# 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.

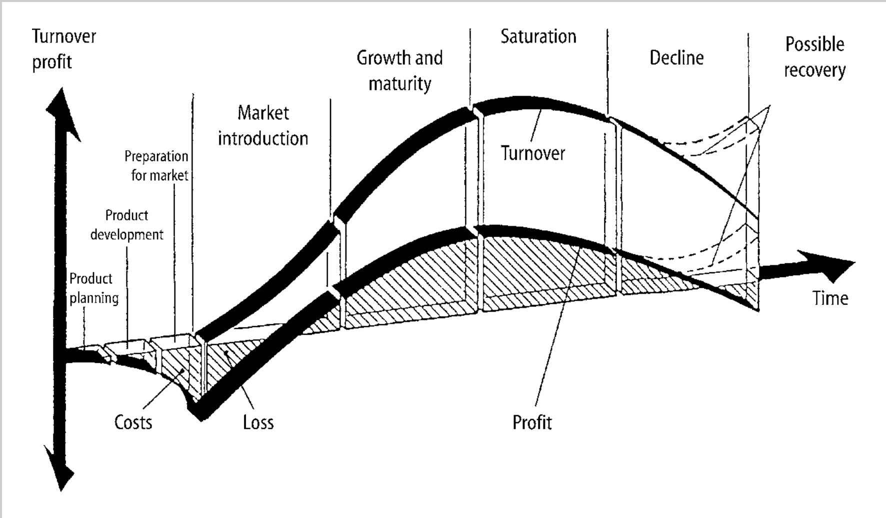



**Figure 3.1.** Life cycle of a product. After [3.45]

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

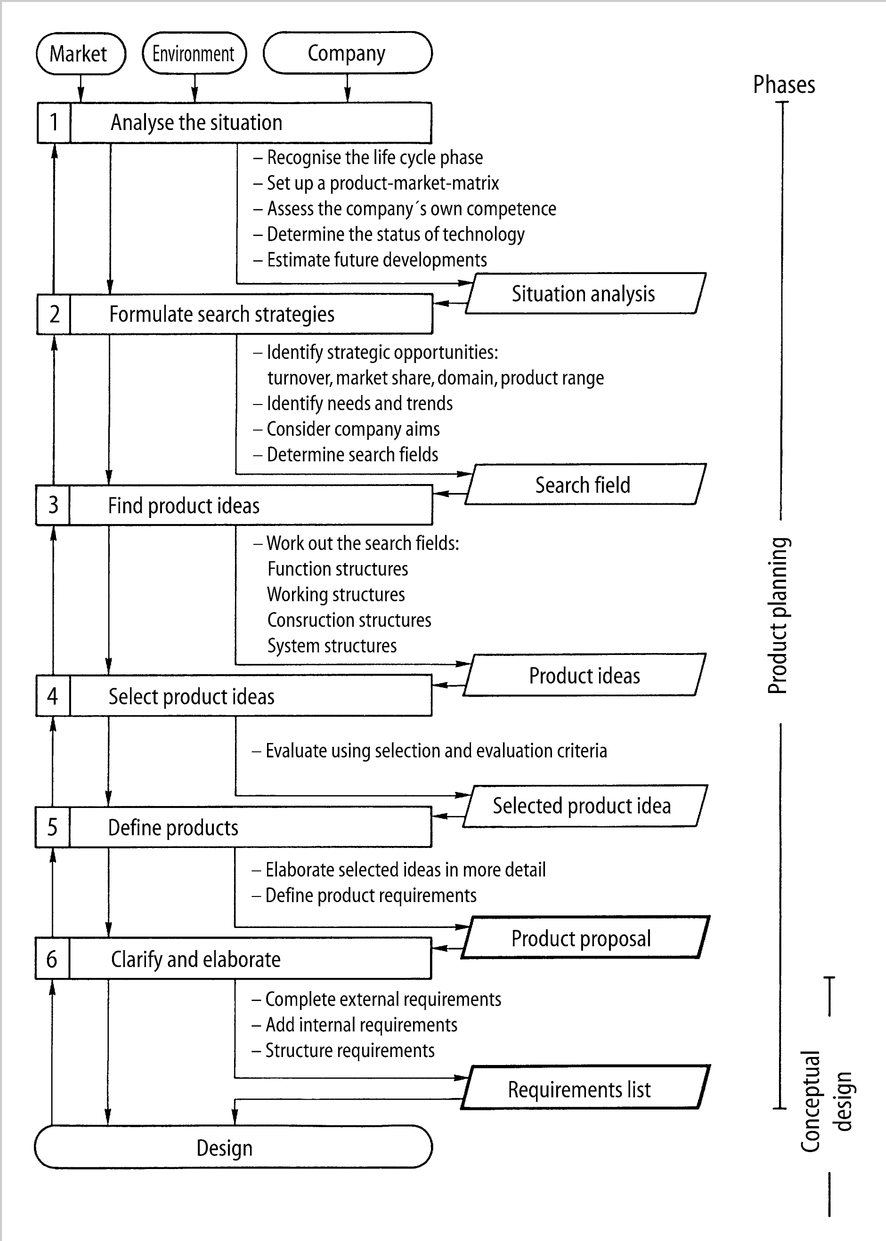



**Figure 3.2.** Product planning procedure. After [3.45, 3.69]

- 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.

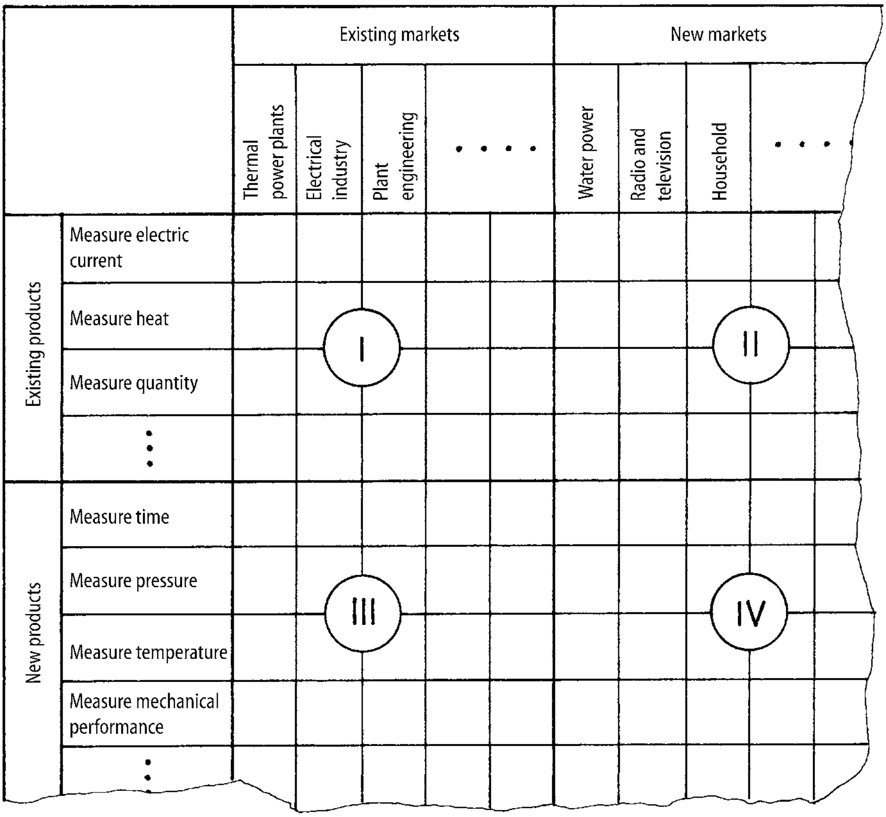



**Figure 3.3.** Product–market matrix, after [3.19] and [3.42], for a company producing measuring devices for industry

*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]

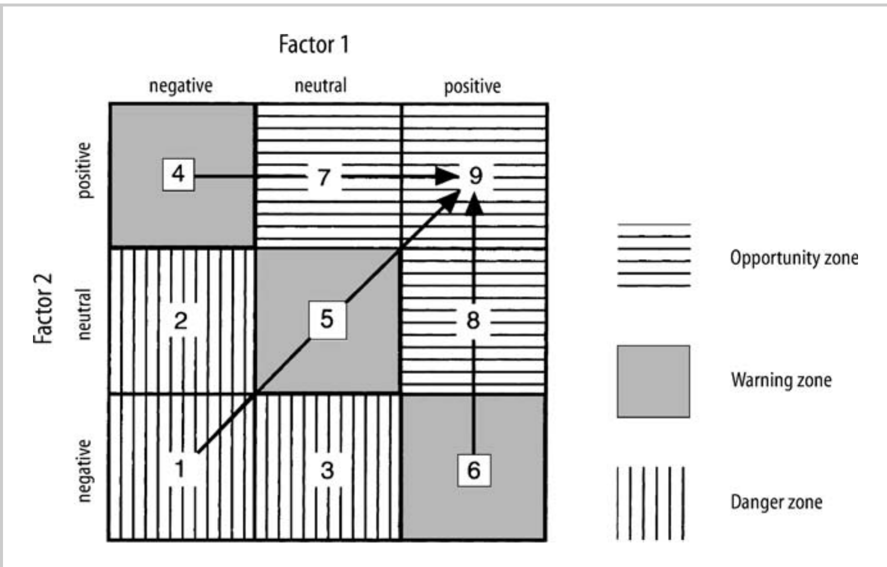



**Figure 3.5.** General structure of a portfolio matrix [3.21, 3.38, 3.45]

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* | ≥ 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* | ≥ 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* | ≥ 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

| | | Strengths and competences of the company (in decreasing order) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Electronic measuring | Mechanical measuring | Electro-optics | Lithographic printing | Bonding | |
| Customer needs (in decreasing order) | Adaptive control, microprocessors | X | | | X | X | |
| | Thermal control | X | X | | | | |
| | Remote control | X | | X | | | |
| | Traffic count | X | | X | | | |
| | Measure wind direction and velocity | | X | | | | |
| | | | | | | | |

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

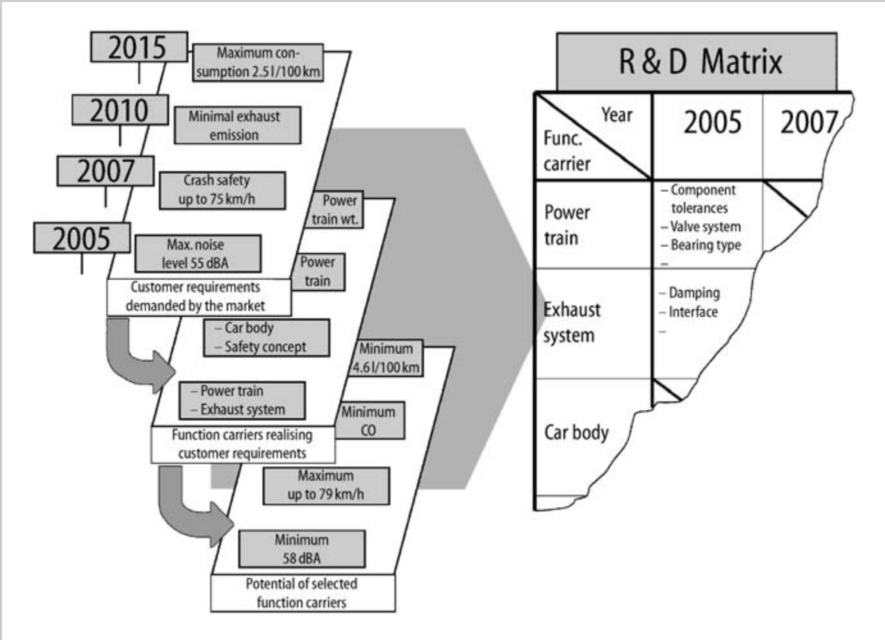



**Figure 3.7.** Product goals derived from customer requirements

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].

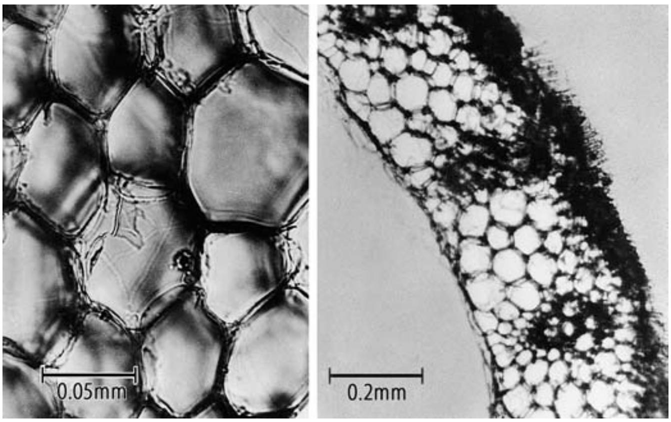



**Figure 3.8.** Wall of a wheat stem [3.29]

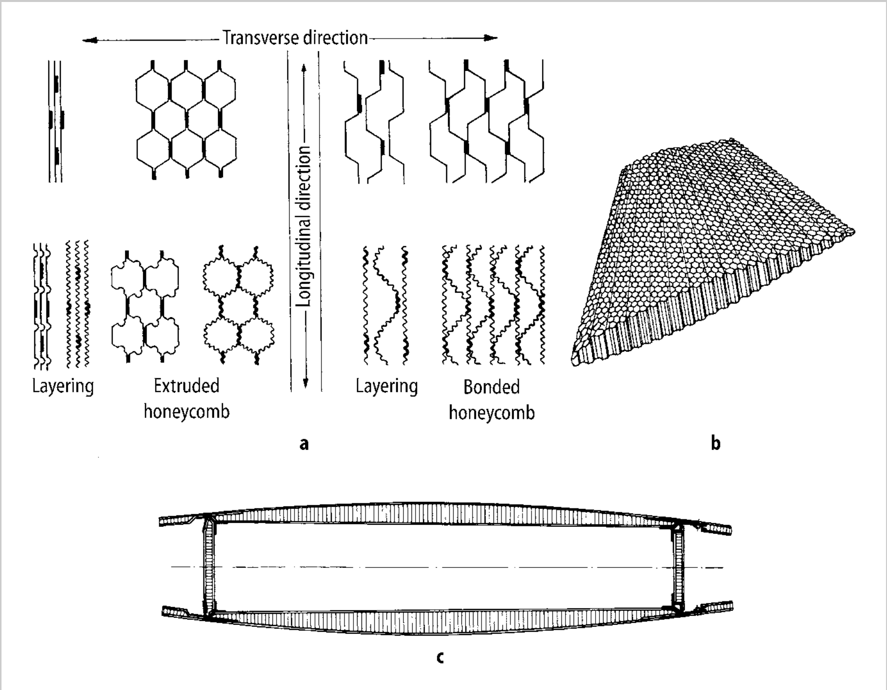



**Figure 3.9.** Sandwich construction for lightweight structures [3.30]. **a** A few honeycomb structures. **b** Completed honeycomb structure. **c** Sandwich box girder

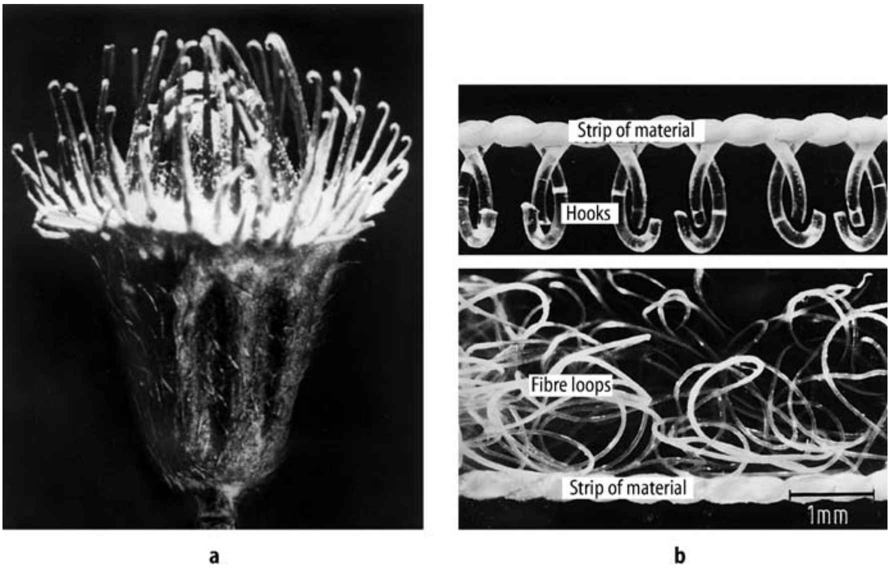



**Figure 3.10.** **a** Hooks of a burr. **b** Velcro fastener. After [3.29]

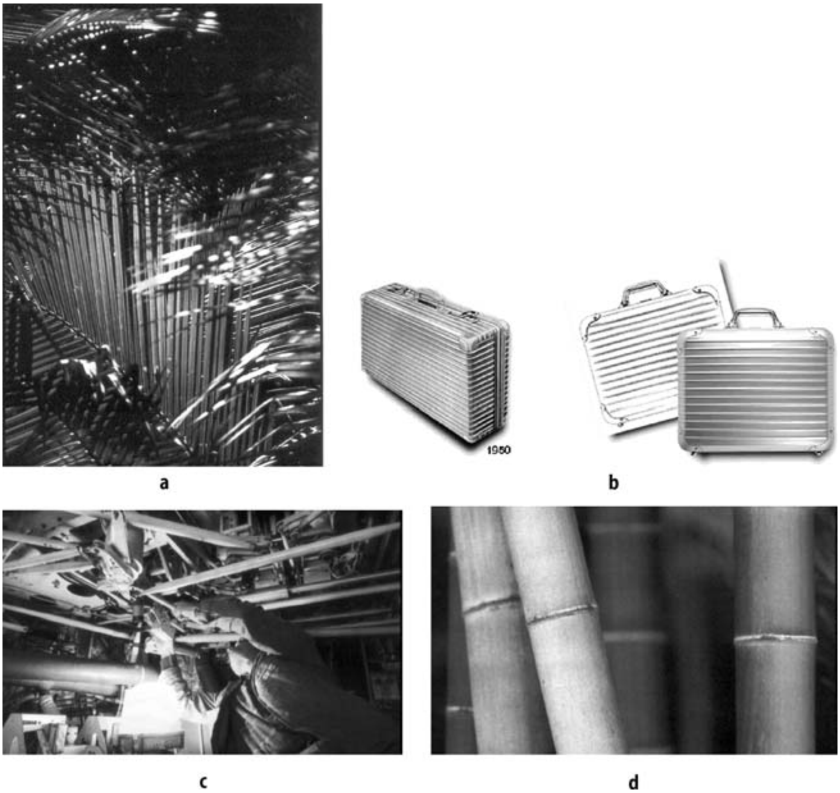



**Figure 3.11.** **a** Palm leaves (Lufthansa publication 2/96). **b** Aluminium suitcase (Rimowa Kofferfabrik 10/01). **c** Tubular structure in an aircraft. **d** Bamboo stems (Lufthansa publication 5/96)

### *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.

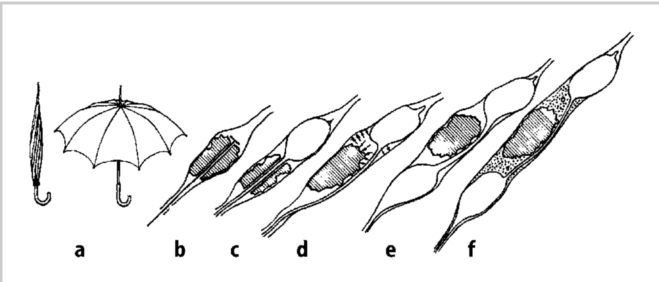



**Figure 3.12.** Step-by-step development of a solution principle for the removal of urinary calculi based on analogy and stepwise improvement

### *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 $\Delta p$ 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: $\Delta r \sim \eta$ ($\dot{V}$, $\Delta p$ and $l$ = constant).

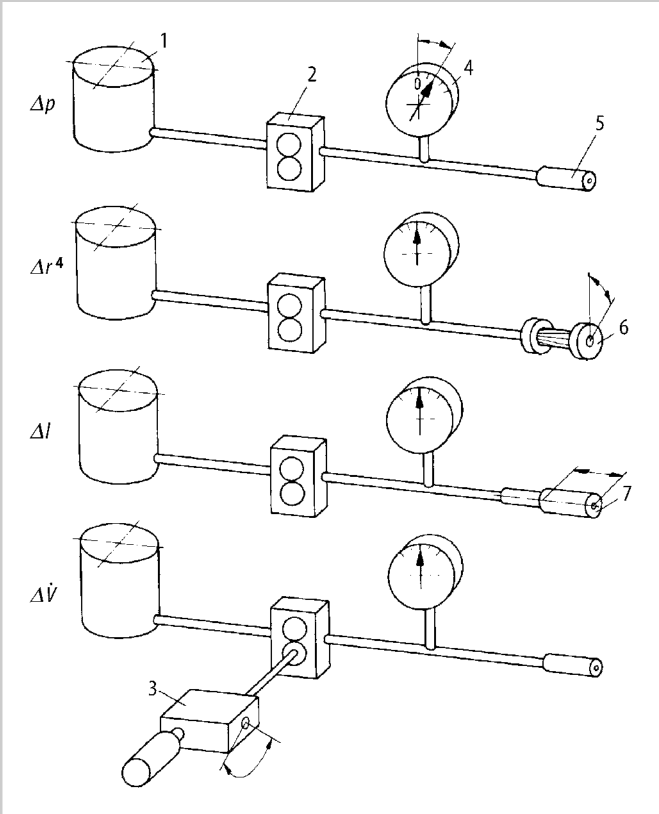



**Figure 3.13.** Schematic representation of four viscometers, after [3.59]. *1*, container; *2*, gear pump; *3*, variable drive; *4*, pressure gauge; *5*, fixed capillary tube; *6*, capillary tube with variable diameter; *7*, capillary tube with variable length

3. A solution based on changes in the length of the capillary tube: $\Delta l \sim \eta$ ($\Delta p$, $\dot{V}$ and $r$ = constant).
4. A solution based on changes in the volume flow rate: $\Delta\dot{V} \sim \eta$ ($\Delta p$, $r$ 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, $\beta$ = helix angle, $d$ = mean thread (t) diameter, $P$ = pre-load, $D$ = mean face (f) diameter, $\mu_v$ = virtual (v) coefficient of friction in the thread, $\mu_t$ = actual coefficient of friction in the thread, $\mu_f$ = coefficient of friction on the head or nut face, $\alpha$ = flank angle, $\phi$ = 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 $\beta$.

- 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 $\mu$.
- 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 $\alpha$ 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.

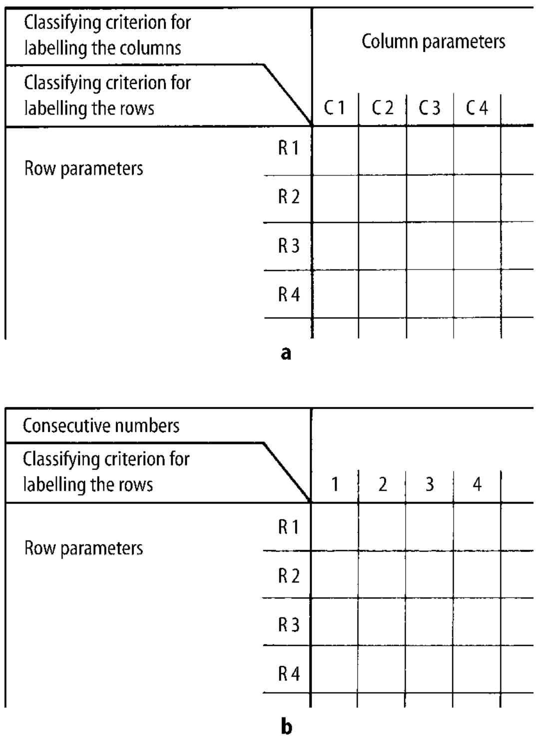



**Figure 3.14.** General structure of classification schemes. After [3.10]

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-

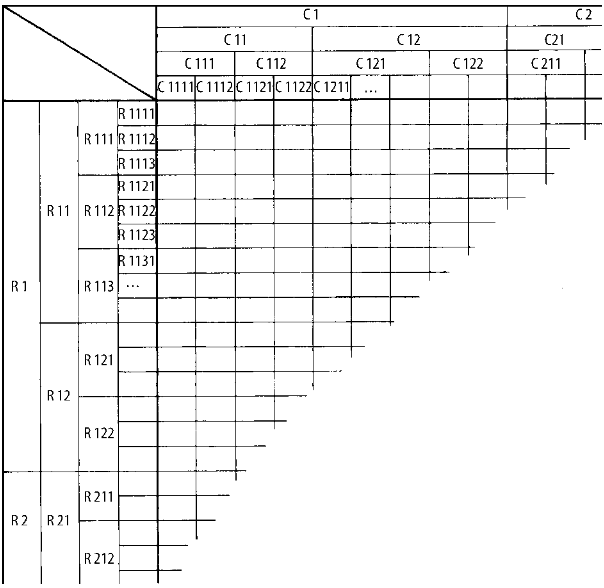



**Figure 3.15.** Classification scheme with further subdivision of parameters. After [3.10]

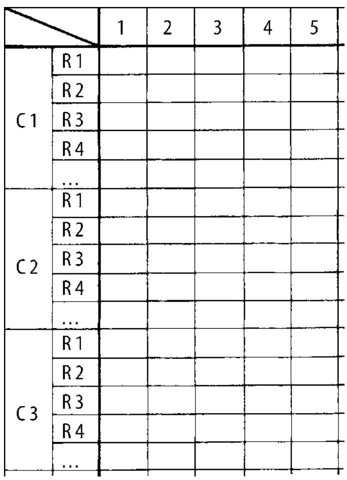



**Figure 3.16.** Modified classification scheme. After [3.10]

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<br>Triangle, square, rectangle, pentagon, hexagon, octagon<br>Cylinder, cone, rhomb, cube, sphere<br>Symmetrical, asymmetrical |
| Position | Axial, radial, tangential, vertical, horizontal<br>Parallel, sequential |
| Size | Small, large, narrow, broad, tall, low |
| Number | Undivided, divided<br>Simple, double, multiple |

Working motions

| *Headings* | *Examples* |
|---|---|
| Type | Stationary, translational, rotational |
| Nature | Uniform, non-uniform, oscillating<br>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 | Pot. energy (m, h) | Liquid reservoir (pot. energy) (h) | Battery (V) | Mass (m, s, Δϑ) |
| 2 | Moving mass (v, m) (transl.) | Flowing liquid | Capacitor (electr. field) (C) | Heated liquid |
| 3 | Flywheel (J, ω) (rot.) | | | Superheated steam |
| 4 | Wheel on inclined plane (J, v, ω) (rot. + transl. + pot.) | | | |
| 5 | Metal spring (d, F) | Other springs (compression of fluid + gas) (Δp; ΔV) | | |
| 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.

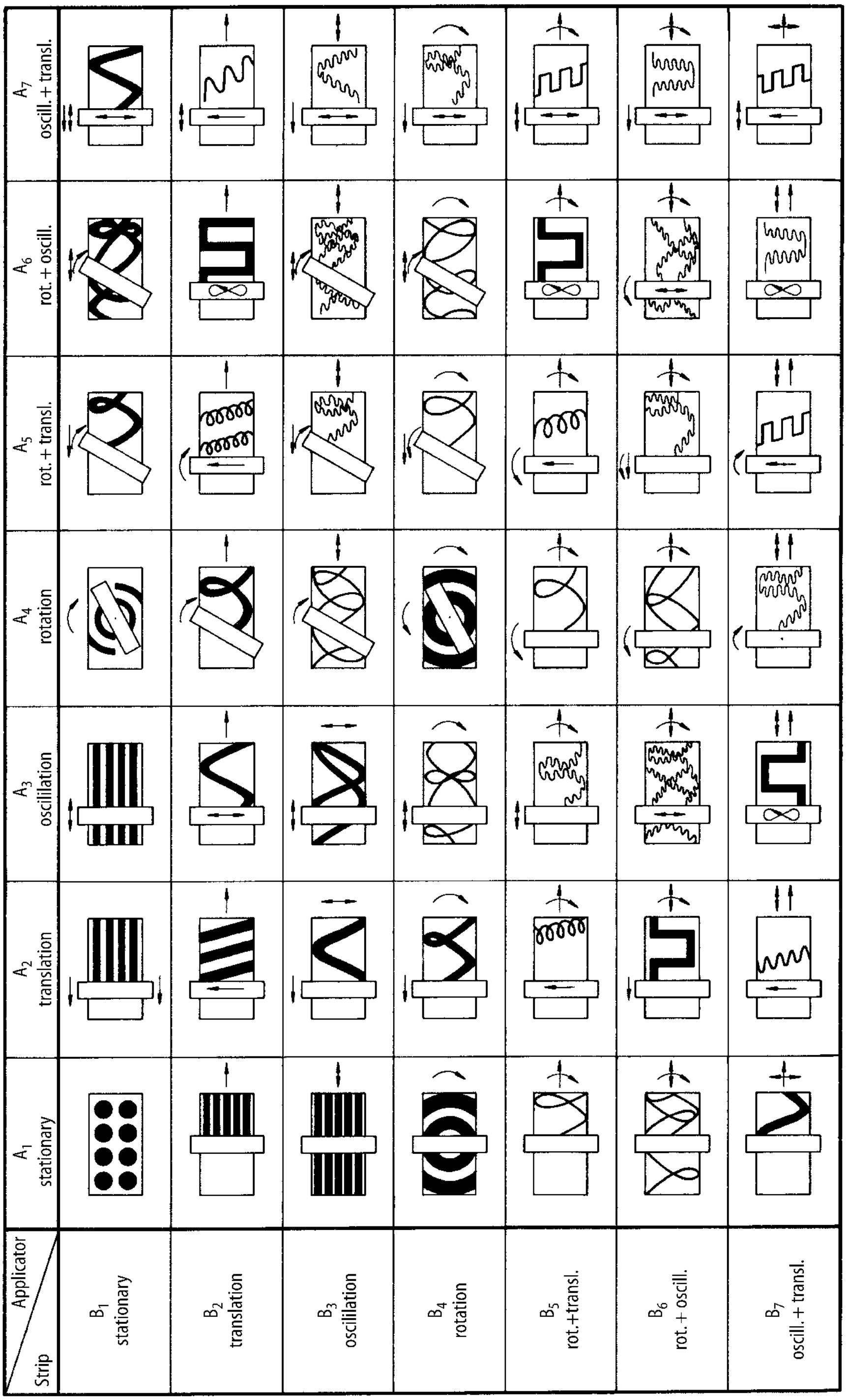



**Figure 3.20.** Means of coating the backs of carpets by combining the motions of the carpet (strip) and those of the applicator

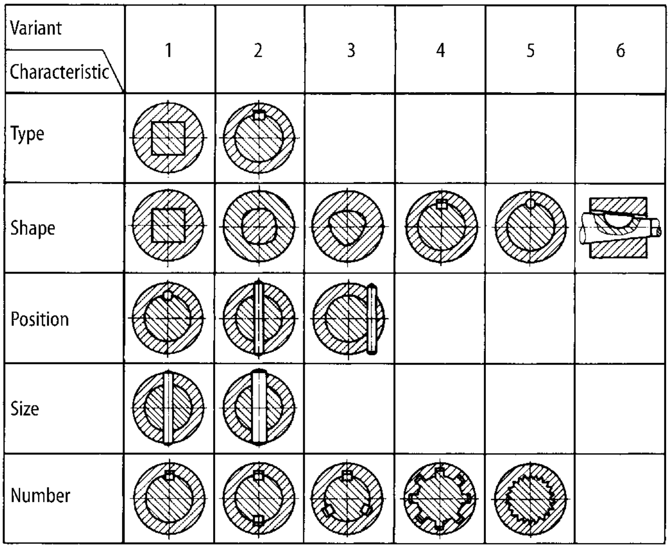



**Figure 3.21.** Variations in the working geometry for shaft–hub connections

### *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

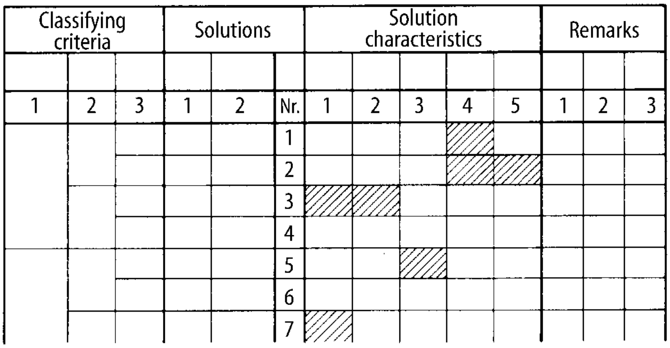



**Figure 3.22.** Basic structure of a design catalogue. After [3.62]

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 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $E_{mech}$ → $E_{mech}$ | 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 | ... | ... | ... | ... | ... | ... |
| $E_{mech}$ → $E_{hyd}$ | Force, length, speed, pressure | Speed, pressure | Bernoulli | Viscosity (Newton) | Torricelli | Gravitational pressure | Boyle-Mariotte | Conservation of momentum | ... |
| $E_{hyd}$ → $E_{mech}$ | Speed | Force, length | Profile lift | Turbulence | Magnus-effect | Flow resistance | Back pressure | Reaction principle | ... |
| $E_{mech}$ → $E_{therm}$ | Force, speed | Temperature, quantity of heat | Friction (Coulomb) | 1st law | Thomson-Joule | Hysteresis (damping) | Plastic deformation | ... | ... |
| $E_{therm}$ → $E_{mech}$ | Temperature, heat | Force, pressure, lenght | Thermal expansion | Steam pressure | Gas Law | Osmotic pressure | ... | ... | ... |
| $E_{elektr}$ → $E_{mech}$ | Voltage, current, magn. field | Force, speed, pressure | Biot-Savart-effect | Electrokinetic effect | Coulomb I | Capacitance effect | Johnsen-Rhabeck-effect | Piezoeffect | ... |
| $E_{mech}$ → $E_{elektr}$ | Force, length, speed, pressure | Voltage, current | Induction | Electrokinetics | Electrodynamic effect | Piezoeffect | Frictional electricity | Capacitance effect | ... |
| $E_{elektr}$ → $E_{therm}$ | Voltage, current | Temperature, heat | Joule heating | Peltier-effect | Electric arc | Eddy current | ... | ... | ... |
| $E_{therm}$ → $E_{elektr}$ | Temperature, heat | Voltage, current | Electr. conduction | Thermo-effect | Thermionic emission | Pyroelectricity | Noise-effect | Semiconductor, Superconductor | ... |
| $E_{mech}$ → $E_{mech}$ | Force, length, pressure, speed | Force, length, pressure, speed | Lever | Wedge | Poisson´s effect | Friction | Crank | Hydraulic effect | ... |
| $E_{hyd}$ → $E_{hyd}$ | Pressure, speed | Pressure, speed | Continuity | Bernoulli | ... | ... | ... | ... | ... |
| $E_{therm}$ → $E_{therm}$ | Temperature, heat | Temperature, heat | Heat conduction | Convection | Radiation | Condensation | Evaporation | Freezing | ... |
| $E_{elektr}$ → $E_{elektr}$ | 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

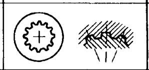
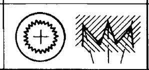
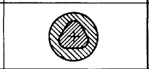
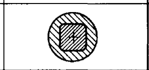
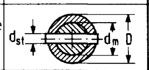
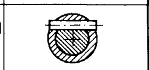
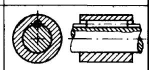
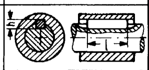
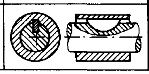
| Classifying criteria | | Solutions | | | | Solution characteristics | | | | | | | | | | | | | | | Remarks | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type of interface | Type of force transmission | Equation | Name | Configuration | | Transferable torque | Torque transmission depending on | Axial forces | Stress concentration | Applicable for | Behaviour at overload | Centering possible | Unbalanced force | Axial displacement of hub | Hub moveable | Joint adjustable | Shaft diameter (mm) | Material | Manufacturing effort | Assembly effort | Standard (DIN) | Application examples | Remarks |
| 1 | 2 | 1 | 2 | 3 | Nr. | 1 | 2 | 3 | | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| Normal (form fit) | Direct | $T \leq K \cdot \frac{d}{2} \cdot A_s \cdot \tau_{max}$ or $T \leq K \cdot \frac{d}{2} \cdot A_p \sigma_{max}$ | spline shaft |  | 1 | large | h, i, l (shaft diameter, (form) factor, centering factor, material) | — | large | pulsating or alternating | 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 | | | — | | | | | | | | | 150 – 500 | | | | 5481 | | |
| | | | 3-sided polygon-shaft |  | 4 | | e, i, l | — | medium | pulsating or alternating | | self-centering | no | clearance fit without load | | yes for taper | 10 – 100 | | small, special machinery necessary | | — | | 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 | $d_p$, 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 grooved pin possible |
| | | | tangential pin |  | 7 | | | | | — | | | | — | no | | | | | | | | |
| | | | in line pin |  | 8 | | $d_p$, 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

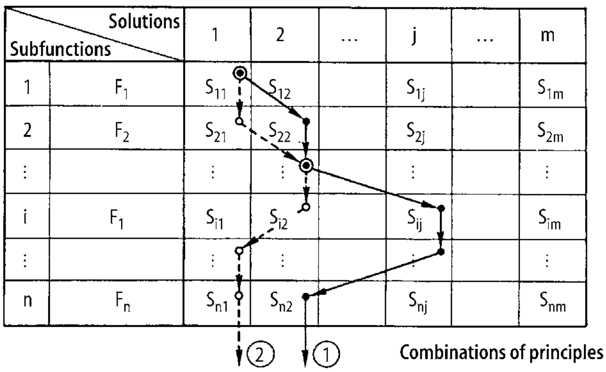



**Figure 3.25.** Combining solution principles into combinations of principles: Combination 1: $S_{11} + S_{22} + \ldots S_{n2}$; Combination 2: $S_{11} + S_{21} \ldots S_{n1}$

- 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

| Change energy / Vary mechan. energy component | | 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.

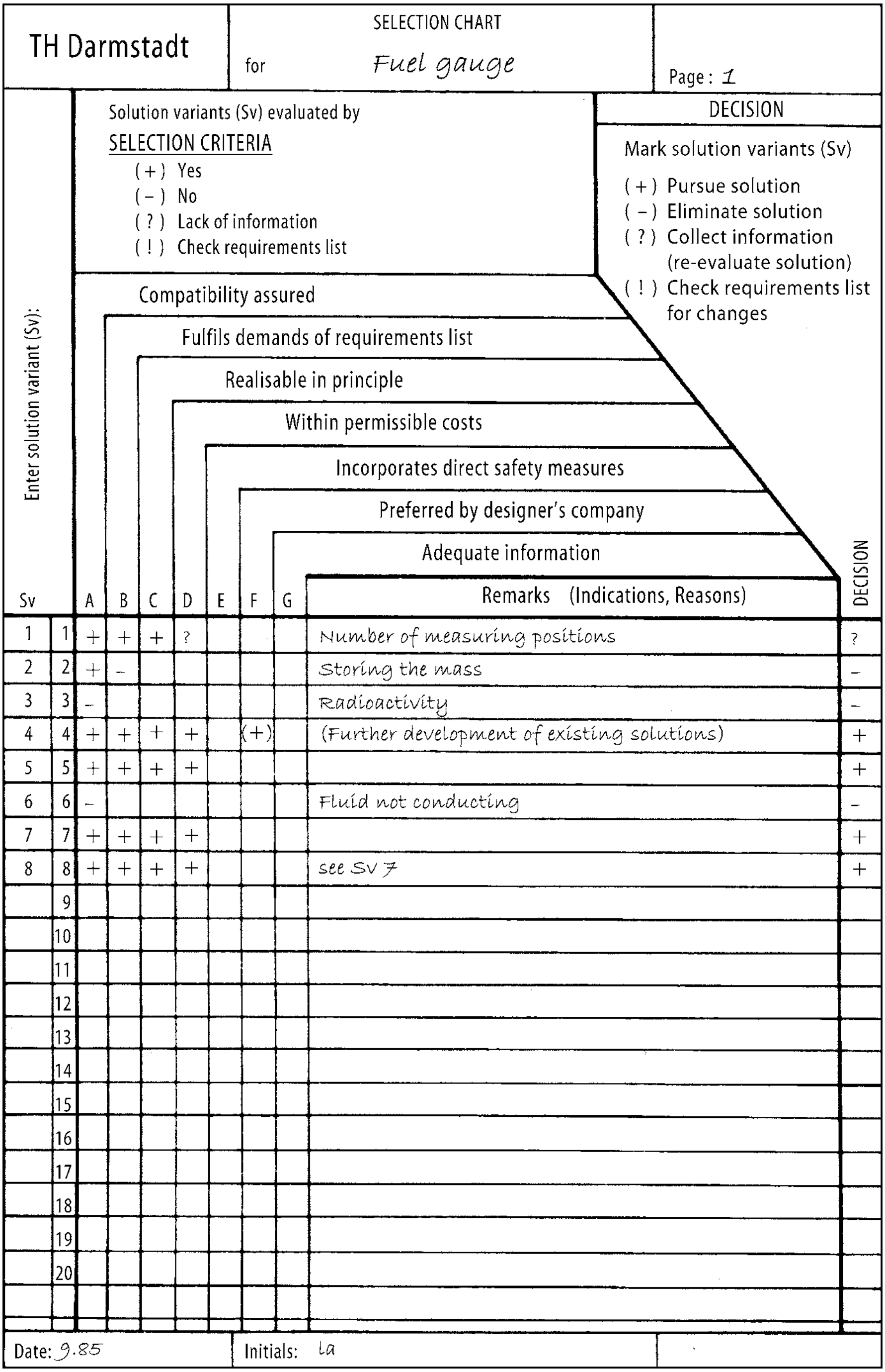
A preference is justified if, among the very large number of possible solutions, there are some that:

- 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<br>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.

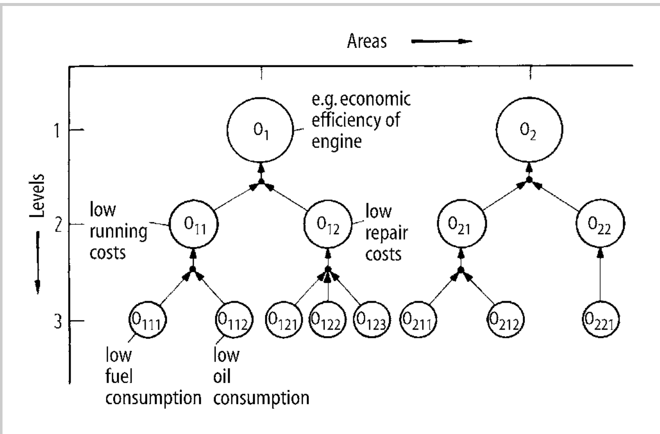



**Figure 3.28.** Structure of an objectives tree

*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

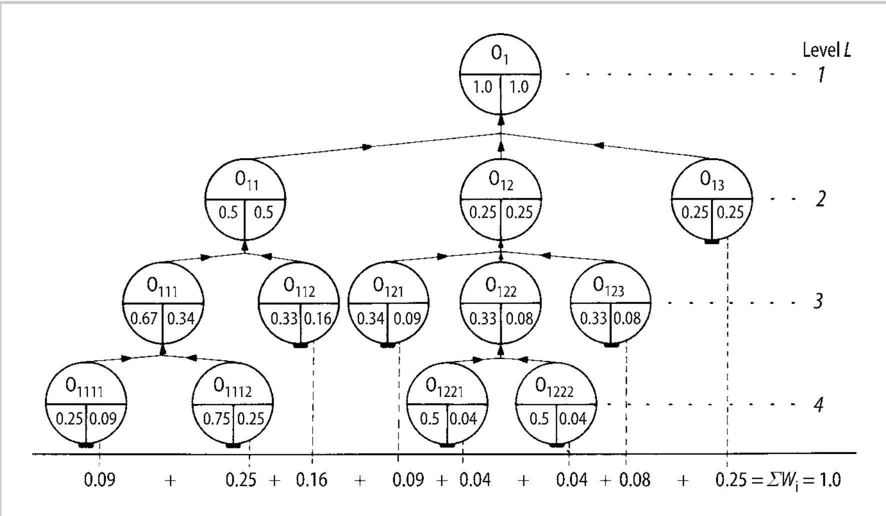



**Figure 3.29.** Objectives tree with weighting factors. After [3.76]

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.

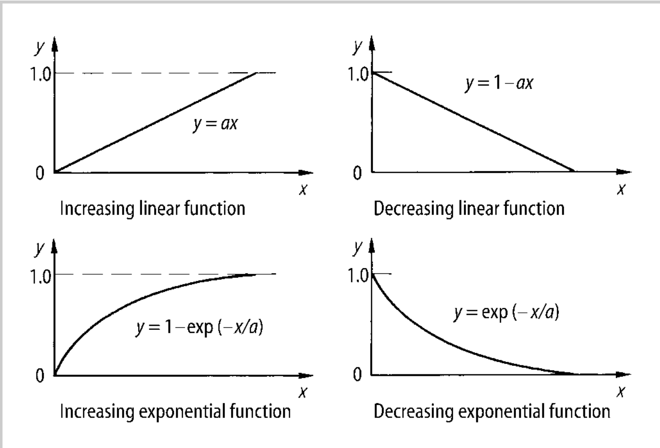



**Figure 3.32.** Common value functions, after [3.76]; $x \triangleq m_{ij}, y \triangleq v_{ij}$

| 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:

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

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:

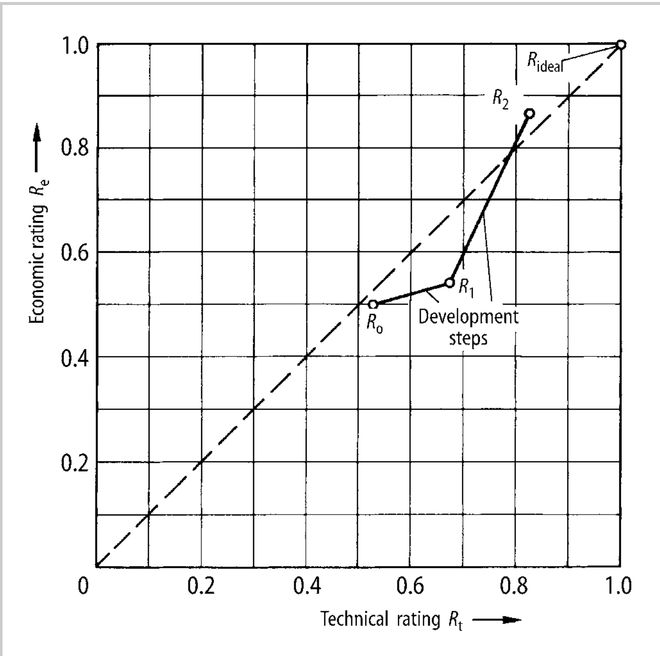



**Figure 3.35.** Rating diagram. After [3.36, 3.71]

- 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

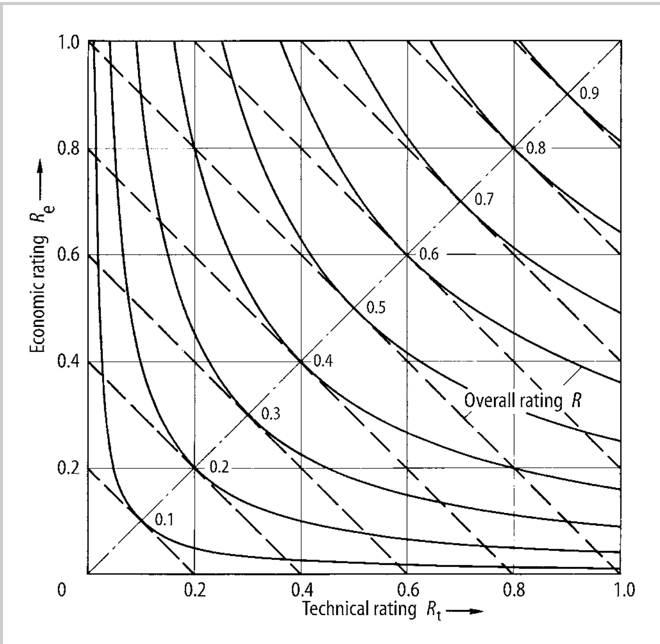



**Figure 3.36.** Determining the overall rating by the straight-line and hyperbolic methods. After [3.1]

| 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].

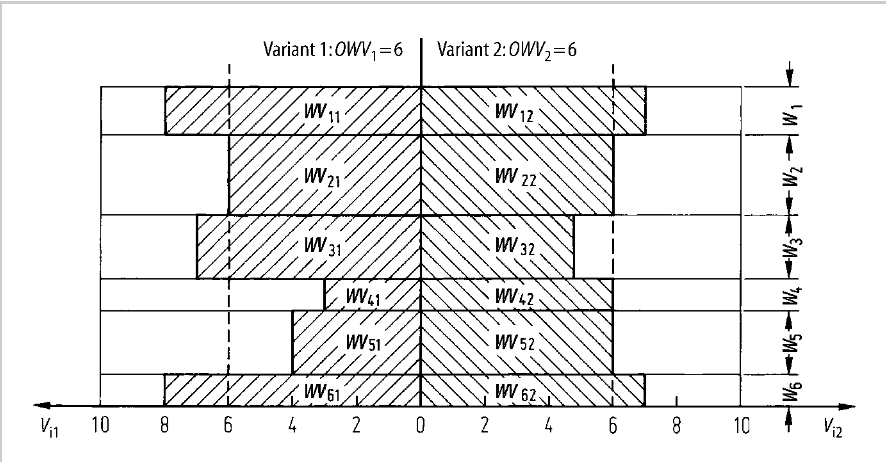



**Figure 3.38.** Value profiles for the comparison of two variants ($\sum w_i = 1$)

## *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.