1 Introduction

1.1 The Engineering Designer

1.1.1 Tasks and Activities

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

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

Design is an interesting engineering activity that:

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

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

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

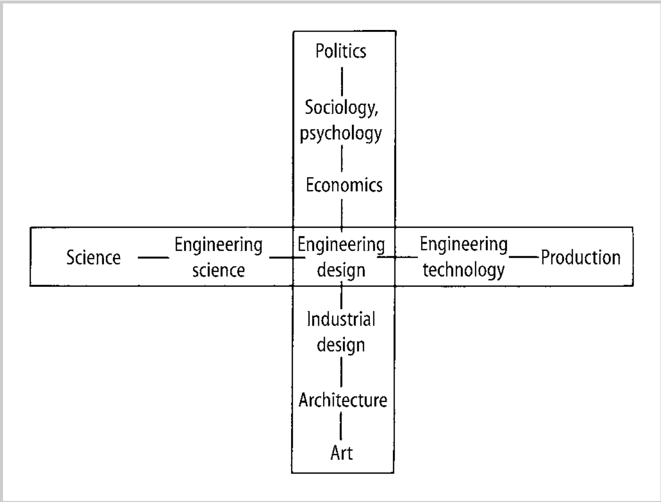

Figure 1.1. The central activity of engineering design. After [1.39, 1.144]

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

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

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

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

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

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

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

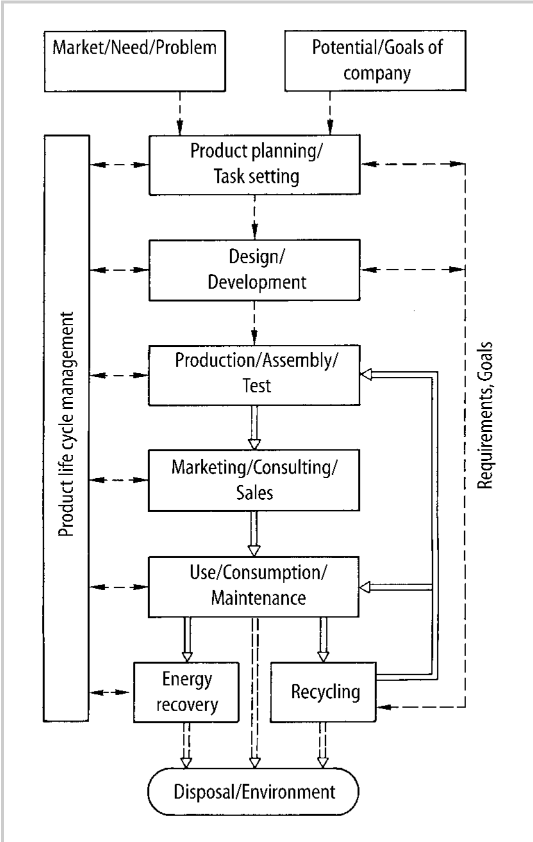

Figure 1.2. Life cycle of a product

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

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

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

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

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

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

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

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

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

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

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

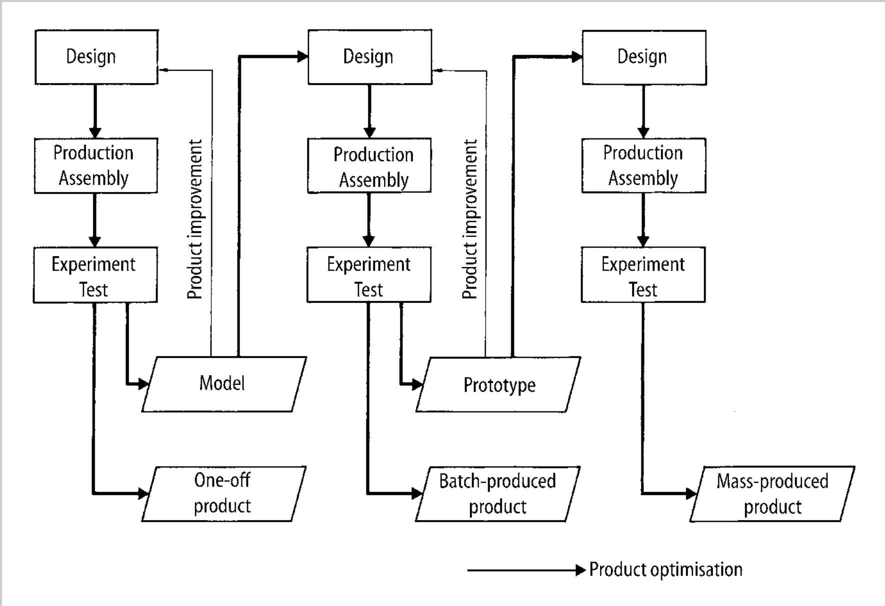

Figure 1.3. Stepwise development of a mass-produced product. After [1.191]

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

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

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

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

The activities of designers can be roughly classified into:

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

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

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

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

1.1.2 Position of the Design Process within a Company

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

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

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

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

1.1.3 Trends

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

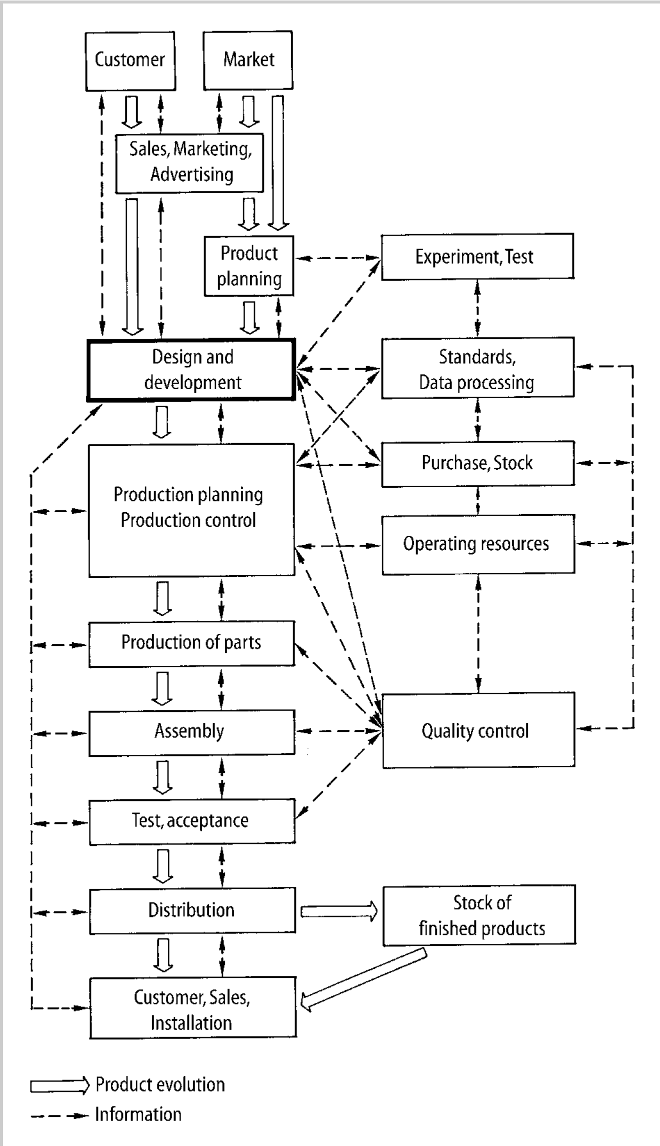

Figure 1.4. Information flows between departments

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

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

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

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

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

1.2 Necessity for Systematic Design

1.2.1 Requirements and the Need for Systematic Design

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

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

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

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

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

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

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

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

A *design methodology*, therefore, must:

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

1.2.2 Historical Background

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1.2.3 Current Methods

1. Systems Theory

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

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

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

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

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

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

2. Value Analysis

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

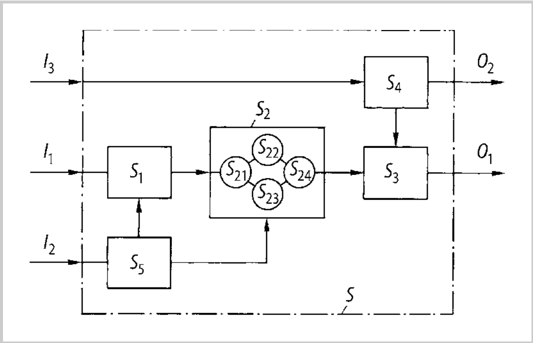

Figure 1.5. Structure of a system. S: system boundary; S_1–S_5: subsystems of S; S_{21}–S_{24}: subsystems or elements of S_2; I_1–I_3: inputs; O_1–O_2 outputs

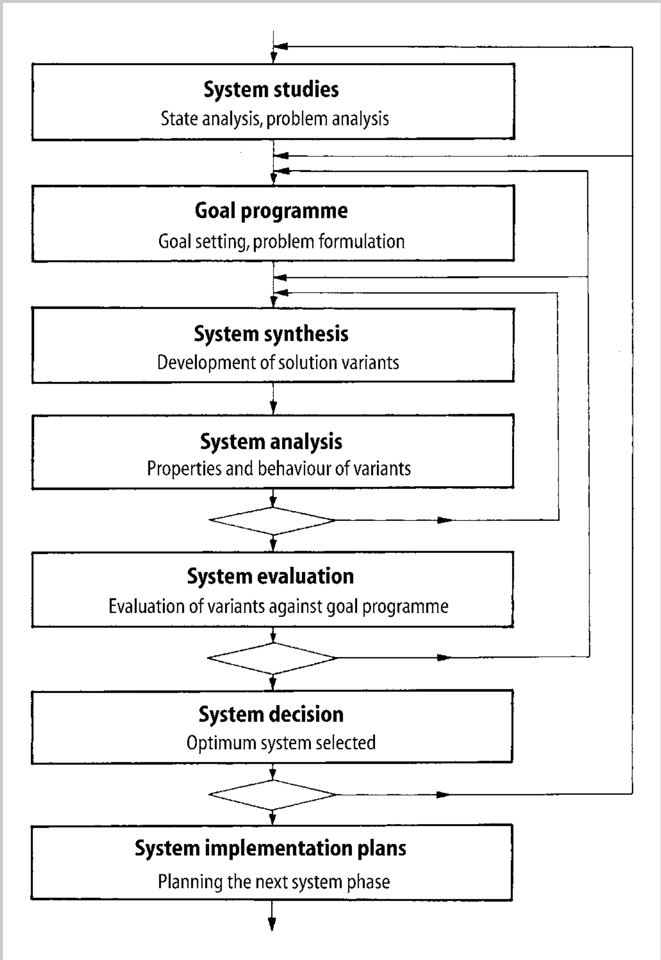

Figure 1.6. Steps of the systems approach

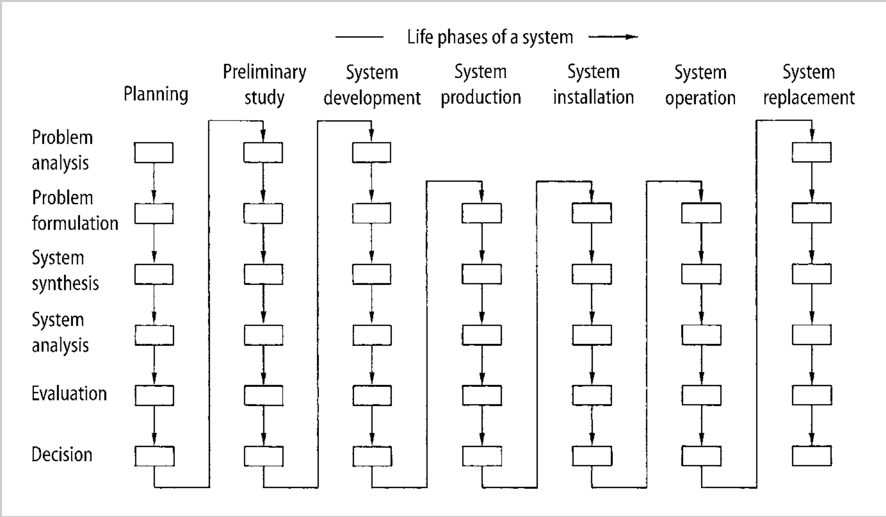

Figure 1.7. Model of the systems approach. After [1.23, 1.52]

Prepare project

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

Analyse actual state

- Recognise functions
- Determine function costs

Determine target state

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

Develop solution ideas

- Collect existing ideas
- Search for new ideas

Determine solutions

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

Realise solutions

- Detail chosen solutions
- Plan their implementation

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

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

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

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

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

3. Design Methods

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

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

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

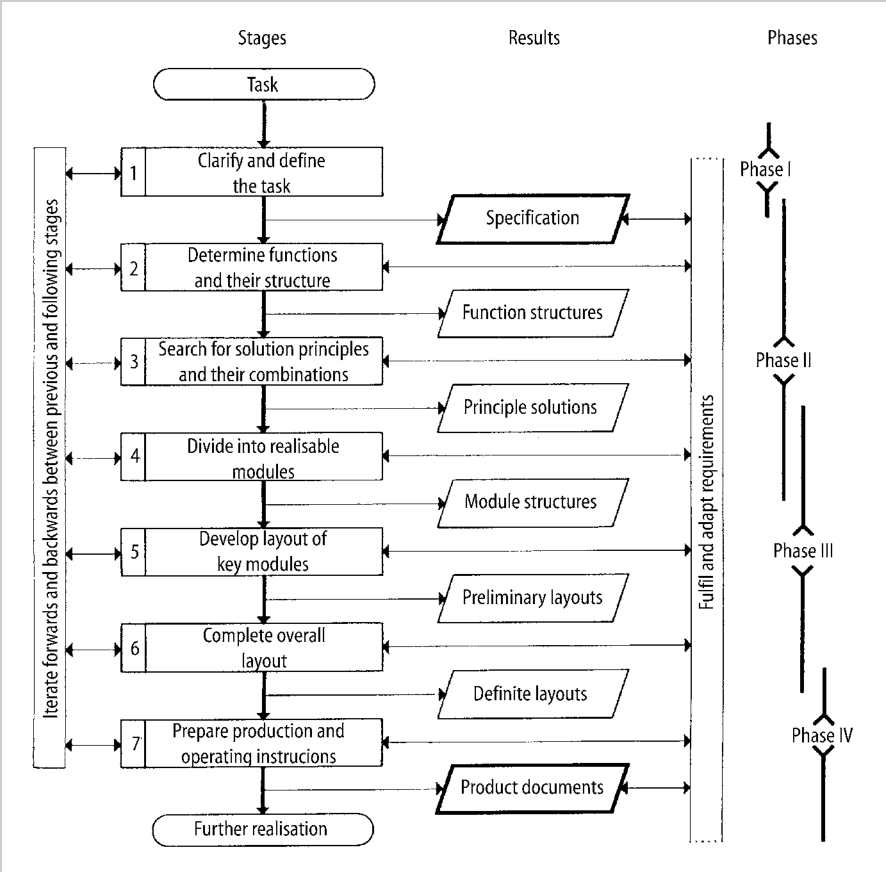

Figure 1.9. General approach to design. After [1.191]

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

1.2.4 Aims and Objectives of this Book

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

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

Table 1.1. Chronological overview of the development of design methodology

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

Table 1.1. (continued)

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

Table 1.1. (continued)

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

Table 1.1. (continued)

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

Table 1.1. (continued)

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

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

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

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

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

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