault-tree analysis, designers are able to improve and complete the requirements list (see Figure 10.7) before they proceed to the embodiment phase. As a result, the design will be greatly improved and potential faults avoided.

The second example concerns the *embodiment phase*. A packing ring shaft seal is used to prevent the leakage of pressurised cooling air in a generator connected to a turbine (see Figure 10.8). This large diameter seal interfaces with a sleeve that acts as a thermal barrier. The seal has to withstand a pressure difference of 1.5 bar. Possible malfunctions of this assembly have to be analysed.

The overall function is "prevent leakage of cooling air". At the beginning of the investigation, it is useful to clarify the subfunctions that have to be fulfilled by the various parts. When no function structure has been established, one can use a table such as the one shown in Figure 10.9. For the "prevent leakage" function the following subfunctions are essential:

			Requirements List *for* *Safety blow-off valve*	1st issue 1/9/73 *Page* 1
Changes	*D W*	*No.*	*Requirements*[x)]	*Responsible*
1.9.73		22	Valve head with plane sealing surface (valve without taper)	
"		23	No rigid joint between valve head and spindle	
"		24	Easy maintenance or exchange of sealing surfaces	
"		25	Valve lift limited	
"		26	Damping of valve movement	
"	W	27	Installation in a closed, ice-proof area	
"		28	No sliding seals, avoid friction	
"		29	Ensure foolproof mounting (e.g. different flange sizes for inlet and outlet)	
			x) Requirements were revised after construction of fault-tree	
			Replaces *issue of*	

Figure 10.7. Revision of requirements list after fault-tree analysis

- generate compression force
- seal yet allow sliding
- remove frictional heat.

Next these subfunctions are negated and, at the same time, possible causes of malfunctions are sought (see Figure 10.10).

The results of the Fault-Tree Analysis point, first of all, to a malfunctioning of the thermal barrier *2* caused by unstable heat patterns (see Section 7.4.4). The frictional heat generated at the sliding interface can only flow away through the barrier into the shaft. This causes the barrier sleeve to heat up and expand. This increases the friction and at a certain temperature the barrier sleeve lifts off the shaft. This results in additional air leakage and damage to the shaft surface caused by the barrier sleeve slipping on the shaft. This layout is bad and the design principle needs improving. Either the barrier should be removed and the seal connected to the shaft so it rotates with the shaft (removal of heat through the housing *5*) or a sliding ring seal with radial sealing surfaces should be used.

Further necessary design measures:

- The connection of housing *5* to frame *6* is insufficient and the housing can start rotating with the shaft due to the pre-loading of the packing ring seals against the shaft. The compression force from the pressure difference is too low for the O-ring seal *7* to transfer the moment through a frictional connection. *Remedy:* reposition seal *7* towards the outer diameter of housing *5*; even better would be an additional form-fit connection to transfer the moment.

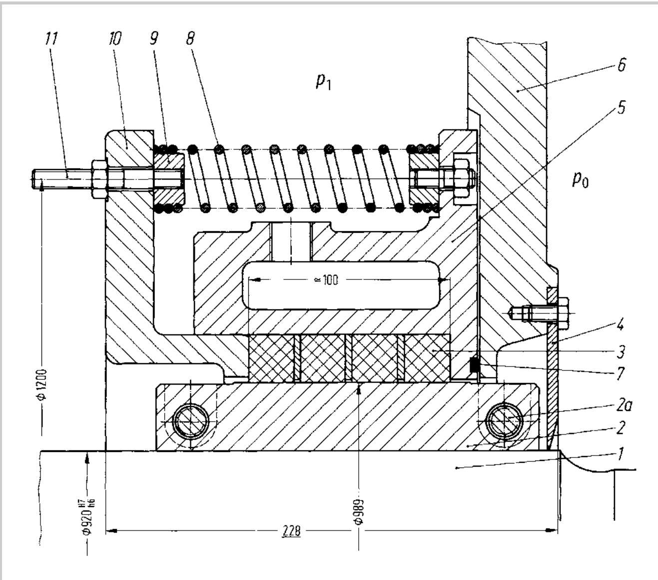


Figure 10.8. Packing ring shaft seal in a generator

Nos.	Components	Functions
1	Shaft	Transmit torque, carry sleeve, dissipate frictional heat
2,2a	Sleeve (barrier)	Provide rotation and seal surface, protect shaft, dissipate frictional heat
3	Packing rings	Seal medium yet allow sliding, carry compression force and provide sealing pressure
4	Scraper ring	Protect against splashed oil
5	Gland housing	Carry packing rings, carry and transmit compression force
6	Frame	Carry components *4* and *5*
7	O-ring	Seal p_1 from p_0
8	Tension spring	Generate compression force
9	Spring support	Transmit spring force
10	Transfer ring	Transmit compression force, carry tension spring
11	Bolt	Preload springs and adjust loading

Figure 10.9. Analysis of the components in Figure 10.8. to identify their functions

- With the current layout, the loading of springs *8* cannot be adjusted. *Remedy:* include sufficient space.
- For reasons of safety and simplicity, it is advantageous to use a compression rather than a tension spring.

Basically, designers should not only include design measures to improve the embodiment, but also measures to improve production, assembly and operation (use and maintenance) procedures, where these seem necessary. In certain cases it might be necessary to enforce specific test procedures (see Figure 10.10).

In summary, the following procedure should be followed to identify and rectify faults and disturbing factors:

- Identify and negate functions.
- Search for causes of possible malfunctions from: a function structure that lacks clarity; a less than ideal working principle; a less than ideal embodiment; less than ideal materials; and less than ideal inputs caused by variations in the material, energy and signal flows. In line with the guidelines given for the embodiment design phase, further influences that might cause undesired system behaviours should be sought in the following areas: loading, shape changes, stability, resonance, wear, corrosion, sealing, safety, ergonomics, production, quality control, assembly, transport, operation and maintenance.
- Determine the prerequisites for malfunctions to occur, e.g. through OR and AND relationships.
- Introduce suitable design measures by choosing another solution or making improvements to the existing solution. Quality control measures during production, assembly, transport, operation and maintenance can also be introduced. Preference, however, should always be given to the removal of a cause through an improved solution.

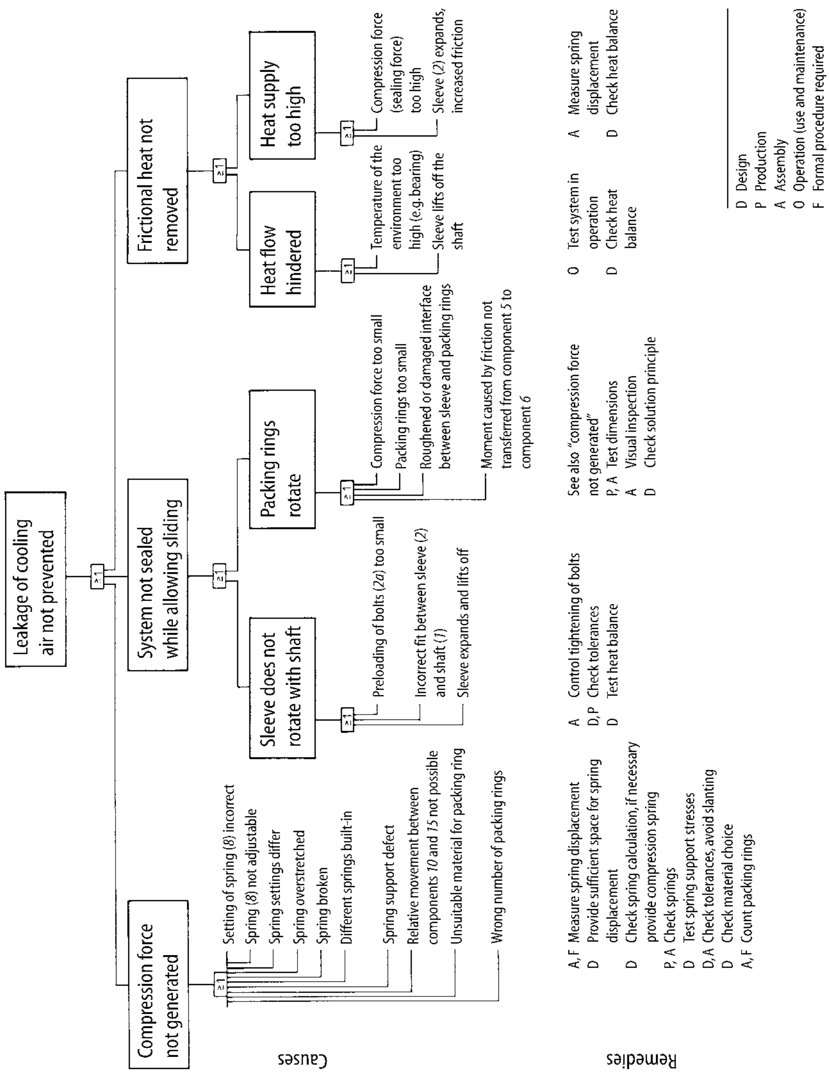


Figure 10.10. Fault-tree analysis of the shaft seal in Figure 10.8

It has to be noted that because of the effort required to complete a full Fault-Tree Analysis, this method is usually limited to important areas and critical processes. It is desirable that designers incorporate this way of thinking into their normal work patterns so that they can apply it almost unconsciously.

10.4 Failure Mode and Effect Analysis (FMEA)

FMEA is a formalised analytical method for the systematic identification of possible failures and the estimation of the related risks (effects) [10.19, 10.26, 10.32]. The main goal is to limit or avoid risk. An FMEA involves a direct analysis of failures and their consequences and causes. This means that only direct relationships between causes and consequences are identified. This method is usually applied during the development of new products. A distinction is made between a design or development FMEA and a process or production FMEA. The design FMEA is used to verify whether the functions set out in the requirements list are fulfilled. The process FMEA is used to verify whether the planned production process can produce the required product characteristics.

Figure 10.11 shows an FMEA chart with an example in which possible failures are listed together with their consequences, causes, risk numbers (RN), proposed test measures, and suggested and applied remedial measures. The chart also shows the following steps of FMEA:

1. Risk analysis of each component (or process step) regarding:
   - potential failures (failure types)
   - failure consequences
   - failure causes
   - planned measures to avoid failures
   - planned measures to detect failures.
2. Risk assessment:
   - estimation of the probability of occurrence
   - estimation of the effects of the failure on the customer
   - estimation of the probability that the failure can be detected before delivery (a high probability of detection implies a small risk and thus a small numerical value).
3. Risk number calculation: (RN) > 125 is considered critical.
4. Risk minimisation: development of measures to improve the design of the product (or its production process).

The assessment of risk using risk numbers is important. They provide estimates of: the probability of occurrence; the severity of failure; and the difficulty of detection. The latter requires an experienced assessment team to maximise the probability

TU-Berlin

Failure Mode and Effect Analysis
Design (product)-FMEA ☒ Process-FMEA ☐

Name/ Department/ Supplier/ Telephone
Institute for Machine Design-Engineering Design

Component name
Cylindrical cam

By (Name/ Department/ Telephone)
Mr Wende

Failure location/characteristic	**Failure type**	**Failure consequence**	**Failure cause**	**Current situation**					**Suggested remedial measures**	**Improved situation**				
				Proposed test steps	O	S	D	RN		Applied steps	O	S	D	RN
Shaft	Shaft fracture	Complete breakdown	Type of loading not identified correctly		3	10	10	300	Determine loading using suitable calculations	Proof of strength of the shaft	1	10	10	100
Bearing	Play in bearing assembly	Imprecise function fulfilment	Slackening of shaft nut during operation (impulse loading)		3	8	10	240	Additional locking of the shaft nut		1	8	10	80
	Sealing leakage	Early wear of bearing	Sealing not as required		2	5	10	100	Use of radial shaft seals recommended by DIN		1	5	10	50
Shaft-hub-connection (flange-bolt connection)	Insufficient frictional fit	Shear stress in bolts	Layout error (friction values neglected)		2	6	10	120	Application of a sufficiently high safety factor		1	6	10	60
	Precision of fittings	Joining not possible or centering insufficient	Design fault		2	5	1	10	Check tolerance calculation		1	5	1	5
	Failure of bolts	Complete breakdown	Type of loading not identified correctly		3	10	10	300	Suitable calculation for loading situation	Appropriate bolt dimensions	1	10	10	100
Cylindrical cam	Surface pressure too high	Pitting in the running surface	Lever pressure on surface too high		7	8	10	560	Suitable combination of materials and adapted geometry		2	8	10	160

O: Occurrence

Probability of occurence
(failure can exist)

very low = 1
medium low = 2–3
medium = 4–6
medium high = 7–8
high = 9–10

S: Significance

Effect on customers

effects hardly noticeable = 1
failures not important (little trouble to the customer) = 2–3
reasonably serious failure = 4–6
serious failure (annoying for the customer) = 7–8
failure with large negative effects = 9–10

D: Detection

Probability of detection
(before delivery to customers)

high = 1
medium high = 2–5
medium = 6–8
medium low = 9
low = 10

RN: Risk number

high = 1000
medium = 125
no risk = 1

Figure 10.11. FMEA chart with an example of the shaft, bearing and cylindrical cam of the design discussed in Section 7.7 (Figure 7.160)

of detecting a failure. FMEA is qualitative in nature and is a method for evaluating quality. Staff from design, development, production planning, quality control, purchasing, sales and customer service should be included in an FMEA team, for the same reasons as for their inclusion in a Value Analysis team (see Section 1.2.3). Apart from evaluating possible malfunctions caused by failures and disturbing factors, FMEA encourages early cooperation between the various departments involved in product development. Fault-Tree Analysis is intended to assist designers alone, whereas FMEA also functions as a means of handing over to production and supporting the overall quality assurance process.

After a period of use, the information in the FMEA records and analyses of the FMEA charts provide valuable insights into successful quality measures that can be used in subsequent products.

For the production process, an additional process FMEA is carried out using the same charts. This evaluation of the production processes, however, is often contained indirectly in the design FMEA, because production issues should already have been taken into account during the design process.

10.5 Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a methodology for quality planning and quality assurance [10.1, 10.9, 10.10, 10.17, 10.20–10.22, 10.25, 10.31]. It supports a systematic customer orientation of product and process planning. The customer requirements are translated into technical requirements. These in turn are translated into organisational processes and production requirements. The main question is whether all the functions required by the customer can be realised.

The QFD methodology is a four-step procedure as shown in Figure 10.12. Similar to FMEA (see 10.4), QFD also assists with the integration of the main activities in the product creation process.

The main working chart of QFD is the so-called "House of Quality". An example of this chart for the manual winding device shown in Figure 10.13 is provided in Figure 10.14. The chart documents clearly the translation of customer requirements (referred to as the "what"), which are often vaguely formulated, into technical requirements (also referred to as target requirements or the "how") of the product to be developed. The roof of the house shows if the technical requirements interrelate with each other and the strength of any interrelationship. The matrix in the middle of the chart shows the interrelationship between the customer requirements and the technical requirements. Weighting factors can be added to the customer requirements, as well as an estimation of competing products from the point of view of the customer. Underneath the central matrix, target values for the technical requirements are plotted along with a technical assessment of competing products (benchmark). At the very bottom the weighted values (priorities) of the technical requirements are listed.

This basic scheme can also be applied to the subsequent phases of the product creation process. The "how" of one House of Quality becomes the "what" of the following one [10.6, 10.10].

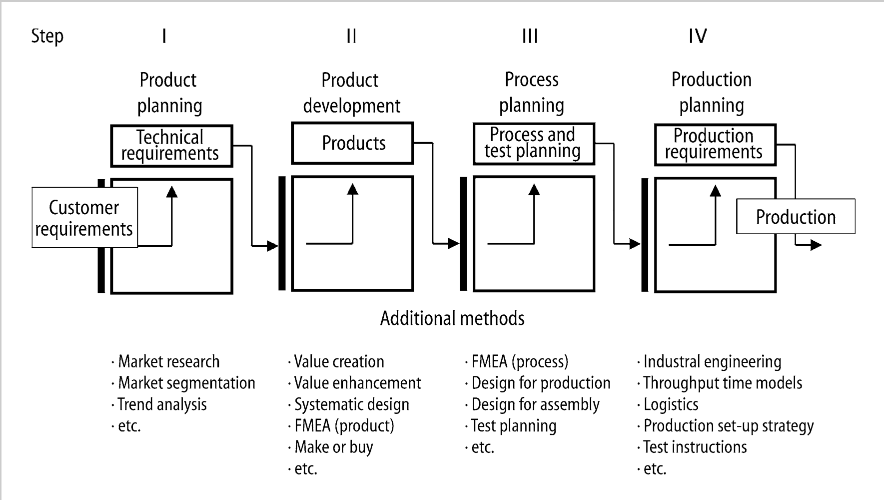


Figure 10.12. QFD as an integration tool

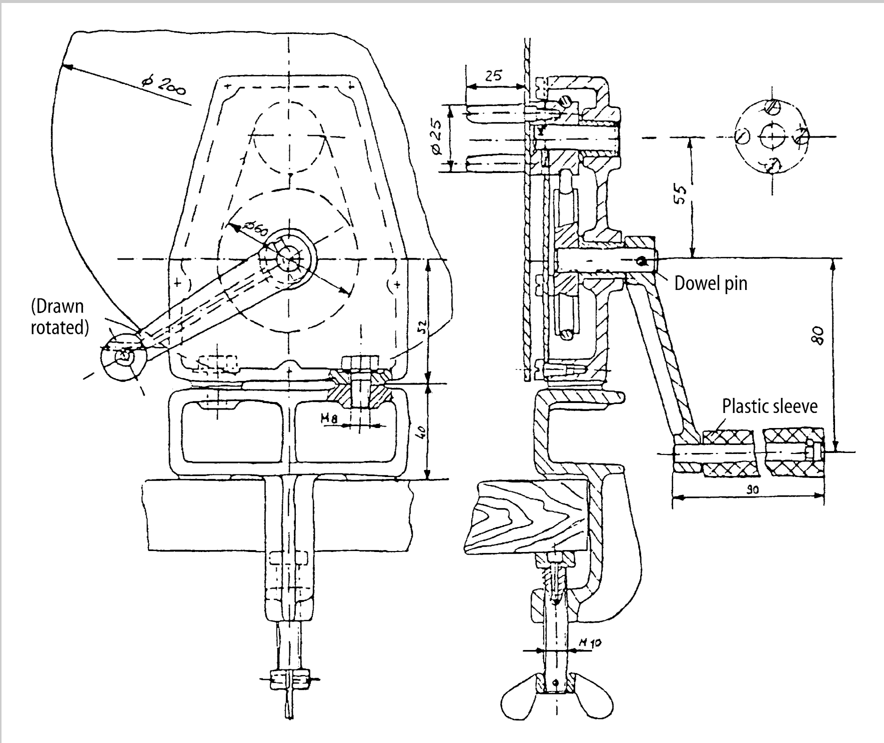


Figure 10.13. Rough layout of a manual winding device for perforated strip

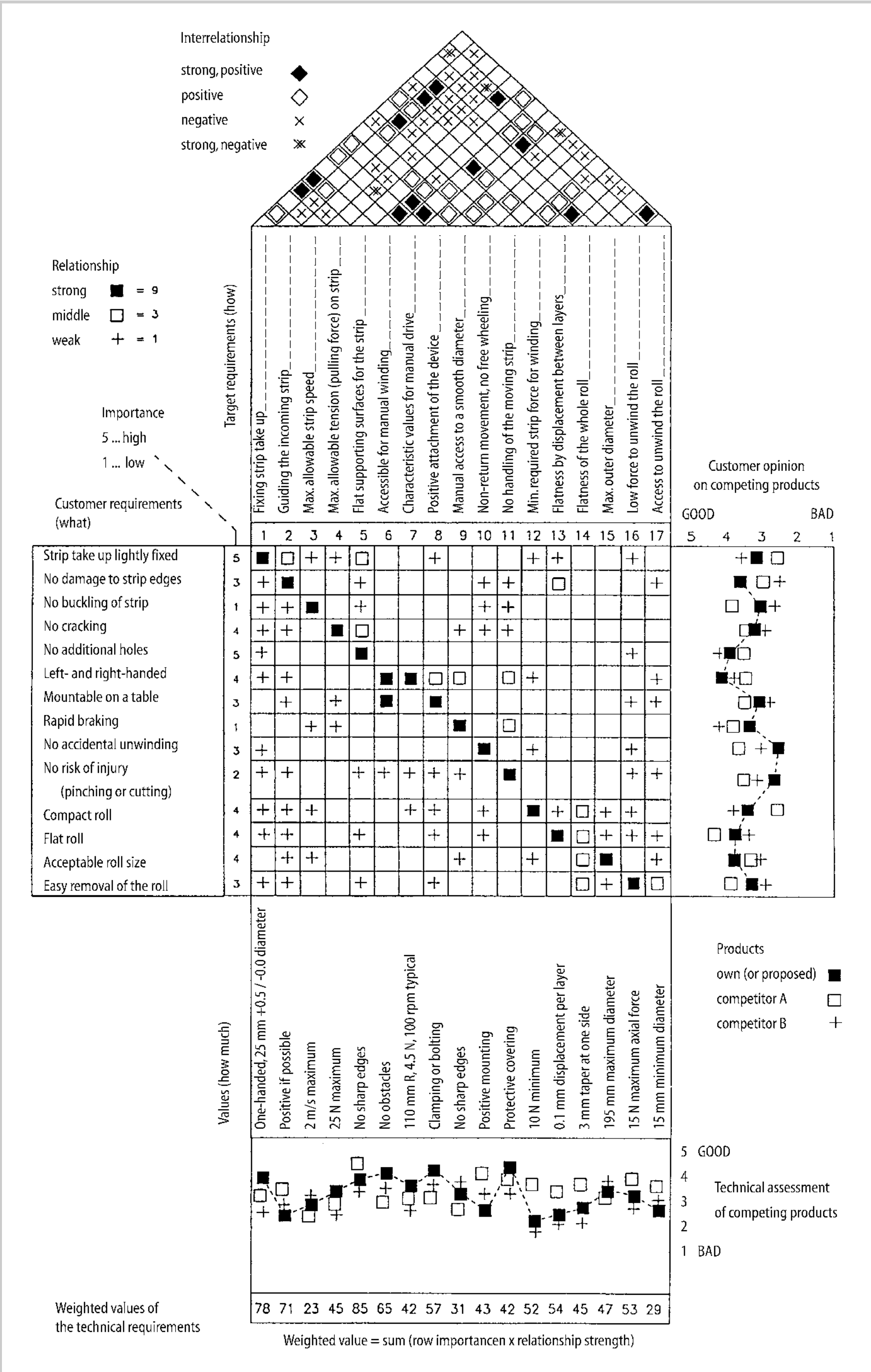


Figure 10.14. House of Quality for the example shown in Figure 10.13

In the context of the systematic approach, the use of QFD provides the following benefits:

- improved formulation of requirements lists through a better representation of customer requirements
- identification of critical product functions (customer-oriented function structures)
- definition of critical technical requirements and identification of critical components
- recognition of future development goals and cost targets on the basis of customer requirements and analyses of competing products.

The extensive effort needed to undertake every stage of this planning activity in detail is only justified for major long-term projects. These projects, however, should also start with the much simpler and quicker methods of task clarification and requirements formulation presented in Chapter 5.

11 Design for Minimum Cost

11.1 Cost Factors

It is important to identify cost factors as early and as accurately as possible in the design process. This is true for all types of design, including the development of size ranges and modular products. It is well known that the majority of costs have been committed when the principle solution has been selected and its embodiment completed. During the production and assembly stages there are relatively few opportunities to reduce costs. It is important, therefore, to start cost optimisation as early as possible since any design changes that have to be made during production are usually very costly. This might prolong the design process, but overall it is more economical than a retrospective drive to reduce costs [11.17].

In some of the examples in this chapter values for currency are given in Monetary Units (MU), with 1 MU approximately equivalent to 0.5 Euro.

The *overall cost* of producing a product can be divided into direct costs and indirect costs (overheads). *Direct costs* are those costs that can be allocated directly to a specific cost carrier, for example material and labour costs for producing a specific component [11.6]. *Indirect costs* are those costs that cannot be allocated directly, for example the costs of running the stores and illuminating the workshop.

Some costs depend on the number of items ordered, the degree of facility utilisation or the batch size. Material costs, production labour costs and consumable materials costs, for example, increase with higher turnover. In a cost calculation these are *variable costs*. *Fixed costs* are those that are incurred in a certain period and do not change, for example, management salaries, rent of space and interest on borrowings.

The *manufacturing cost* (see Figure 11.1) is the total of the costs for material and production including additional costs such as for production tooling and fixtures, and for design, development, models and tests as far as they relate to a specific product. Manufacturing cost therefore consists of fixed and variable costs. For decision making during the design process, however, only variable costs are of interest [11.35]. This is because they are influenced directly by designers, for example, by the choice of material types, production times, batch sizes, production processes and assembly methods. Of interest, therefore, are the variable manufacturing costs which comprise direct costs and indirect costs (overheads).

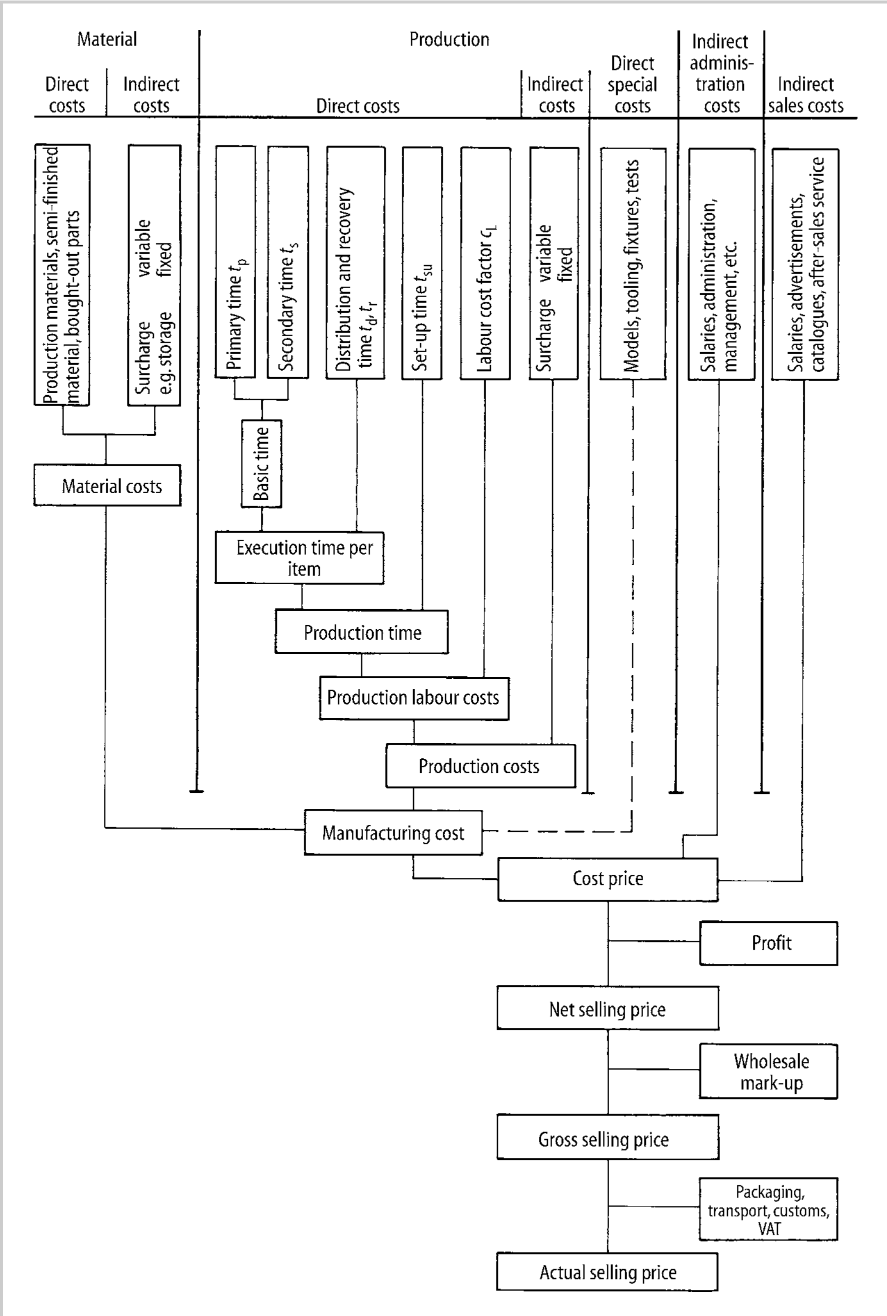


Figure 11.1. Cost sources and cost structure

Variable and fixed indirect costs are taken into account differently in different companies. Usually they are combined with the direct costs by using multiplication factors, such as a factor of 1.05 to 1.3 for indirect material costs, a factor 1.5 to 10 (or higher) for indirect production labour costs; and also by additions based on machine utilisation. The choice depends on the production processes and types of machine tool. When the factors are high or when machine utilisation is considered, it is useful to check whether it is possible, at least in theory, to reduce costs by using another production process. This avoidance strategy, however, increases the specific multiplication factors if the organisational structure does not change. This suggests a modification to the factory planning to take into account the modified product and production structure.

Concluding from what has been said, variable overheads are usually taken into account through multiplication factors on the direct costs and in this way they influence the manufacturing cost. In general designers can limit themselves to calculating variable direct costs when comparing the costs of solution variants.

At an early stage it is important to make rough cost estimates rather than detailed calculations, which should only be undertaken when really necessary. New methods to identify costs early in the design process will be discussed in the following sections.

11.2 Fundamentals of Cost Calculations

In Section 11.1 the *variable part* of the manufacturing cost ($VMfC$) was recommended as a basis for decision making. It comprises direct material costs ($DMtC$) and production labour costs (PLC), including assembly costs. All costs for production and assembly operations have to be added:

$$VMfC = DMtC + \sum PLC \tag{1}$$

The *direct material costs* are determined by the weight W or volume V and the specific cost c, that is cost per unit weight or volume, as follows:

$$DMtC = c_{\mathrm{W}} \cdot W = c_{\mathrm{V}} \cdot V \tag{2}$$

The *direct production costs* can be calculated from the times needed for the individual production processes and assembly operations multiplied by a labour cost factor c_{L} (see Figure 11.1). The production time is based on the primary time t_{p}, secondary time t_{s} and set-up time t_{su}, as well as distribution and recovery time. The last two times are generally taken into account as a constant factor on the basic time t_{b}, which is the sum of primary and secondary times and results in a time per unit. For the calculation of costs, therefore, primary, secondary and set-up times are important. Using the labour cost factor, the following simplified equation for a particular production operation can be used:

$$PLC = c_{\mathrm{L}}(t_{\mathrm{p}} + t_{\mathrm{s}} + t_{\mathrm{su}}) \tag{3}$$

For a more precise calculation, taking into account variable production overheads, see [11.21, 11.22, 11.36, 11.37].

We have indicated that the *manufacturing cost* is the sum of direct and indirect costs. Direct costs are usually linked to the type of product, for example the primary time for turning [11.31] which can be calculated from:

$$t_{\mathrm{p}} = \frac{D \cdot \pi \cdot L \cdot i}{v_{\mathrm{c}} \cdot f \cdot 1\,000} \text{ minutes} \tag{4}$$

with:

D = diameter in mm
L = length in mm
i = number of cuts
v_{c} = cutting speed in m/min
f = feed in mm/revolution.

The individual cost terms, for example turning cost (Equation (4)), can thus be represented by exponential functions consisting of variables x with exponents p and constants K. The generic form of a cost equation, e.g. manufacturing cost, would be as follows:

$$VMfC = \sum_{i=1}^{n} K_{\mathrm{i}} \cdot \prod_{j=1}^{m} x_{\mathrm{ij}}^{p_{\mathrm{ij}}} \tag{5}$$

with m equal to the number of variables x_{j} in cost term i and with n equal to the number of cost terms. In the case of three influencing variables, this results in:

$$VMfC = \sum_{i=1}^{n} K_{\mathrm{i}} \left(x_{\mathrm{i1}}^{p_{\mathrm{i1}}}\right) \cdot \left(x_{\mathrm{i2}}^{p_{\mathrm{i2}}}\right) \cdot \left(x_{\mathrm{i3}}^{p_{\mathrm{i3}}}\right) \tag{6}$$

The variable direct costs of the manufacturing cost for a turned component, for example, comprise the direct material costs and the turning costs. For t_{P} Equation (4) is used:

$$VMfC = \frac{\pi}{4} D^2 \cdot L \cdot c_{\mathrm{V}} + \left(\frac{D \cdot \pi \cdot L \cdot i}{v_{\mathrm{c}} \cdot f \cdot 1\,000} + t_{\mathrm{s}} + t_{\mathrm{su}}\right) c_{\mathrm{L}} \tag{7}$$

in which the following approximations are made:

$D \approx D_{\mathrm{raw}}$ (Diameter of raw material)
$L \approx L_{\mathrm{raw}}$ (Length of raw material).

The variable terms of the manufacturing cost considered here can thus be represented as power series of different orders. When adding up several production operations, an equivalent number of cost terms in the power series is created using Equations (1) and (5) as appropriate.

For *cost estimations* based on quick or all-inclusive calculations, it is too much effort to determine the direct costs strictly according to their individual dependencies. A better way is to define *relative costs* that are more generic and have long-term validity (see Section 11.3.1). It is also possible to estimate costs based on the *share of the material costs* (see Section 11.3.2). This method is only valid when comparing items (components, assemblies) of similar size. Recently cost profiles in several companies have been analysed statistically. Using *regression analysis*, researchers have attempted to correlate variable costs and influencing factors (see Section 11.3.3).

To determine the regression function, a power series is selected whose exponents and coefficients are determined in such a way that the resulting equation deviates as little as possible from the findings. The selected exponents and coefficients generally do not represent the real dependencies, but only mathematical relations. In [11.25] it is shown that very different regression functions can provide good approximations for the same set of circumstances.

In cases where one influence dominates and this has been identified and introduced into the regression function by selecting the relevant variables, it is likely that this influence represents physical reality. When it is possible to relate back all cost factors to only one characteristic variable x, for example diameter or weight, the cost function can be reduced to a simple equation of the following form:

$$VMfC = a + bx^p \tag{8}$$

For an example see Section 11.3.3.

Extrapolation using *similarity relationships*, on the other hand, is based on the physical relationships involved in the particular technology and uses power series with the appropriate exponents taken from the equations for material costs, primary times, secondary times and times per item. The coefficients of the cost terms are derived from company-specific data using a reference item (basic design or operation element) (see Section 11.3.4). The reason for developing this procedure was to make designers more aware of existing dependencies so that they can make more goal-directed decisions. The application of similarity relationships requires the availability of a sufficiently similar item, e.g. part, assembly or production operation.

In the case of *geometric similarity* (see Section 9.1.4), very simple cost-growth laws with polynomials of maximum order 3 can be set up based on a geometric reference length. For *semi-similar variants* (see Section 9.1.5) (most geometric magnitudes remain constant, but some deviate from geometric similarity) the cost-growth laws consist of many terms comprising all geometric and material variables that are involved. They have the form of power series with functions that can have fractional exponents. They are often called differential cost-growth laws. They achieve relatively high precision and only require a reasonable effort to apply.

Much effort is currently going into the identification of costs at an early stage through making available such methods in combination with computer support, including CAD and Knowledge-Based Systems [11.10].

In the following sections, the different methods are explained in more detail. Which method should be used depends on the available time, required precision and the available data.

11.3 Methods for Estimating Costs

11.3.1 Comparing with Relative Costs

In this method prices or costs are related to a reference value. For this reason, the results are valid for much longer than when absolute costs are used. In [11.7] principles are described for creating relative cost catalogues. Catalogues for materials, semi-finished materials, and bought-out parts are common. The *relative material costs* c^* are usually based on a standard size of channel-section steel (USt 37-2) and can be calculated from the following equation, which uses the specific material costs c^*_{W} or c^*_{V} derived from weight and volume respectively:

$$c^*_{\mathrm{W,V}} = \frac{c_{\mathrm{W,V}}}{c_{\mathrm{W,V}}(\text{reference value})}$$

It has to be noted that the resulting value is magnitude dependent. VDI Guideline 2225 Part 2 [11.34] therefore gives values for small, medium and large dimensions of all common materials. Material utilisation depends on the goals to be achieved. When strength requirements dominate, a different material has to be selected than when stiffness requirements dominate.

Figure 11.2 lists the relative material costs c^* for some materials with medium dimensions including the relation with tensile strength σ_{T} (strength requirement) and with Young's modulus E (stiffness requirement). The cost relation for machining based on [11.28] is also listed. This shows, for example, that in the case of tempered steels and case hardened steels strength increases generally faster than the material cost. This indicates the economic advantages of using these materials. For stressed shapes that have to be stiff, grey cast irons and plastics are substantially more expensive than steel. However the relations listed in Figure 11.2 change substantially in favour of cast or plastic parts when the shapes are complex and when there are additional corrosion resistance or surface finish requirements. In the case of highly alloyed materials, for example, obtaining a good surface finish can require very expensive machining.

Of particular interest are casting costs. In principle the overall cost is based on total weight, but the weight per item, number to be produced and item complexity play a role. Our own investigation [11.25] for steel castings resulted in the relationships shown in Figure 11.3. This figure shows that for steel castings specific cost reduces with increasing item weight, that is $\varphi_{\mathrm{c}} = \varphi_{\mathrm{W}}^{-0.12}$, so that the material costs increase by $\varphi_{\mathrm{M}} = \varphi_{\mathrm{W}}^{0.9}$, and not by $\varphi_{\mathrm{M}} = \varphi_{\mathrm{W}}^{1}$ (see cost-growth laws in Section 11.3.4).

For *semi-finished materials*, Figure 11.4 shows that shape has little influence on specific price provided they are produced by rolling. Drawn materials are considerably more expensive (factor ≈ 1.6). Closed sections cost about twice as much for the same weight. Figure 11.4 also shows the material utilisation advantages of particular sections when subjected to bending moments. For carrying bending moments, the required sectional area, that is weight per unit length, of some sections is considerably smaller and therefore cheaper.

The relative costs of *bought-out parts* vary strongly with size (see also cost-growth laws in Section 11.3.4). Rieg [11.27] developed a procedure for determining and representing these costs. Figure 11.5 gives an example of such a relative cost diagram for rolling element bearings. A particular deep groove ball bearing from series 60 with $d = 50$ mm is used as a reference ($\varphi_{\mathrm{d}} = 1$). The price of this bearing was 24.8 MU ($\varphi_{\mathrm{P}} = 1$). The current price for a deep groove ball bearing 6007 with $d = 35$ mm is 18.33 MU. To find the price for bearing 6036 with $d = 180$ mm the procedure is as follows:

	Name No	Density ρ g/cm³	Young's modulus E N/mm²	Yield strength σ_Y N/mm²	Tensile strength σ_T N/mm²	Strain to failure σ_F %	E/E_{St37}	σ_T/σ_{St37}	C^*_W	C^*_V	$\frac{C^*_W}{\sigma_T/\sigma_{TSt37}}$ 7	$\frac{C^*_W}{E/E_{St37}}$	Relative costs for machining
General construction steels DIN 17100	USt37-2 1.0112	7.85	$2.15 \cdot 10^5$	215...235	360...440	25	1	1	1	1	1 - 0,82	1	1
	St50-2 1.0532	7.85	$2.15 \cdot 10^5$	275...295	490..590	20	1	1.36...1.64	1.1	1.1	0.81 - 0.67	1.1	1
Cold drawn DIN 1652	St37-2K+G 1.0161	7.85	$2.15 \cdot 10^5$	195...215	330...440	25	1	0.92...1.22	1.6	1.6	1.75 - 1.31	1.6	1
Machining steels DIN 1651	10S20K+N 1.0721	7.85	$2.10 \cdot 10^5$	195..225	340...350	25	0.98	0.94...0.97	1.9	1.9	2.01 - 1.95	1.94	0.73
	9SMn28K+N 1.0715	7.85	$2.10 \cdot 10^5$	205...235	350...370	23	0.98	0.97...1.03	1.8	1.8	1.85 - 1.75	1.89	
	45S20K+N 1.0727	7.85	$2.10 \cdot 10^5$	305...335	570...700	14	0.98	1.58...1.94	2	2	1.26 - 1.03	2.05	
Tempering steels DIN 17200	Ck35V 1.1181	7.85	$2.15 \cdot 10^5$	295...420	490...770	22...17	1	1.36...2.14	1.6	1.6	1.18 - 0.75	1.6	0.91
	Ck45V 1.1191	7.85	$2.15 \cdot 10^5$	380	630...780	17	1	1.75...2.17	1.78	1.78	1.02 - 0.82	1.78	1.05
	34Cr4V 1.7033	7.85	$2.15 \cdot 10^5$	470	700...850	15	1	1.94...2.36	2.13	2.13	1.1 - 0.9	2.13	1.43
	42CrMo4V 1.7225	7.85	$2.15 \cdot 10^5$	650	900...1100	12	1	2.30...3.05	2.24	2.24	0.9 - 0.73	2.24	1.73
	50CrV4V 1.8159	7.85	$2.15 \cdot 10^5$	700	900...1100	12	1	2.50...3.05	2.25	2.25	0.9 - 0.74	2.25	2.09
	C35K+N 1.0501	7.85	$2.15 \cdot 10^5$	275	490...590	22	1	1.36...1.64	1.7	1.7	1.25 - 1.04	1.7	
	Ck35K+V	7.85	$2.15 \cdot 10^5$	325...410	540...790	20...16	1	1.50...2.19	1.85	1.85	1.23 - 0.84	1.85	

Figure 11.2. Characteristic values and relative material costs c^* for some materiels (Reference Ust 37.2 with $\sigma_T = 360$ N/mm²)

Case hardening steels DIN 17210	C15 1.0401	7.85	$2.15 \cdot 10^5$	355...440	590...890	14...12	1	1.64...2.47	1.1	1.1	0.67 - 0.45	1.1	0.86
	Ck15 1.1141	7.85	$2.15 \cdot 10^5$	355...440	590...890	14...12	1	1.64...2.47	1.4	1.4	0.85 - 0.57	1.4	
	16MnCr5G 1.7131	7.85	$2.15 \cdot 10^5$	440...635	640...1190	11...9	1	1.78...3.30	1.7	1.7	0.96 - 0.51	1.7	1.14
Nitriding steels DIN 17211	34CrAlNi7V 1.8550	7.85	$2.15 \cdot 10^5$	590	780...980	13	1	2.17...2.72	2.6	2.6	1.2 - 0.95	2.6	2.0
	41CrAlMo7V 1.8509	7.85	$2.15 \cdot 10^5$	635...735	830...1130	14...12	1	2.30...3.14	2.6	2.6	1.13 - 0.83	2.6	
	31CrMoV9 1.8519	7.85	$2.15 \cdot 10^5$	700	900..1050	13	1	2.50...2.92					2.0
Stainless steels DIN 17440	X20Cr13 1.4021	7.70	$2.10 \cdot 10^5$	440...540	640...940	18...8	0.99	1.78...2.61	3.14	3.2	1.8 - 1.2	3.21	1.25
	X12CrNi188 1.4300	7.80	$2.03 \cdot 10^5$	220	500...700	50	0.94	1.39...1.94	8.45	8.4	6.08 - 4.35	8.95	
Casting materials without cores and recesses	GG - 25 0.6025	7.35	$1.30 \cdot 10^5$		250		0.60	0.69	2.0	1.2	2.88	3.3	1.24
	GS - 45 1.0443	7.85	$2.15 \cdot 10^5$	225	445...590	22	1	1.24...1.64	1.8	1.8	1.46 - 1.1	1.8	1.45
Non-ferrous metals	AlMg3F23 3.3535.26	2.66	$0.70 \cdot 10^5$	140	230	9	0.33	0.64	10.0	3.4	15.65	30.7	0.36
Light metals	AlMg5F26 3.3555.26	2.64	$0.72 \cdot 10^5$	150	250	8	0.33	0.69	11.6	3.9	16.70	34.6	
	AlMgSi1F32 3.2315.72	2.70	$0.7 \cdot 10^5$	250	310	10	0.33	0.86	8.72	3.0	10.13	26.8	0.51
Non-metals	Woven laminate Hgw 2088	1.25	$7 \cdot 10^3$		50		0.033	0.14	62.8	10	452.2	1928	(0.4)
	Glass fibre reinforced polyester HM 2472	1.60	$10 \cdot 10^3$		100		0.046	0.28					(0.71)
	Nylon 66 PA 66	1.14	$2 \cdot 10^3$		65		0.009	0.18	22.72	3.3	125.8	2442	(0.27)

Figure 11.2. (continued)

$d = 35\,\text{mm} \quad \varphi_\text{d} = 35/50 = 0.7 \quad \text{from Figure 11.5: } \varphi_{\text{P}_{6007}} = 0.61$

$d = 180\,\text{mm} \quad \varphi_\text{d} = 180/50 = 3.6 \quad \text{from Figure 11.5: } \varphi_{\text{P}_{6036}} = 28$

$P_{6036} = P_{6007} \quad (\varphi_{\text{P}_{6036}}/\varphi_{\text{P}_{6007}}) = 18.33(28/0.61) = 841\,\text{MU}$

Diagrams for screws, circlips, connectors and valves are given in [11.26, 11.27]. Figure 11.6 shows a cost comparison for different threaded connectors based on [11.5]. As described in Sections 11.3.4 and 11.3.5, the cost relations can vary with size and this can be seen in Figure 11.6.

Relative cost data has to be applied with caution, taking into account all the relevant circumstances [11.1]. When comparing and selecting items, not only must the cost relations be assessed but also the required functions, the application conditions and the space requirements. Extrapolations are generally are not allowed. It is not sufficient simply to compare the costs of items without considering their effect on the rest of the design.

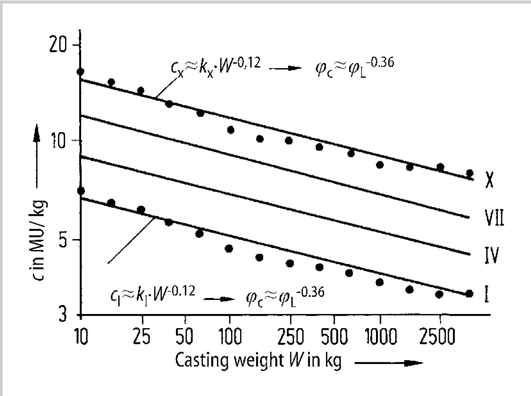


Figure 11.3. Costs for steel castings depending on weight per casting and level of complexity, after [11.27]. Level I: Solid castings without cores and recesses; Level IV: Solid castings with simple cores and recesses; Level VII: Hollow castings (cored) with simple webs and recesses; Level X: Hollow castings (cored) with complex cores

Section	Round 100 DIN 1013	Square 85 DIN 1014	L160 × 17 DIN 1028	Pipe 159×5.6 DIN 2448	U 160 DIN 1026	I 160 DIN 1025
H/A in mm	12.5	14.1	20.8	37	48.3	54
I/A in mm²	625	601	2374	2944	3854	4323
c_w^* rolled	1	1.02	1.06	1.6 - 2.1	1	1
c_w^* drawn	1.6	1.6		2.8		

Figure 11.4. Specific material costs c_w^* for semi-finished materials. The reference first moment of area is $H \approx 10^5\,\text{mm}^3$ (the first moment of area of round 100 and of square 85). H/A: ratio of first moment of area/section area. I/A: ratio of second moment of area/section area

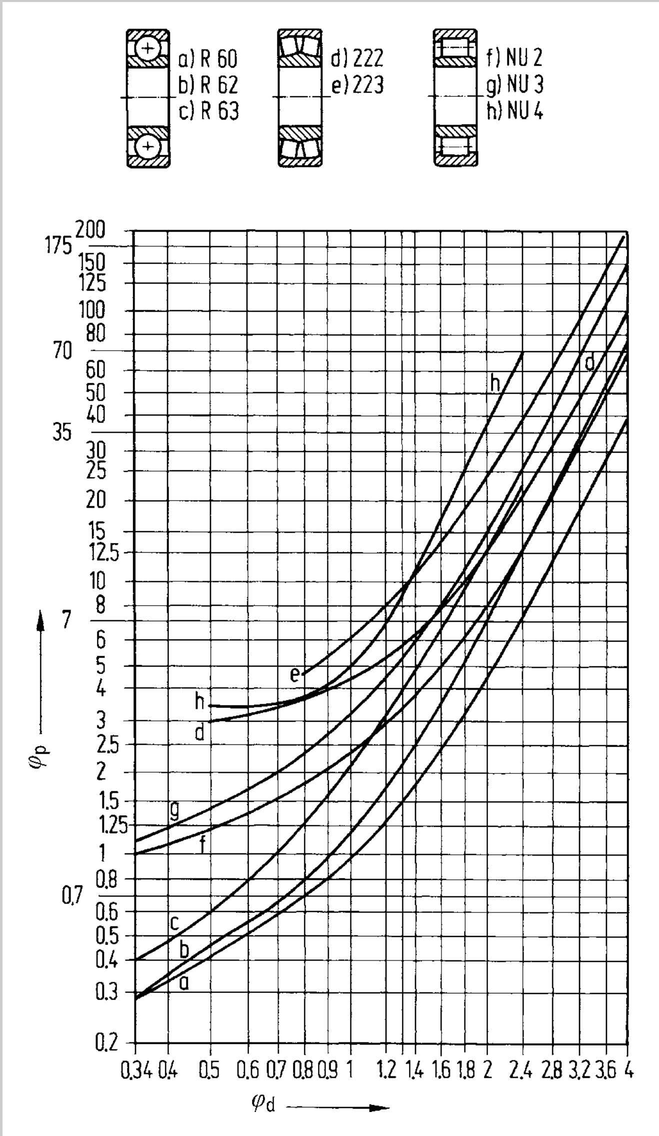


Figure 11.5. Relative costs for rolling element bearings, after [11.27]. Reference: a deep groove ball bearing from series 60 with $d = 50$ mm ($\varphi_d = 1$) and $P = 24.80$ MU ($\varphi_P = 1$)

11.3.2 Estimating Using Share of Material Costs

If in a particular application area the ratio *m* of material costs *MtC* to the manufacturing cost *MfC* is known and almost identical, it is possible to estimate the manufacturing cost after determining the material costs, *MfC* = *MtC*/*m*. This procedure is described in VDI Guideline 2225 [11.33]. The procedure cannot be used,

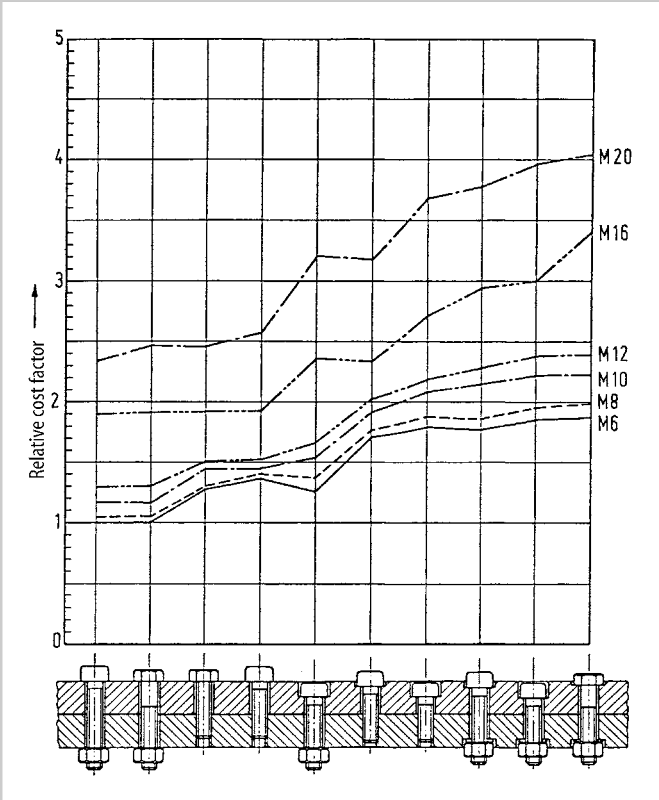


Figure 11.6. Relative cost factors for threaded connections using cap screws and hexagonal bolts, M6 to M20, class 8.8, after [11.5, 11.6]

however, when the cost structure changes, in particular with large size changes (see cost estimation using similarity relations in Section 11.3.4 and cost structures in Section 11.3.5).

11.3.3 Estimating Using Regression Analysis

Based on a statistical analysis of data, the relation between costs or prices and the characteristic parameters (output, weight, diameter, shaft height, etc.) are determined. The results can be presented graphically for each of these parameters. Regression analysis is used to find a relation that determines the regression equation using regression coefficients and exponents. Using this equation the costs can be calculated within certain limits. The effort needed to set up the equation can be considerable and usually involves computer support. The regression equation should be built up in such a way that parameters that may change, such as hourly labour rates, are represented as individual terms, or in the form of relative costs, so that they can be updated easily.

An example is the regression equation of Pacyna [11.23] for the cost of hand-moulded grey iron castings:

$$C = 7.1479 \cdot B^{-0.0782} \cdot V^{0.8179} \cdot D^{-0.1124} \cdot T^{0.1655} \cdot P^{0.1786} \cdot N^{0.0387} \cdot \sigma_{\mathrm{T}}^{0.2301} \cdot F^{1.0000}$$

in MU per unit, with:

C = *DMtC*, direct material costs of the cast item
B = batch size
V = material volume in litres
D = dimension ratio (see Figure 11.7)
T = wall thickness ratio (see Figure 11.7)
P = packing ratio (see Figure 11.7)
N = number or cores (without cores = 0.5)
σ_{T} = tensile strength in N/mm^2
F = factor of difficulty (normal = 1, main range 0.9 to 1.4).

This equation might need updating. Further guidelines for this procedure and examples of regression calculations can be found in [11.11–11.13] and in VDI Guideline 2235 [11.35].

Regression analyses can also be used to set up more easily maintainable *cost functions* by introducing simplifications and similarity considerations (see Section 11.3.4). The following example from Klasmeier [11.18] shows the calculation

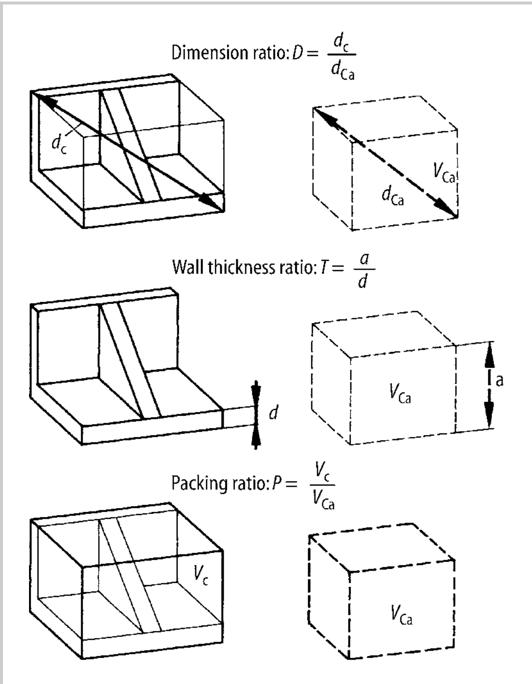


Figure 11.7. Shape characteristics for casting [11.23]. The reference shape is a cube with casting volume V_{Ca}

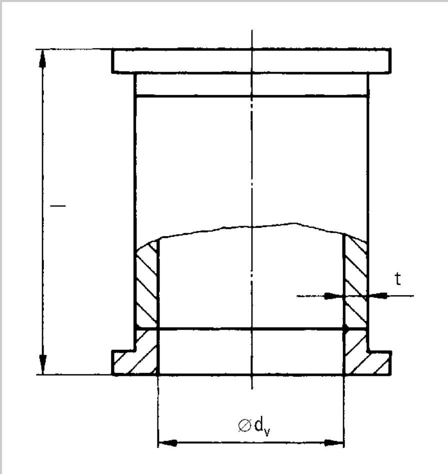


Figure 11.8. Geometric parameters of a pressure vessel for a high-voltage switch. Inner diameter of the vessel d_v. Length of the vessel l. Wall thickness of the vessel t. Nominal pressure NP

of the costs for a pressure vessel for a high-voltage switch. The influencing parameters on the variable costs are shown in Figure 11.8.

The regression equation for welded pressure vessels is:

$$VMfC = a + b \cdot d_v^{1.42} \cdot NP^{0.94} \cdot l^{0.21} \cdot t^{0.17}$$

The factors a and b cannot be given because they are commercially sensitive.

We will now derive a specific simple cost function. Based on electro-technical laws: Voltage V is proportional to the distance between electrodes e, which in turn is proportional to the inner vessel diameter d_v, thus

$$V \propto e = k_1 \cdot d_v$$

Where k_1 takes into account the conductor dimensions and the safety distance with constant gas pressure and constant temperature.

For thin-walled vessels, such as the one discussed here, the standard thin-walled formula can be applied. Because the calculated wall thickness based on the required strength remains below the prescribed minimum wall thickness, we can take $t = t_{min}$ = constant. We can also take l = constant, because the allowable voltage is independent of the vessel length. In this way we can base the cost function simply on the variable parameter voltage:

$$VMfC = a_1 + b_1 \cdot V^{1.42}$$

11.3.4 Extrapolating Using Similarity Relations

1. Basic Design as Reference

When geometrically similar or semi-similar components are available in a size range or as variants of known components, it is useful to determine the cost-growth laws using similarity relations [11.27]. The step size of the variable manufacturing cost φ_{VMfC} is equal to the ratio of the variable cost of the *sequential design* $VMfC_s$ (cost to be calculated) to the variable cost of the *basic design* $VMfC_0$ (known cost) and is calculated using a similarity analysis (see Section 9.1.1):

$$\varphi_{\mathrm{VMfC}} = \frac{VMfC_s}{VMfC_0} = \frac{DMtC_s + \sum PLC_s}{DMtC_0 + \sum PLC_0}$$

The basic design (Index 0) is selected such that it can represent the largest possible size range. When the size of this design places it roughly in the centre of the range, the extrapolation errors are minimised. For the extrapolation to be valid, the sequential design should have sufficient similarity to the basic design in terms of production facilities, production processes etc.

The ratio of direct material costs to the manufacturing cost, and the ratio of the individual production costs or times (for example drilling, turning, grinding, etc.) to the manufacturing cost are calculated for the basic design and result in the following:

$$a_{\mathrm{m}} = \frac{DMtC_0}{VMfC_0}\,; \quad a_{\mathrm{P_k}} = \frac{PLC_{\mathrm{k_0}}}{VMfC_0} \quad \text{for the } k\text{-th production operation}\,.$$

The ratios defined in this way are part of the variable manufacturing costs and represent the cost structure of the basic design (see Section 11.3.5).

When the cost-growth laws of the individual terms are known, the overall cost-growth law is:

$$\varphi_{\mathrm{VMfC}} = a_{\mathrm{m}} \cdot \varphi_{\mathrm{DMtC}} + \sum_k a_{\mathrm{P_k}} \cdot \varphi_{\mathrm{PLC_k}}$$

When the length is the dependent characteristic parameter, this can be written generically as follows:

$$\varphi_{\mathrm{VMfC}} = \sum_i a_{\mathrm{i}} \cdot \varphi_{\mathrm{L}}^{x_{\mathrm{i}}}\,, \quad \varphi_{\mathrm{L}} = \frac{L_{\mathrm{s}}}{L_0} \quad \text{(see Section 9.1.1) with} \sum_i a_{\mathrm{i}} = 1 \text{ and } a_{\mathrm{i}} \geq 0$$

This procedure is not company specific. The results can be made company specific through the introduction of coefficient a_{i} derived from the basic design. This also ensures the use of up-to-date knowledge.

Determining exponents x_{i} that depend on the appropriate dimensions (characteristic parameter length) is easy for *geometrically similar components*. According to [11.27] one can use integer exponents for making *quick estimates*. This results in the following polynomial:

$$\varphi_{\mathrm{VMfC}} = a_3 \cdot \varphi_{\mathrm{L}}^3 + a_2 \cdot \varphi_{\mathrm{L}}^2 + a_1 \cdot \varphi_{\mathrm{L}}^1 + \frac{a_0}{\varphi_{\mathrm{z}}} \quad \text{with} \quad \varphi_{\mathrm{z}} = \frac{z_{\mathrm{s}}}{z_0}$$

with z = batch size.

For material costs one can usually apply $\varphi_{\mathrm{DMtC}} = \varphi_{\mathrm{L}}^3$. For production operations Figure 11.9 can be used [11.26, 11.27].

Machine types	Processes	Exponents calculated	Exponents rounded	Accuracy
Universal lathe	External and internal turning Threading Parting Groove turning Chamfer turning	2 ≈1 ≈1.5 ≈1	2 1 1 1	+ + + + +
Vertical boring and turning mill	External and internal milling	2	2	+ +
Radial drill	Drilling Threading Counter sinking	≈1	1	0
Drilling and milling machine	Turning Drilling Milling	≈1	1	0
Groove milling machine	Key groove milling	≈1.2	1	+
Universal cylindrical grinding machine	Surface grinding	≈1.8	2	+ +
Disc saw	Sawing section	≈2	2	0
Guillotine shears	Cutting sheet metal	1.5...1.8	2	+
Plate bending machine	Bending sheet metal	≈1.25	1	+
Press	Straightening section	1.6...1.7	2	+
Chamfering machine	Chamfering sheets	1	1	+ +
Flame cutting machine	Cutting sheets	1.25	1	+ +
MIG arc and manual electric arc welding	I-welds V, X, fillet, corner welds	2 2.5	2 2	+ + + +
Annealing		3	3	+ +
Sand blasting (depending on using weight or surface in the calculation)		2 o. 3	2 o. 3	+ +
Assembling		1	1	+ +
Tacking before welding		1	1	+ +
Trimming or cleaning by hand		1	1	+ +
Enamelling or coating		2	2	+ +

Figure 11.9. Exponents for the time per item for various production operations for geometrically similar items, after [11.26, 11.27]; Legend: ++ accurate; + less accurate ++; 0 large deviations possible

The terms a_i are calculated from the basic design and assigned to the individual integer exponents. The cost-growth law for the example shown in Figures 11.10 and 11.11 with $\varphi_z = 1$ becomes:

$$\varphi_{VMfC} = 0.49 \cdot \varphi_L^3 + 0.26 \cdot \varphi_L^2 + 0.20 \cdot \varphi_L + 0.05$$

A geometrically similar variant that is twice as large with $\varphi_L = 2$ would give a cost increase with step size $\varphi_{VMfC} = 5.41$.

This procedure can also be used for a more *precise extrapolation* and for *semi-similar variants* as shown in the following example of a drive shaft (see Fig-

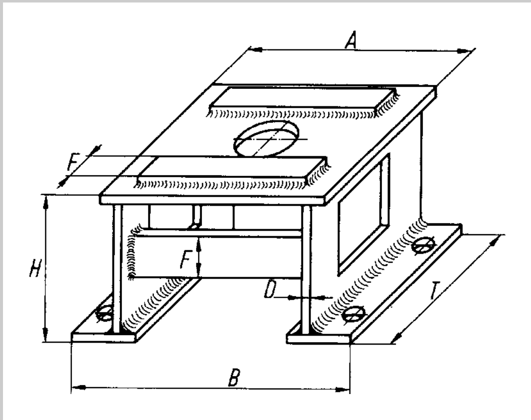


Figure 11.10. Basic design (welded) for geometrically similar series [11.27]

Operations	Costs increase with $\varphi_L{}^3$	Costs increase with $\varphi_L{}^2$	Costs increase with φ_L	Constant costs
material	800			
flame cutting (joining)			60	15
chamfering (joining)			35	
tacking (joining)			105	
welding (joining)		500		
annealing	80			
sand blasting	40			
marking out (machining)			40	
horizontal boring (machining)			100	70
radial drilling (machining)			30	15
1890 MU $= C_0$	Σ_3 (=920)	Σ_2 (=500)	Σ_1 (370)	Σ_0 (100)
	Σ_3/C_0 $a_3=0.49$	Σ_2/C_0 $a_2=0.26$	Σ_1/C_0 $a_1=0.20$	Σ_0/C_0 $a_0=0.05$

Figure 11.11. Calculation scheme for determining cost contributions a_i to the basic design

ure 11.12). The product is a friction-welded shaft journal, with main dimensions *d* and *l*, with two drop-forged disc-shaped elements welded together to form a cylinder. The component is finally turned to size.

The characteristic parameters cylinder diameter *D* and length *B* can be selected independently. The shaft journal diameter *d* and the journal length *l* have to be chosen in proportion to the cylinder diameter *D*.

The relations between the times and each of the individual geometric parameters was based on an analysis of the primary and secondary times according to [11.24, 11.26, 11.27]. For turning, for example, the primary time is determined by the area of the surface to be turned, represented by the diameter and length of the component. The secondary time is constant for this size range. The welding costs, however, increase in relation to the seam thickness *t*, with $\varphi_t^{1.5}$, and linearly with the welding length *l*, that is with φ_l^1 [11.24]. The preparation cost for welding depends not only on the number of components but also on the square root of the weight which gives $\varphi_W^{0.5}$ or $\varphi_D \cdot \varphi_B^{0.5}$.

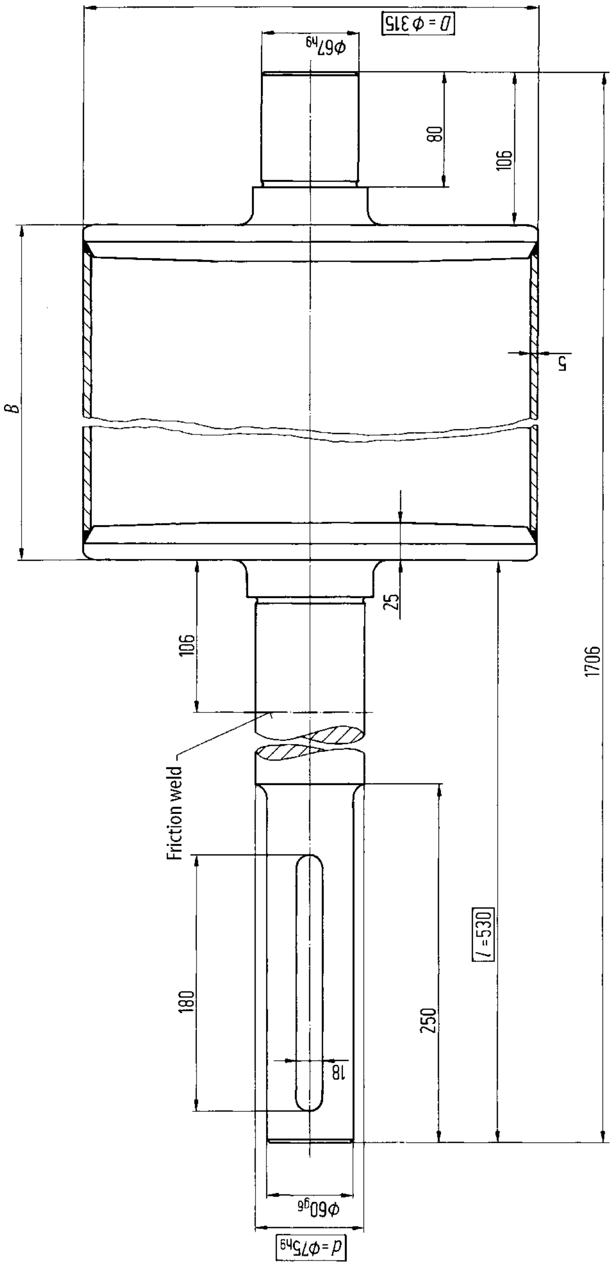


Figure 11.12. Drive shaft (basic design)

Materials, production operations	Cost contributions	Cost growth laws
Materials		
Cylinder	0.164	$\varphi_{cWC} \cdot \varphi_D^2 \cdot \varphi_B$
Disc and journal	0.222	$\varphi_{cWJ} \cdot \varphi_d^2 \cdot \varphi_l$
Constant part	0.070	
Production operations		
Preparing for welding	0.049	$\varphi_{cL} \cdot \varphi_D \cdot \varphi_B^{0.5}$
Welding	0.081	$\varphi_{cL} \cdot \varphi_D^{2.5}$
Trimming, cleaning	0.011	$\varphi_{cL} \cdot \varphi_D$
Turning, cylinder axial	0.054	$\varphi_{cL} \cdot \varphi_D \cdot \varphi_B$
Turning, journal axial	0.097	$\varphi_{cL} \cdot \varphi_d \cdot \varphi_l$
Turning, journal radial	0.038	$\varphi_{cL} \cdot \varphi_d^2$
Turning (constant)	0.114	φ_{cL}
Milling	0.016	$\varphi_{cL} \cdot \varphi_d \cdot \varphi_l$
Milling (constant)	0.021	φ_{cL}
Surface treating	0.021	$\varphi_{cL} \cdot \varphi_D \cdot \varphi_B$
Preparing for surface treatment	0.032	$\varphi_{cL} \cdot \varphi_D \cdot \varphi_B^{0.5}$
Cutting	0.001	$\varphi_{cL} \cdot \varphi_D$
Cutting (constant)	0.009	φ_{cL}
	1.000	

Figure 11.13. Cost contribution for the basic design of the drive shaft (see Figure 11.12); $D = 315$ mm, $B = 1000$ mm, φ_{cW} = step size of the specific material costs, φ_{cL} = Step size of the labour costs

Figure 11.13 lists the cost contributions of the individual operations for a basic design with $D = 315$ mm and $B = 1000$ mm.

When the terms that have the same relations and parameters are brought together, the general form of the differential growth law for our example becomes:

$$\begin{aligned}\varphi_{VMfC} &= 0.164 \cdot \varphi_{cWC} \cdot \varphi_D^2 \cdot \varphi_B + 0.222 \cdot \varphi_{cWJ} \cdot \varphi_d^2 \cdot \varphi_l + \varphi_{cL}(0.081 \cdot \varphi_D^{2.5} \\ &\quad + 0.075 \cdot \varphi_D \cdot \varphi_B + 0.113 \cdot \varphi_d \cdot \varphi_l + 0.038 \cdot \varphi_D^2 + 0.081 \cdot \varphi_D \cdot \varphi_B^{0.5} \\ &\quad + 0.012 \cdot \varphi_D + 0.144) + 0.07\end{aligned}$$

The diagram in Figure 11.14 for the total cost range of the available variants is based on the use of $\varphi_D = \varphi_B = \varphi_d = \varphi_l$ for geometric similarity of the cylinder dimensions, and the use of $\varphi_D = \varphi_d = \varphi_l$ = constant with φ_B being variable for semi-similar variants. The terms φ_{cL} and φ_{cWJ} are constant for all sizes, whereas φ_{cWC} increases with 1.25 when $D = 355$ mm because of a price supplement due to a smaller batch size.

The cost curve for the variable manufacturing costs for a component or assembly size range is, even when drawn using a double logarithmic scale, curved and not linear (see Figure 11.14). The reasons are that the direct costs always include constant parts, such as set-up costs for a specific batch size, and that some costs increase with high powers, such as material costs which increase with the third power of the characteristic parameter length.

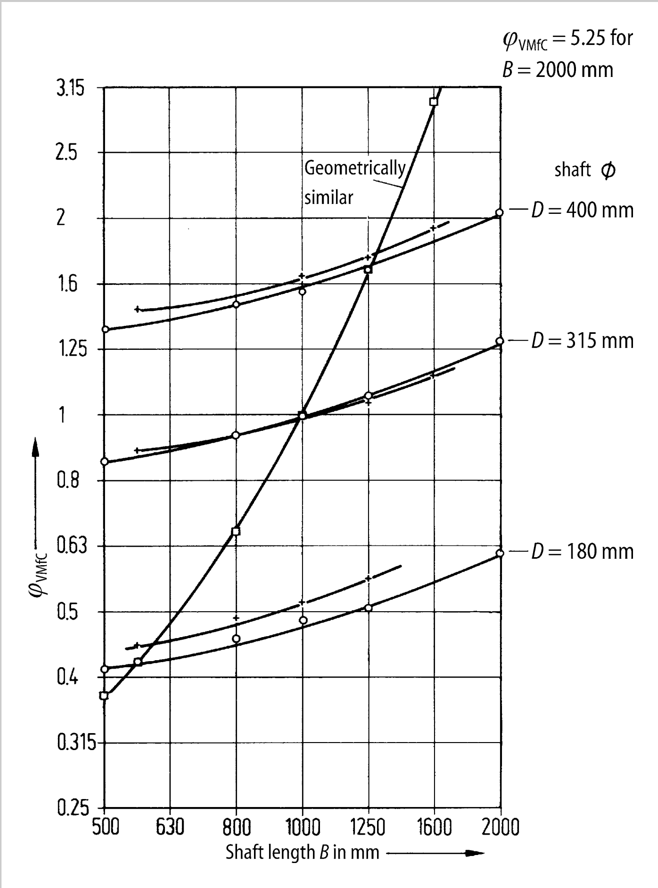


Figure 11.14. Relative manufacturing costs for geometically similar and semi-similar drive shafts as shown in Figure 11.12. Basic design $D = 315$ mm, $B = 1000$ mm. Curves indicated "+" are calculated in the conventional way

The comparison between a conventional calculation and an extrapolation using cost-growth laws shows that the latter gives a sufficiently precise estimate of the costs. The estimation of the manufacturing cost is quite accurate because the large number of individual terms balance out the errors. The error is, in general, smaller than ±10%. The individual operations, however, can have larger errors [11.16, 11.27]. Further examples can be found in [11.18, 11.24, 11.26, 11.27].

2. Operation Element as Reference

According Beelich [11.24] a so-called *operation element* representing a specific production process can be used instead of a basic design. The main idea is to define a normalised, relatively simple element that has be subjected to all the essential partial operations of the specific production operation, for example turning, grinding, welding, etc. The cost of a real component is extrapolated from this simple element. The normalisation involves setting all dimension-determining geometric parameters equal to 1 so that specific production times result. For the operation element, the required production times are determined from the specific technology involved.

The next step is to determine the cost-growth law of this operation element as described before, only now using the step size $\varphi_i = X_{iP}/X_{iO}$ (X_{iP} = parameter of the actual component or part, and X_{iO} = parameter of the operation element).

The use of operation elements is particularly advantageous when one main production operation is involved. On the other hand, operation elements for various different production operations allow extrapolation into complex components and assemblies.

For the production operation "manual electric arc welding" Beelich [11.24] describes the *generation of an operation element*. An analysis of this operation resulted in the following times for the various partial operations.

Times to combine, align and clamp parts into a welding assembly can be determined based on Ruckes [11.29] as follows:

$$t_{\mathrm{wr}} = C_{\mathrm{r}} \cdot \alpha \cdot \sqrt{W} \cdot \sqrt{x}$$

with: α = factor of difficulty (see Figure 11.15)
W = overall weight
x = number of parts.

The primary time for seam welding can be calculated from the time necessary to fill a specific seam volume with a specific volume of electrode as follows [11.24]:

$$t_{\mathrm{ws}} = C_{\mathrm{p}} \cdot t^{1.5} \cdot l$$

with:
t = seam thickness (= plate thickness for a V-weld)
l = seam length.

Type and shape of the seam		V-weld 60°	Fillet weld 90°
Type of construction	Shape of the part Length of the seam		
2D	Tank shape Long seam	1	2
3D	Plate, sheet metal Short seam	1.5	2.5
	Sections such as U, L Pipe	2	3
	Sections such as T, I	2.5	4

Figure 11.15. Factor of difficulty α for normal tolerances and basically right angles. (In case of higher precision and oblique angles, the factors have to be increased by 1 to 2 points.)

The secondary times for changing electrodes and initiating the welding sequence (t_{wci}), and for removing slag and cleaning the seam (t_{wrc}) relate to the number of electrodes n_e and the number of weld runs n. Both parameters can be linked and compared with the volumes and cross-sections of seams and electrodes [11.24]. Analyses also revealed the influence of the factor of difficulty α. It was considered useful to include this factor as a square root:

$$t_{wci} + t_{wrc} = C_s \cdot \sqrt{\alpha} \cdot t^{1.5} \cdot l$$

The material costs of the welding material can be calculated from the specific weld seam weight W_s^* and the specific cost factor c_W:

$$MC_w = W_s^* \cdot t^2 \cdot l \cdot c_W$$

This results in the following formula for the total production cost of welding in MUs:

$$PC_w = c_L \left[C_r \cdot \alpha \cdot \sqrt{W} \cdot \sqrt{x} + \left(C_p + C_s \cdot \sqrt{\alpha} \right) t^{1.5} \cdot l \right] + W_s^* \cdot t^2 \cdot l \cdot c_W$$

For the operation element "manual electric arc welding" (see Figure 11.16), the welding costs can be calculated with the following normalised data and company-specific production times:

$\alpha = 1$ $\quad c_L = 1$ MU/min (labour cost)

$W = 1$ kg $\quad c_W = 10$ MU/kg (specific material cost)

$$\left.\begin{array}{ll} x = 1 & C_r = 1\ \text{min/kg}^{0.5} \\ t = 1\ \text{mm} & C_p = 0.8\ \text{min/mm}^{1.5} \cdot \text{m} \\ l = 1\ \text{m} & C_s = 1.2\ \text{min/mm}^{1.5} \cdot \text{m} \end{array}\right\} \text{Specific production times}$$

$W_s^* = 0.0095\ \text{kg/mm}^2 \cdot \text{m}$

(W_s^* is the specific seam weight with a raised seam of $k_{rs} = 1.21$)

$PC_{w0} = 3.095$ MU

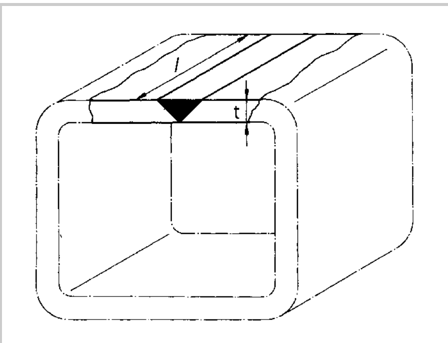


Figure 11.16. Operation element "manual electric arc welding"

With this information, the cost terms for operation element 0 can be calculated as follows:

$$a_{\mathrm{r}} = \frac{PC_{\mathrm{wr0}}}{PC_{\mathrm{w0}}} = \frac{1}{3.095} = 0.32$$

$$a_{\mathrm{sp}} = \frac{PC_{\mathrm{ws0}}}{PC_{\mathrm{w0}}} = \frac{0.8}{3.095} = 0.26$$

$$a_{\mathrm{ss}} = \frac{PC_{\mathrm{wci0}} + PC_{\mathrm{wrc0}}}{PC_{\mathrm{w0}}} = \frac{1.2}{3.095} = 0.39$$

$$a_{\mathrm{m}} = \frac{MC_{\mathrm{w0}}}{PC_{\mathrm{w0}}} = \frac{0.095}{3.095} = 0.03$$

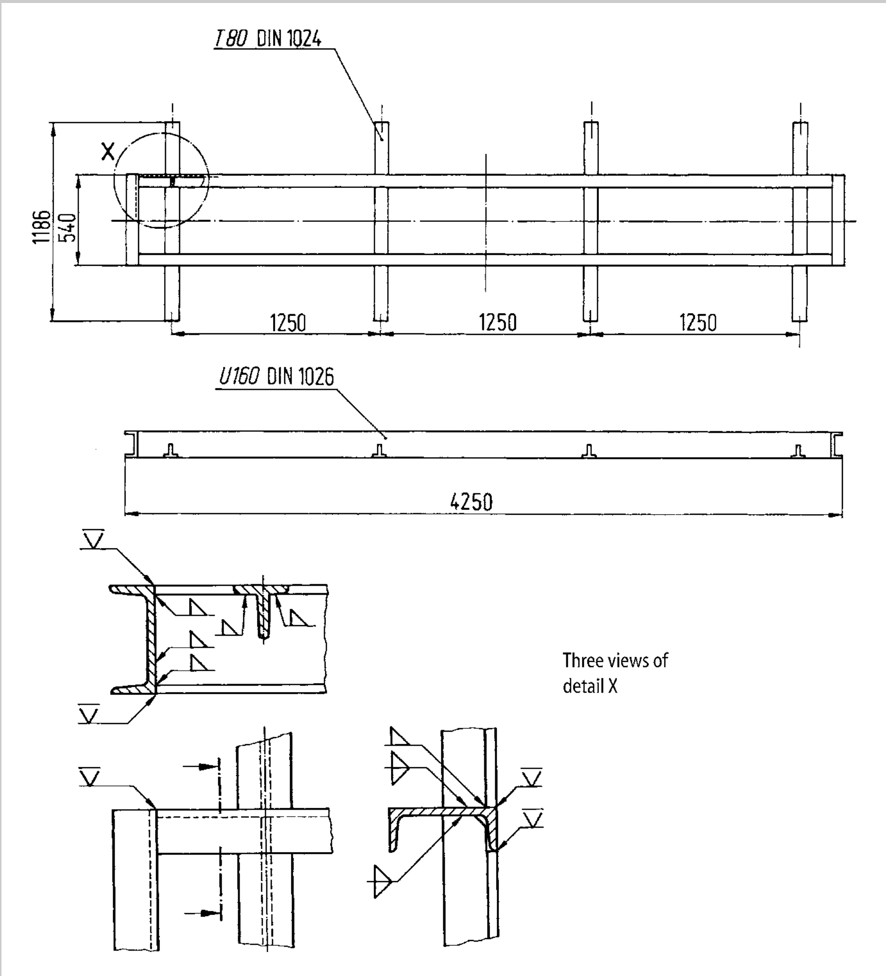


Figure 11.17. Assembly "welded frame"

The resulting cost-growth law for the operation element "manual electric arc welding" thus becomes:

$$\varphi_{\mathrm{PC_W}} = \varphi_{\mathrm{c_L}} \big(\underbrace{0.32 \cdot \varphi_\alpha \cdot \varphi_{\mathrm{W}}^{0.5} \cdot \varphi_{\mathrm{x}}^{0.5}}_{\substack{\text{preparing:}\\ \text{combining}\\ \text{aligning}\\ \text{clamping}}} + (\underbrace{0.26}_{\substack{\text{welding:}\\ \text{seam}\\ \text{welding}}} + \underbrace{0.39 \cdot \varphi_\alpha^{0.5}}_{\substack{\text{changing electrodes,}\\ \text{initiating welding}\\ \text{sequence, removing}\\ \text{slag}}}) \cdot \varphi_{\mathrm{t}}^{1.5} \cdot \varphi_{\mathrm{l}}\big) + \underbrace{0.03 \cdot \varphi_{\mathrm{t}}^{2} \cdot \varphi_{\mathrm{l}} \cdot \varphi_{\mathrm{cW}}}_{\substack{\text{welding}\\ \text{material}}}$$

With this formula the cost of components that have to be welded can be extrapolated using the relevant parameter values to determine step sizes φ.

As an example of how to use this operation element, the cost of the welded frame shown in Figure 11.17 has to be estimated. The welding costs can be calculated with the data for the assembly and the step sizes related to the operation element as shown in Figure 11.18. When the values are substituted into the above equation separately for V-welds and fillet welds, the step size is:

$$\varphi_{\mathrm{PC_W}} = 163.67 \quad \text{(see Figure 11.19)}$$

The manufacturing cost for the production operation "manual electric arc welding" thus becomes:

$$MfC = PC_{\mathrm{w0}} \cdot \varphi_{\mathrm{PC_W}} = 3.095 \cdot 163.67 = 506\ \mathrm{MU}$$

As the equation shows, the thickness of the weld has a large influence. If the V-weld, for example, could be reduced from 10 to 8 mm, this would result in a considerable cost saving, since φ_{W} would be 8 rather than 10. Because of the exponents 2

	Table for welded frame					
Production operations Materials	Labels		Dimensions	Data from the welded assemblies	Data for the operational elements	Step sizes φ
Preparing for welding	Weight of the assembly	W	kg	226	1	226
	Number of parts	x		16	1	16
	Factor of difficulty	α		3	1	3
	Labour cost factor	c_L	MU/min	1	1	1
Seam welding – Fillet weld	Seam thickness	a	mm	4	1	4
	Seam length	l_f	m	4.52	1	4.52
	Factor of difficulty	α		3	1	3
Seam welding – V-weld	Sheet thickness	t	mm	10	1	10
	Seam length	l_V	m	2.44	1	2.44
	Factor of difficulty	α		2	1	2
Welding material	Specific material costs	c_W	MU/kg	10	10	1
Data: 1/85	Author: BI					

Figure 11.18. Table for calculating step sizes

Production operations Materials		Growth laws	Calculations	Stepsizes φ $t=100$mm	$t=8$mm
Preparation		$\varphi_r = 0.32\cdot\varphi_{cL}\cdot\varphi_\alpha\cdot\varphi_W^{0.5}\cdot\varphi_x^{0.5}$	$0.32\cdot1\cdot3\cdot226^{0.5}\cdot16^{0.5}$	57.73	57.73
Welding	Fillet weld	$\varphi_s = (0.26+0.39\cdot\varphi_\alpha^{0.5})\cdot\varphi_t^{1.5}\cdot\varphi_l\cdot\varphi_{cL}$	$(0.26+0.39\cdot3^{0.5})\cdot4^{1.5}\cdot4.52\cdot1$	33.83	33.83
	V-weld		$(0.26+0.39\cdot2^{0.5})\cdot10^{1.5}\cdot2.44\cdot1$	62.62	44.81
Welding material	Fillet weld	$\varphi_m = 0.03\cdot\varphi_t^2\cdot\varphi_l\cdot\varphi_{cW}$	$0.03\cdot4^2\cdot4.52\cdot1$	2.17	2.17
	V-weld		$0.03\cdot10^2\cdot2.44\cdot1$	7.32	4.68
			$\varphi_{PC_W} =$	163.67	143.22

Figure 11.19. Calculating the step size for the welding costs of the operation element for the welded assembly in Figure 11.17

and 1.5 respectively, the values of φ_W and φ_M are lower (see Figure 11.19) and the manufacturing cost is reduced significantly:

$$MfC = 3.095 \cdot 143.22 = 443 \text{ MU}$$

11.3.5 Cost Structures

In the previous discussion it became clear that the *cost structure* changes with the overall dimensions and with semi-similar variants. Dominating are the cost terms that increase with φ_L^3 and φ_L^2 such as material costs and surface finish costs. Figure 11.20 shows the change in manufacturing cost structure in relation to overall dimensions and batch size based on Ehrlenspiel [11.12]. With increasing batch size, the one-off costs and the terms that are independent of the dimensions, which

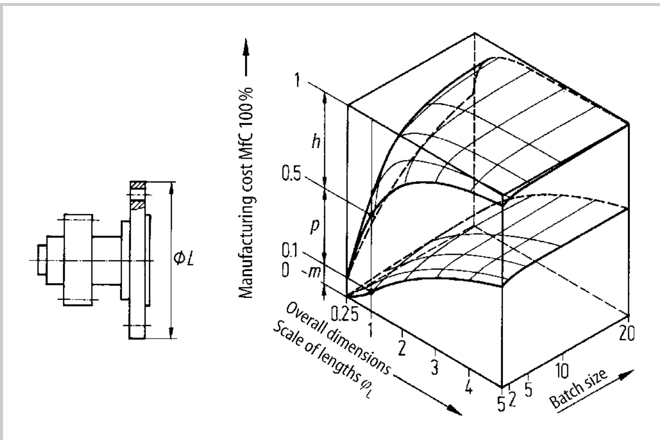


Figure 11.20. Manufacturing cost structure for gear boxes depending on overall dimensions, or length step size φ_L, and batch size, after [11.11, 11.35]. m = material costs contribution, p = production costs contribution, o = costs that occur only once (set-up costs)

are mainly the set-up costs, are reduced. Figure 11.21 shows the cost structure in relation to the overall dimensions for the example shown in Figure 11.10. This figure shows that when the overall dimensions vary from $\varphi_L = 0.4$ to $\varphi_L = 2.5$, i.e. with a factor 6.25, the cost structure changes from an emphasis on production costs to an emphasis on material costs. Cost structures for cast items can be found in [11.14].

Without knowledge of the cost structure, that is, without knowledge of the contributions of direct material costs and production labour costs to the variable

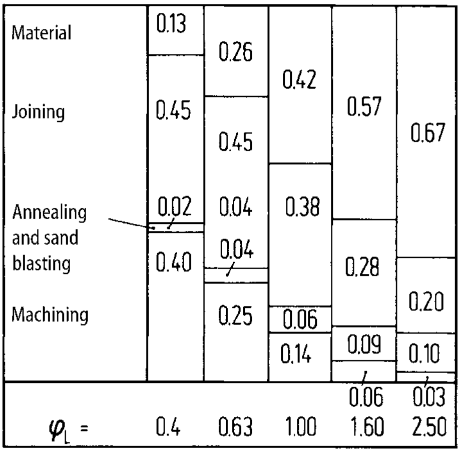


Figure 11.21. Cost structure for the example in Figure 11.10, showing a large change in the contributions of the various factors when the overall dimensions change

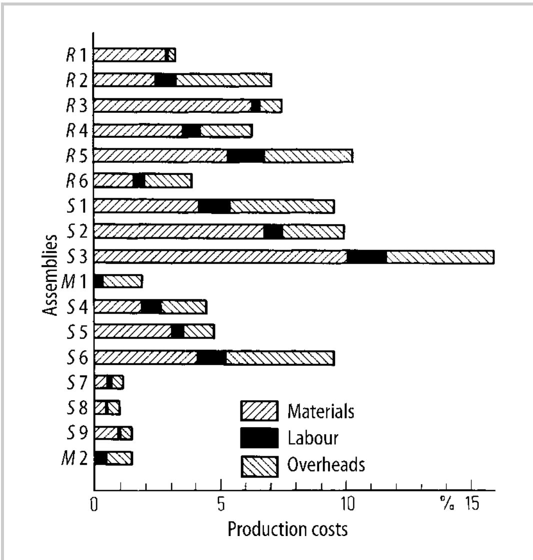


Figure 11.22. Cost structure of a synchronous generator, after [11.19] (Siemens). Examples $R1$: rotor shaft; $R2$: rotor body; $S3$: stator housing; $S5$: bearing; $S6$: spider; $M2$: mountings, etc.

manufacturing costs, designers cannot identify the measures that would lead to cost reduction. Therefore it is important to provide the appropriate data. For original designs, estimates based on rough calculations or similarity relations are useful. For adaptive designs, useful data are final calculations from previous designs.

Figure 11.22 shows an example of the cost distribution for a synchronous generator [11.19]. This shows, for example, that it is not advantageous to redesign rotor shaft *R*1 to reduce production labour costs and indirect production costs. A weight reduction or a more suitable choice of material, however, could lead to substantial cost reductions because of the high contribution of material costs. The situation is different for stator housing *S*3 because the high contribution of indirect production costs indicates advantages in changing the production process by modifying the design.

11.4 Target Costing

The market price and operating costs are the most important criteria for a customer when selecting between competing products and processes. An unfavourable cost situation in the market is often an important reason for new or further developments, even if a product's existing properties are satisfactory. The primary development goal will then be to reduce the manufacturing cost in order to improve the market situation. In such a case, project management will attempt to fulfil specific cost requirements from the start by establishing target costs [11.3, 11.30]. The development process focusing on this type of cost management proceeds more or less as follows.

Following a market analysis (see Section 3.1.4), an attractive selling price is established that is in line with customer expectations and compares favourably with competing products. Taking into account profit and internal overheads (see Figure 11.1), the acceptable but allowable manufacturing cost is estimated. As far as possible and where identifiable the overall manufacturing cost is broken down into the different functional groups or assemblies to enable target costs for individual subsystems to be set. A comparison with the manufacturing cost of the existing product then shows which individual cost elements have to be reduced. If necessary, operating costs are included in an appropriate way.

Compared to conventional product development, the manufacturing cost is not determined retrospectively, in the sense of a cost evaluation, but given as target costs for the subsystems to control the development of solutions [11.4, 11.9]. The derived permissible manufacturing cost is thus an important development goal. Similar to Value Analysis (see Section 1.2.3 and [11.8, 11.32, 11.38]), existing functions, features and construction methods are questioned. If possible, functional improvements, performance gains and material reductions, etc. should be considered to increase the product's attractiveness while at the same time lowering costs.

Opportunities for cost reduction can, in particular, be found in those subsystems (function groups or assemblies) that contribute significantly to the overall cost, and that offer the potential for considerable cost reduction through changing, for example, the task, the principle solution, the embodiment, the materials, the production processes and the assembly methods. The main priority remains the fulfilment of customer expectations regarding the combination of functionality, reliability and attractiveness for a favourable price and low operating costs. Ehrlenspiel gives in [11.9, 11.15] an instructive example for the original development of a concrete mixer based on target costing.

It will be clear, that Target Costing can only be successful when applied by a *development team* that includes all those involved in the product creation process, similar to the approach adopted for Simultaneous Engineering (see Section 4.3) or Value Analysis (see Section 1.2.3). The application of the methods of cost estimation and minimisation proposed in this chapter facilitates the realisation of the target costs at an early stage, e.g. during the search and selection of solutions.

An interesting application of Target Costing for modular systems is proposed in the dissertation of Kohlhase [11.20]. For the individual modules and for their combinations, the projected permissible costs are determined by splitting the target cost. These costs comprise production costs and recurring process costs. Using neural nets, the reciprocal influences are captured and taken into account. If sufficient data are available, it is possible to determine economic module combinations based on the demands.

11.5 Rules for Minimising Costs

In addition to the statements made in Sections 7.5.8 and 7.5.9, the following general rules to minimise costs can be stated [11.11, 11.13, 11.35]:

- Aim for low complexity, that is, a low number of parts and few production processes.
- Aim for small overall dimensions to reduce material costs, because these costs increase disproportionately with size, most frequently diameter.
- Aim for large numbers (large batch sizes) to spread the once-only costs, because, for example, set-up costs can be spread, high performance production processes can be used, and benefits of repetition can be exploited.
- Aim for minimising precision requirements, that is, specify, where possible, large tolerances and rough surface finishes.

In applying these rules one has to take into account the task and the size of the artefact.

With respect to costs, it has been shown that the economic viewpoint does not have to contradict the environmental viewpoint, in fact they can be mutually supportive [11.2]. This is particularly true when energy and material reducing measures are taken into account during the search for solutions and their embodiment. This results both in a reduction of costs and a reduction of resources and environmental load. This is illustrated with the following checklist.

Save energy by:

- avoiding energy transformations (see Section 6.3: establishing function structures)
- reducing flow losses
- reducing friction losses (see Section 7.4.1: principle of balanced forces)
- using waste energy (see Section 7.4.3: principle of self-help)
- using machine sizes suitable for the process
- dividing the system into subsystems to achieve a higher overall efficiency
- using machine components with reduced losses.

Save material by:

- selecting suitable materials (see Section 11.3.1: relative costs)
- adopting tension/compression force transfer (see Section 7.4.1: principle of short and direct force transmission paths)
- selecting the best sections for the loading (see Section 11.3.1: relative costs)
- distributing and channelling flows effectively (see Section 7.4.2: principle of division of tasks)
- increasing speed
- adopting integral construction and function integration (see Section 7.3.2: simplicity and Section 7.5.7: design for production)
- avoiding overdesign while maintaining safety (see Section 7.3.3: safety, fail-safe principle)
- producing components using material-saving processes such as casting, forging, deep drawing, etc.

12 Summary

12.1 The Systematic Approach

After examining the historical background, the fundamentals and generally applicable problem solving and evaluation methods, this book describes the product development process, starting with product planning and clarification of the task and proceeding to the conceptual and embodiment design phases. The generic solutions chapter provides stimulation for the search for solutions. To reduce development effort, approaches for developing size ranges and modular systems are introduced. The methods for quality assurance and cost estimation help increase customer satisfaction and improve market competitiveness.

Conceptual design and *embodiment design* are the two crucial phases in the creation of technical products and systems. Their respective steps are shown in Figures 12.1 and 12.2, where the various methods are correlated with their main or supporting applications (see [12.11] for an overview of methods). The figures also chart the *progress* of engineering design work and the *importance* and the *timing* of the various methods. Tasks and problems differ from product to product, and the approach and use of the methods is influenced by the branch of engineering and the characteristics of each company. This can lead to differences in the sequence of the working steps, the applications of the methods, and the uses of the terminology. The approach proposed in this book should be adapted flexibly without neglecting the underlying philosophy of the systematic approach and the various methods. In addition, not all problems or all working steps require every applicable method to be utilised.

The various methods should only be applied when they are required and useful for a particular objective. Work should never be done for the sake of systematics or for pedantic reasons alone. Depending on their inclinations, experiences and skills, designers will tend to prefer certain methods. This is particularly true when several methods are appropriate for a particular step, as it helps switch between different viewpoints and thinking levels. Switching can be achieved by large jumps forward (executing concrete steps early in the process) and subsequently returning to the original step (analysing the results and creating new ideas). When searching for solutions, switching between thinking levels plays a particularly important role. The adaptation and selection of suitable methods requires knowledge about these methods and some experience of their application. This means that methods have to be learnt and practised.

Steps / Methods (● main, ○ supporting)			Product planning Selecting the task	Clarifying the task Setting up the requirements list	Abstracting to identify essential problems	Establishing function structures	Searching for working principles	Combining working principles	Selecting suitable combinations	Firming up into principle solutions	Evaluating principle solutions
Trend studies Market analysis		3.1	●	○							
Requirements list		5.2		●	○						
Abstraction		6.2			●	○					
Black box representation Function structure		6.3			○	●					
Literature search		3.2.1	○	○			●			○	
Analysis	natural systems	3.2.1				○	●				
	known solutions	3.2.1.		○		●	●	●		○	
	mathematical – physical relationships	3.2.1				●	●				
Tests, measurements		3.2.1					●	●		●	
Brainstorming, Gallery method, Synectics		3.2.2.	○				●				
Systematic study of physical processes		3.2.3					●				
Classification schemes		3.2.3					●	●			
Design catalogues		3.2.3					●	●			
Sketches Intuitive improvements		6.5.1					○	●		●	
Selection methods		3.3.1				○	○	●	●	○	
Evaluation methods		3.3.2									●
Quality assurance methods		10						○	○	●	●
Costing methods		11							○		●
Value analysis		1.2.3							○		○

Figure 12.1. Correlation of methods with the various steps of the conceptual design phase (numbers refer to chapters and sections)

The ability to abstract, to work systematically and to think logically and creatively complement the professional knowledge of designers. In the various design steps, these abilities are demanded to varying degrees. *Abstraction* is needed particularly for identifying essential problems, for setting up function structures,

Methods (● main, ○ supporting) \ Steps		Identifying embodiment-determining requirements	Specifying spatial constraints	Identifying main function carriers	Developing preliminary layouts of main function carriers	Selecting suitable preliminary layouts	Developing preliminary layouts for the remaining main function carriers	Searching for solutions to auxiliary function carriers	Developing detailed layouts of main function carriers	Developing detailed layouts of auxiliary function carriers	Evaluating preliminary layout	Preparing definitive layout	Checking for errors and disturbing factors	Preparing preliminary parts list and production documents
Requirements list	5.2	●	●								○		○	
Function structure	6.3			●										
Solution concept	6	●	●	●	○		○							
Solution methods Generic solutions	4 8							●						
Checklist	7.2				●	○	●		●	●				
Basic rules: simplicity, clarity, safety	7.3				●	○	●	○	●	●	○	○	○	○
Principles Force transmission Divison of tasks Self-help Stability and bistability Fault-free design	7.4			●	●		●	○	○					
Guidelines Durability (Stress) Deformation Stability Resonance Expansion Creep Relaxation Corrosion Wear Ergonomics Aesthetics Standards Production Assembly Quality control Transport Operation Maintenance Recycling	7.5				○		○		●	●		●		●
Selection methods	3.3.1					●		●						
Quality assurance Risk reduction	10 7.5.12										○	●	●	
Cost identification	11					○					●			
Evaluation methods	3.3.2 7.6							○			●			

Figure 12.2. Correlation of methods with the steps of the embodiment design phase (numbers refer to chapters and sections)

for determining the characteristics of classification schemes and for applying the principles and rules of embodiment design. *Systematic and logical thinking* help in elaborating function structures, in setting up classification schemes, in analysing systems and processes, in combining elements, in identifying faults, and in evaluating solutions. *Creative ability* helps in varying function structures, in searching for solutions with the help of intuitive methods, in combining elements with the help of classification schemes or design catalogues, and in applying the basic rules, principles and guidelines. *Professional knowledge* is needed particularly for drawing up requirements lists, for searching for weak links, for selecting and evaluating, and for checking using the various checklists and fault-tracing methods.

Experience with the use of methods supports the planning and monitoring of the product development process. Domain-specific experience helps focus on and

Task clarification	Conceptual design		Embodiment design	
Setting up the requirements list	Selecting	Evaluating	Embodying	Evaluating
Determining requirements	Identifying the best combination of principles	Discovering optimum concept	Checking embodiment Determining layout, forms and materials	Identifying optimum embodiment
(Figure 5.3)	(Figure 3.27)	(Figure 6.22)	(Figure 7.3)	(Figure 7.148)
Geometry	Compatible with the overall task	Function	Function	Function, working principle
Kinematics		Working principle	Working principle	Layout desgin
Forces	Fulfils demands of the reqirements list	Embodiment	Layout Durability Deformation Stability Resonance Expansion Corrosion Wear	Form design
Energy				
Material	Realisable in principle			
Signals				
Safety	Incorporates direct safety measures	Safety	Safety	Safety
Ergonomics		Ergonomics	Ergonomics	Ergonomics
Production		Production	Production	Production
Quality control		Quality control	Quality control	Quality control
Assembly	Preferred by designer's company	Assembly	Assembly	Assembly
Transport		Transport	Transport	Transport
Operation		Operation	Operation	Operation
Maintenance	Within permissible costs	Maintenance	Maintenance	Maintenance
Recycling		Recycling	Recycling	Recycling
Costs		Costs	Costs	Costs
Schedules			Schedules	Schedules

Figure 12.3. Summary of checklists with main characteristics and related working steps

speed up finding solutions, and "separate the wheat from the chaff". Frankenberger [12.5] observed in his research that experience does have a large positive effect but can also have a negative effect when that experience leads to inflexibility and fixation.

Figure 12.3 lists the *guidelines* and their main characteristics that support the creative and corrective activities in the various design phases. The lists are in accordance with the general suggestions given in Section 2.1.7, and ensure that the technical function is implemented economically and safely. To find solutions, the relationships between function structure, working structure and construction structure should be considered, as well as the general and task specific constraints. The characteristics are adapted to the level of concretisation.

Before a requirements list can be set up, the requirements must be known in detail so that the functions and important constraints can be identified. For that reason, the main characteristic "function" makes way for the associated characteristics "geometry", "kinematics", "forces", "energy", "material" and "signals", all of which facilitate the identification and description of the overall function. Similarly in the embodiment phase, the characteristic "embodiment" is replaced with the appropriate "layout" characteristics. Similar characteristics apply to evaluation; they have a welcome redundancy which ensures that they cover all contingencies. Methods of quality assurance and cost identification should be applied as early as possible, but during the embodiment phase at the very latest.

Some of the methods we have examined are applicable at different levels of embodiment and can therefore be used *repeatedly*. This is particularly the case with documentation (for example, requirements lists, function structures, selection and evaluation charts). Moreover, it has been found that systematically elaborated documents for certain product groups have a wider application in that they can be used again for other products, thus reducing the overall effort of the systematic approach.

12.2 Experiences of Applying the Systematic Approach in Practice

The overall approach and the specific methods described in this book have been applied many times to solve problems in industry. They have been applied by engineering students working on projects in industry, by faculty assisting with industrial projects, and by practising designers. The experiences gained from these activities have been analysed and published [12.1–12.3, 12.8]. With respect to the individual methods, the following conclusions can be drawn:

- Task clarification and setting up the *requirements list* prove to be essential and important methods.
- Abstracting and creating *function structures* often causes difficulties because of the abstract representation. Designers are more used to thinking in objects and visual images [12.6]. Nevertheless it is necessary and helpful that at least the main functions are identified and listed.

- *Intuitive search methods* are mainly applied when no solution seems achievable using conventional methods. For embodiment issues the gallery method is more effective than brainstorming. Both, however, can only encourage ideas. A careful analysis and further development of the results are necessary.
- *Discursive solution methods* such as classification schemes and morphological matrices initially cause some difficulties because the appropriate but abstract classifying criteria and their characteristics are not, or not fully, recognised. This suggests insufficient training in the systematic approach. However when such systematics are recognised and applied, they help to provide a more fundamental overview leading to better solutions and more patent possibilities. They also help to compare the solutions of competitors.
- *Selection and evaluation methods* are frequently used, but often, from a systematic point of view, they are combined in ways that are not recommended, resulting in individual approaches. Despite how they are often applied, selection and evaluation methods nevertheless help designers to make more objective decisions. In most cases these methods are essential.

Recent studies such as the one by Schneider [12.9] confirm the statements above. The work of Wallmeier [12.10] emphasises the importance of experience and of sustained assessment through reflection on the results to hand.

The objection is often raised that applying a systematic approach during the *conceptual design phase* takes too much time. It is true that the time needed for this phase increases for original designs. However, the time normally needed in this phase for concretising ideas into principle solutions, for example through rough calculations, developing solutions, and analyses of various layouts, is about the same as when a systematic approach is not used, that is, around 60 to 70%. Experience shows that any apparent increase in the time required is repaid several times over in the subsequent embodiment and detail design phases because irritations, sidetracks and renewed searches for solutions are avoided. Design work becomes more goal directed and efficient.

The *embodiment design phase* can also benefit directly from a systematic approach. Applying the basic rules, principles and guidelines of embodiment design usually reduces work effort, avoids errors and disturbances, and improves material utilisation and product quality. Checking solutions using the methods for identifying faults and unnecessary costs also improves the product quality, and only takes too much time when not limited to the essential. Evaluations do not take much time in comparison to the benefits, in particular searching for weak spots.

In summary:

- Industrial companies express a clear interest in systematic design especially when they are involved in original design or plan to introduce virtual product development.
- The systematic approach is being widely accepted in industry, although this may involve only the application of individual methods as the need arises.

- In particular, a systematic approach is being adopted for developing new designs where it is necessary to generate unconventional ideas, that is, to fulfil new functions with new solutions.
- The approach has hardly been introduced at all for adaptive or variant design [12.2, 12.4]. This is understandable because working with functions and function structures is not the most important task in these types of design. Adaptive and variant design benefit more from computer support.

Industrial companies applying a systematic approach state:

- The number of patents, in particular defensive patents, has increased.
- The overall duration of development projects is shorter, despite longer conceptual design phases.
- The probability of finding good solutions is greater.
- It is easier to manage the increasing complexity of problems and products.
- Creativity increases while maintaining realistic deadlines [12.7].
- A transfer effect is noticeable, that is, staff work more systematically in other areas.

The following side effects are observed:

- information flow improves
- teamwork and motivation benefit
- communication with clients increases.

A particular success of systematic design is that young engineers taught the approach and methods can contribute to a company surprisingly quickly, without first having to gain extensive experience.

The following aspects have been criticised by industry:

- Procedures for estimating costs are insufficiently developed.
- The approach can only be successfully applied when designers and managers have both been trained to use it; and both groups consistently require the other to apply it.
- Intuition and creativity cannot be replaced by a systematic approach—they can only be supported.

The overall conclusion is clear: the benefits from applying a systematic approach to design far outweigh any disadvantages.

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Chapter 2

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Chapter 8

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AED, the International Conference on Advanced Engineering Design (annually)
DESIGN, the International Design Conference (biannually)
DTM, the Design Theory and Methodology Conference (annually) as part of the ASME IDETC (International Design Engineering Technical Conferences)
ESDA, the Engineering Systems and Design Analysis Conference (biannually)
EPDE, the Engineering and Product Design Education International Conference (annually)
ICED, the International Conference on Engineering Design (biannually)
NordDesign (annually)
PLM, the International Conference on Product Lifecycle Management (annually)
TMCE, the International Symposium on Tools and Methods of Competitive Engineering (biannually)

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Advanced Engineering Informatics, Elsevier
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Index

abrasion, control of 336
abstraction process 58, 161, 162
active redundancy 252
adaptive designs 171, 178
adaptronics 458
aesthetics
  aims 348–350
  guidelines 351–354
  visual information 350–351
ammonia synthesis process, division of tasks example 284
analogies, study of 82
analysis process 58, 125
  weak spot identification 58
AND-functions 37
animal feed packing, problem formulation 162
assembly processes
  design for 268, 375
  operations 375

backward steps approach 60
balance of forces 278
balanced forces principle 277–279
bearings
  deformation 275
  design arrangements 235
  hydrostatic, axial 296
  lubrication monitoring 38
  oil pressure switches 304
  recycling of plain pedestal 396–399
  system modular approach 503
  taper roller 302
Beelich, K H 553
bending process 368
bending stress, use in design 271
bi-stability, principles of 261, 269, 303–304
biomechanical issues 342
Biot number 482
boilers, division of tasks example 282
bolted joints
  deformation 273
  use of synthetic materials 326
boring, design for 366, 369
bought-out 374
brainstorming 83–85, 204
brakes, self-reinforcing 295
branches of engineering 4, 5
breakdowns, costs 385
Bredtschneider–Uhde self-sealing cover 291
BSI (British Standards Institution) standards 411
building block construction method 361–362

calculi removal method 87, 88
carpet tile packing 33
cast components 363, 364
  costing 540
Cauchy number 467, 482
cavitation
  control of 336
cavitation number 467
CEN (Comité Européen de Normalisation) standards 411
CENELEC (Comité Européen de Normalisation Electrotechnique) standards 411
characteristic number, product range 474
circuit-breaker, division of tasks example 285
clarity rule 235–242
classification schemes 92–96, 182, 189
  Zwicky 104, 184
client focus 66
client–problem analysis 72
clutches
  balancef forces 278
  logical functions 38
coefficient of linear expansion 309
  various materials 310
cold extrusion 363, 367
collaboration, interdisciplinary 61
colour support, aesthetics 353
company aims 73
company competence 68

company standards 411
comparative redundancy 252
compatibility matrix 105, 185
components 252
  fastenings fail-safe behaviour 251
composite construction method 361
compressed gases, storage 338
Computer Aided Design (CAD) 7, 8
  effect on design 6
  use of 198
computer support, effect on design 10
Computer-integrated manufacturing (CIM)
  effect on design 8
concept variants 118–121
  searching for 503
conceptual design phase 44, 131, 132, 159, 417, 563
  development 190, 191
  fault check 522
  steps in 159
cone clutch, balance of forces 278
confrontation, problem 126
connections
  elastic force 446
  force 443
  force field 445
  form 441
  friction force 444
  material 440
  mechanical 439
constraints, task solution 43, 165
construction structure 42
continuous adjustment device 308
conversion 29–31
  properties 40
conveyor system, modular 513
corrosion
  abrasion 336
  bimetallic 333
  causes and effects 328
  cavity 331
  contact 333
  crevice 332
  deposit 333
  design against damage 328, 337
  effects on safety 266
  fatigue 334
  free surface 330
  graphite 337
  indentation 331
  intercrystalline 337
  selective 336
  strain-induced 335
  stress 334
  transition zone 333
  uniform 330
cost calculations 537–539
cost estimates
  relative costs 539–543
  using regression analysis 538, 545–547
  using share of material costs 544
  using similarity relations 539, 547
cost functions 546
cost structures 558–560
cost–benefit analysis 110, 113
costs
  bought-out parts 540
  casting 540
  definitions 30, 31, 535–537
  reduction objectives 363
  safety failure 268
coupling system 27, 28
covers
  safety 263
  sealing 328
crane drive assemblies, deformation 276
creativity 49, 127
  tests 49
creep
  design for 323–324, 326
Critical Path Analysis (CPA) 59
critical temperature
  creep 323, 324
  material 323, 324
  materials 321
cut-out components, design for 367, 371

data collection 52
decimal-geometric series 469
decision making process 127, 128
decision making processes 49
definitive layout 227
deformation
  design for 308
  matched 272–277, 279
  plastic 266, 299, 321
deformation, design for 270
degrees of freedom 311
  applications 311–315
Delphi method (solution finding) 87
design catalogues 98, 99, 103
design factors 12
design form
  adaptive 4
  direct 6
  indirect 6
  principle 4
  variant 4
design methods 18
design process 1, 2

methodology 9, 10
designer
definition 1
educational requirements 8
role in company 6
tasks and activities 2–6
detail design phase 132–134
detail design phase, test rig 436
development prototypes 4
dezincification 337
differential construction method 356–359
DIN
safety 248
DIN (Deutsche Institut für Normung) standards 411
DIN 31001, protective function materials 263
DIN EN
safety 248
direct costs 535
direct/short transmission path 279
direct/shortest transmission path 270
disassembling, for preprocessing 392
discursive thinking methods 48, 54, 89
study of physical processes 89–91
use of classification schemes 92–96
use of design catalogues 98, 99, 103
disturbing effects 42, 43
disturbing factors 521
analysis 232
identification 527
rectification 527
division of labour 61
documentation, production 375
dominance matrix 121
drawing process 365
drive shaft, cost estimates 550
drop forging 363, 366
durability, design for 308
dynamic similarity 467

ease of assembly principles
guidelines 377, 378, 380, 383, 384
interfaces 377, 383
layout designs 377
types of assembly 375–377
economic rating 119, 195, 416
effects, types 42, 43
elastic coupling 299
fail-safe behaviour 251
elastic deformation 266
electric motors
size range requirements 483
size ranges 490, 491
embodiment design phase 44, 132, 198, 235–242, 563
basic rules 234–235
checklist 233–234
clarity rule 235–242
division of tasks principle 281–282
evaluating 416–417
fault-free principle 305–308, 525
guidelines 308–309, 354
principles 268–269
process steps 227–232
simplicity rule 242–247
worked example 417
enclosure safety 263
energy conversion 29–31
subfunctions 179
enrgy storage, system stability 269
environmental safety 249
epistemic structure (thought process) 46
equilibrium state 301
ergonomics
constraints 344–346
fundamentals 342–344
identifying requirements 346–347
erosion, control of 336
European (EN) standards 411
evaluating procedure 109, 110
identifying criteria 110, 111
solution variants 109–113, 115, 116, 118–121
weighting criteria 112, 113
evaluation procedure 127
assessment of standards 413
comparison 123, 124
estimating uncertainties 121, 122
identifying criteria 192, 417
weak spots 123
weighting criteria 194
evolutionary developments 189
existing technical systems
study of 81, 178
expansion
design for 308
design for 309–310
of components 310–315
relative 315–321
experimental studies 82
expert systems 8
exponential equations, use in size ranging 484

factorisation process 61
fail-safe principle 250
Failure Mode and Effect Analysis (FMEA) 529–531
fault-free design 305–308
fault-tree analysis 522–529
faults 521
analysis 232

identification 529
feedback effects 42, 43
fences
safety 263
Finite Element (FE) methods 290
fits and tolerances 477
fixed costs 535
flanged connection
relative expansion 316
flanged connections
bolts fail-safe behaviour 251
flat belts construction, division of tasks 286
flowlines of force 269, 279
force transmission
principles 269
force transmission principles 269
forces
associated 277
functionally determined 277
form design 13
for joining 368–370
for separation 366–367
of components 362
primary shaping process 363
secondary shaping process 363–365
Selection and unity 351–353
forward steps approach 60
Fourier number 482
friction drives
continuously adjustable 293
geometrical scaling 470
frictional thread locking device 90
fuel gauge
problem formulation 166–169
function
definitions 31–33
overall 169, 170
function carriers 230, 231
auxiliary 429–436
worked example 419–429
function chain 34
function modules 496, 500
function structure 31
function structures 33
practical use 178–181
functional embodiment 350

gas-washing plant, lye pipework 337
gear coupling
size ranges 477
gear pumps, size ranges 488, 489
gearboxes
division of tasks 282, 288
example of modular systems 510
fault-free design 307
modular systems 510
multiple 288
size range 479, 480
generators
expansion balancing 317
magnet wheel composite construction 361
rotor differential construction 356
rotor integral construction 359
geometric similarity 466
size ranges 476–481
glued connections, deformation 273
goals, effect on design 5
graphics support 354
grinding, design for 366, 370
guidelines, task solution 44

hammer forging 363
Hansen, F 13, 14
helical gears, balance of forces 278
helicopter rotor head
division of tasks 286
safe-life principle 253
heuristic structure (thought process) 46, 48, 50, 51
historical developments 10–14
holistic approach, problem solving 59
Hubka, V 27, 40
human needs
active involvement 345
biomechanical issues 342
passive involvement 346
physiological issues 342
psychological issues 344
hydraulic protection system 257

IEC (International Electrotechnical Commission) standards 411
"if–then" subfunction relationships 35
Ilmenau School 13
in-house parts 375
indirect costs 535
industrial safety 266–268
information
presentation 350, 351
processing,conversion 51–53
processing/conversion 126
specification 131
input effects 42
inspection measures, reduction of 387
integral construction method 359–360
intelligence 49
intelligence tests 49
international standards 411
intuitive thinking 9, 47, 53, 82
brainstorming 83–85

combination of methods 88, 89
Delphi method 87
gallery method 86
method 635 85, 86
synectics 87, 88
ISO (International Organisation for Standardisation) standards 411
iteration process 53, 126
loop 126

joining procedures, form design 368–370

Kesselring, F 12
knowledge-based systems *see* expert systems

lathe, size range requirements 483
layout design 132, 237, 356
building block construction method 361–362
composite construction method 361
differential construction method 356–359
ease of assembly 378
ease of assembly principles 377
integral construction method 359–360
Leyer, A 13
life cycle, product 2, 3, 65, 68
lightweight structures 80
links, logical 37
literature search 78
logical functions 37, 38

Müller, J 14
machining, design for 366
main flow determination 171, 179
maintenance
design for 385–388
safety precautions 268
manufacturing cost 535
marketing and product planning 66
material conversion, subfunctions 179
mathematical methods, use of 106
Matousek, R 13
mechatronics 8, 448
membrane seals, design clarity 240
memory capacity 46
method 635 (solution finding) 85
microfiche reader 308
milling, design for 366, 370
minimum losses, principle of 269
minimum risk design 404
mixing tap, design simplicity 245
model
tests 82
model, development 133
models
advantages 508–510
conveyor system 513
developing 499–500
dimensioned layouts 505
function structures 500–503
gearboxes example 510
limitations 508–510
modular products 465, 495–496
principles and variants 503–508
production documents 508
sectional division 498
systems 496–499
tram system example 510–512
morphological matrix 104, 184
motor housing
integral construction 360
semi-finished materials selection 373
multifunctional materials 458
multiple gears, division of tasks 289

national standards 411
natural forms, study of 79
need–strength matrix 72
negation process 59
new materials, effect on design 8
Niemann, G 12
NOT-functions 37
novelty, effect on design 4

object parameters,cost–benefit analysis 113
objective, task solution 43
objectives tree 112
oil pressure switches 304
operation element 553–558
operational safety 248, 268
operator safety 249
OR-functions 37
organisational structures 3, 4
original designs 171, 178
overspeeding control 260

Pacyna regression equation 546
passive redundancy 252
physical effects 38, 39
physical processes 38
study of 89–91
physiological issues 342
pipeline, sprung elastic supports 486
pistons
relative expansion 316
stable behaviour 301
planning and design process 128, 129, 131
flowchart 130
task clarification 131

plastic deformation, as safety property 266, 299
platform construction 515
potato harvesting machine
  function structure 185
preferred number series 469–472
preliminary layouts 230
preloaded taper joint, design clarity 237
preloading system 324
preprocessing
  embodiment guidelines 393–396
  for recycling 389–392
pressure index 467
pressure safety valve 522
pressure vessels
  cost estimates 547
  regression analysis 547
  safety system 259
primary shaping process, form design 363
principle redundancy 252
principle solution 131, 198, 208
  evaluation of variants 192–198
  firming up variants 190, 191
  searching for 503
problem solving process 125–128
  abstraction 58
  analysis 58
  decision making behaviour 49–51
  definition 126
  identification/formulation 162–164
  information conversion 51–53
  intelligence and creativity 49
  psychology 45, 46
  synthesis 59
  thought structure 46–48
procedural plans 125, 126
Process Steps (PS) 362
product architecture 514
product liability legislation 6
product life cycle 64
product planning 63, 64, 131
  in practice 76, 77
  finding ideas 74, 75
  marketing 66
  situation analysis 68–71
  stimuli 66, 68
product proposal 75
product recycling 388
product–market matrix 68
production design 355–356
  use of standards 413
production documentation 375
  modular products 508
production modules 496
production waste recycling 388
prognostic uncertainty 122
protective equipment/devices 254
  barriers 254, 263
protective system
  self-monitoring 257–258
protective systems 249
  basic requirements 255
  safety relaxations 262
  start-up checks 262
  testability 261–262
  warning 256
prototypes, development 133
psychological issues 344
pump housing adapter, design clarity 240

qualitative definitions 30
quality control 267
  improvement objectives 363
quality engineering 519, 520
Quality Function Deployment (QFD) 520, 531
quantitative definitions 30
questioning approach 59
quick-action shut-off system 260

R 10 series (prefered numbers) 469
reciprocating masses, balance of forces 279
reconditioning, for recycling 392, 396
recycling
  aims 388–389
  design for 242, 393–396
  evaluating of potential 402
  plain pedestal bearings 396–399
  processes 389–393
  white goods 399–400
redundancy principle 251
  safety systems 258–261
regression analysis 538, 545–547
relative expansion
  steady-state 316–317
  unsteady state 317–321
relaxation, design for 324–326
reliability 248
reliably, system 255
repairs
  costs 385
  safety during 268
requirements list 146–158, 178, 192, 228
  analyzing 164
  checklist 149
  formulation 131
  fuel gauge example 166–168
  mechanical system example 199
  practical difficulties 157
resonance, avoidance 266, 308
Reynolds number 483

Ringfeder connector, division of tasks 285
risk limit 248
risk minimisation, design for 402–409
Rodenacker, W G 14
rolling element bearings, division of tasks 285

safe-life principle 249
safety blow-off valve 522
safety factors 265
safety fence 255
safety methods
  design criteria 263–266
  direct 247, 249–253
  indirect 254–263
  industrial aspects 266–268
  requirements relaxation 262
safety rule, embodiment design 247–268
safety standards 413
sandwich construction 80
schedule requirements, safety aspect 268
seals
  fault-free design 525
  selection 266
  self-reinforcing 296
  spindle 320
seals, design simplicty 246
search strategies 71–73
secondary shaping process, form design 363–365
selection procedure 106, 107, 109
selective redundancy 252
self-help principle 290–293
  gain 291
  self-balancing 297
  self-damaging 291
  self-protecting 298–301
  self-reinforcing 293–296
self-monitoring, protective system 257–258
semi-finished materials
  costing 540
  selection 371–374
semi-similar size ranges 481
separation procedure, form design 366–367
sequential designs 465
shaft–hub connection, design clarity 238
shafts, minimum risk design 406
shredding, plastic 392
side-effects, undesired 42, 43
signal conversion subfunctions 29–31, 179
signal flows 179
similarity laws 466–469
  constant stress 467–469
  influence of gravity 481
  influence of thermal processes 482
  physical relationships 482
simplicity rule, embodiment design 242–247
simultaneous engineering 8
sintered components 363, 365
situation analysis 68–71
size ranges 465
  development 484
  electric motors example 490
  gear pump example 488
  geometric similarity 476–481
  overriding similarity laws 481–483
  production requirements 484
  selection of step sizes 473–476
  semi-similar items 481
  task requirements 483
  use of exponential equations 484
soldered connections, deformation 273
solution finding methods 63, 77
  combining 103–106
  conventional 78, 79, 81, 82
  discursive 90–96, 98, 99, 103
  discursive methods 89
  intuitive 82–89
solution variants 106, 107, 109–113, 115, 116, 118–124, 131
Sommerfeld number 467, 482
specification
  of information 131
  of layout 132
  of principle 131, 132
  of production 132
speed control 260
spindle seals 320
spongiosis (graphite corrosion) 337
springs
  for pipeline supports 486
  self-protecting 298
stability
  machinery operation 266
  principle of 269, 301–303, 308
standard parts 374
standardisation, objectives 410
standards
  company 411
  developing 414
  evaluation 416
  information sources 412
  types 410
  using 413–414
static similarity 467
steam valves, minimum risk design 405
step sizes, product range 473–476
stored energy principle, protective system 257, 260
strategic opportunities 71
strength (s-)diagram 119

strength diagram 195
structure analysis 58
stuffing box, minimum risk design 404
subfunctions 31, 38, 170
assignment 281–282
classification 103, 104
relationships 35
symbols 31
working principles 182
superheated steam pipes, division of tasks 283, 287
symbols 31
symmetrical layouts 278
symmetrical layouts, balance of force 279
synectics 87, 88
synthesis process 59, 125
system restarts, prevention 261
systematic design 2
authors aim 563–567
authors' aims 19, 24, 25
design methodology 18, 19
doubting process 59
historical development 10–14
need for 9, 10
practical experience 567–569
problem solving psychology 45
systems theory 14, 15
value analysis 15, 18
variation process 61
VDI Guidelines 18
working methodology 53
systems theory 14, 15
interrelationship 42, 43

tamper resistance 256
target costing 560
tasks 43
assignment of subfunctions 281–282
clarification 131, 145
division for distinct functions 282–286
division for identical functions 287–290
division principle 282
origin 2
solution 43–45
teamaker,systematic variation 349
technical artefacts 27, 42
representation of 15
technical rating 119, 416
technological developments, effect on design 8
tensile testing machine 175
test rig
classification scheme 182
detail design 436
embodiment design (worked example) 418
testability, protective systems 261–262
thermal expansion 266
thinking process 46–48
discursive 48, 53
intuitive 47, 53
threaded fastener, locking properties 91
time constant, thermal expansion 318
time-dependent behaviour 321
tooling, design for 367
torque equations 90
torque-limiter, size range 480
torsion shaft 282
torsion stress, use in design 271
Total Quality Control (TQC) 519
Total Quality Management (TQM) 519
TOTE model (thought process) 48
toughness, as safety property 265
tram
modular system 510–512
transfer link 307
transport processes 268
Tschochner, H 12
turbines
balance of forces 278
creep control 326
housing/casings 283
housings/casings 320
modular approach 498
shrink-fitted rings 296
size range requirements 486
speed control 260
turbo-machines
self-balancing 297
thermo-stable behaviour 302
turning, design for 366, 369

uniform strength, principle of 269, 279
used material recycling 389

V-belt construction, division of tasks 287
value analysis 15, 18, 33, 59
valves
function structure 177
gate 240
safety and alarm 303
safety blow-off 522
self monitoring safety action 257
variant design 4
variants
evaluation 132
VDI 18, 19, 110, 111, 113, 123, 128, 208, 346, 348, 540, 546
rating scale 195
VDI Guideline 18, 19
velcro fastening 79
ventilation system, minimum risk design 409

viscoelastic behaviour 323
viscometer design 89
volume-surface area relationship 319

Wächtler, R 14
warning, safety 256
weak spot analysis 58
Weber–Fechner law 470
welding
  cost estimates 554
welding, design for 368, 372
wheel propulsion, simultaneous 276
white goods, recycling 399–400
winding machine
  differential construction 357
winding machine, minimum risk design 408
workflow, planning 128, 129, 131
working location 39
working motions 39
working principles 40, 181, 184, 208
  combining 184–186
working structures 40, 41
  practical use 186, 187, 189, 190
  selection 186
working surfaces/spaces 39

yield point, effect of exceeding 272

Zwicky morphological matrix 104, 184